Evaluating the Performance of Tire-Derived Aggregate in the Leachate Collection Systems of Alberta Landfills

by

Marclus Kathutwa Mwai

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Environmental Engineering

Department of Civil and Environmental Engineering

University of Alberta

Abstract

The application of tire-derived aggregates as drainage media in leachate collection systems is an important component for recovery and recycling of waste tires. However, there are concerns that tire-derived aggregates may not perform adequately because of rapid clogging that is attributed to shape, particle size distribution and compressibility of the aggregates. Other factors associated with media clogging include biogeochemical characteristics of leachates, type and age of landfill, and climatic conditions. These factors are site dependent and, therefore, difficult to generalize. This study evaluated characteristics of leachates from municipal and industrial landfills in Alberta. It also determined properties of tire-derived aggregates that are processed from end-of-life tires from passenger cars and light trucks, medium trucks, and off-road vehicles. In addition, the study compared long term clogging behavior of tire derived aggregates with that of gravel using column tests for a period of up to 420 days.

The study found that municipal landfills in Alberta had leachates of higher strength than those of industrial landfills and, therefore, greater potential for clogging. However, correlations between regional rainfall amounts and leachate strengths could not be established. Compression tests showed that the aggregates were highly compressible with strains of over 50% at 150 kPa. Hydraulic conductivity decreased with media compression; however, there were no significant differences between media types. Long-term clogging tests showed that leachate characteristics varied with depth but that they did not vary significantly with the type of media.

Site specific pollutant fluxes were not determined, but based on past studies conducted to investigate relative importance of acidogenic and methanogenic leachates, leachate collection systems of Alberta's municipal landfills were considered not susceptible to clogging. Based on the findings of compression tests, the study recommended that the as-spread thickness of tire-derived drainage layer should be 840 - 900 mm for a 20 m high landfill. It is further recommended that the key components of experimental set-up that included the design of the top steel plate, location of inline heater, arrangement of leachate pumps and the leachates storage period be configured to minimize variabilities and uncertainties in the study.

Dedication

Dedicated to my family who braved many odds, including my infrequent long-distance calls.

Acknowledgements

This dissertation would not have been possible without the contribution of a number of people. My supervisor, Dr. Daryl McCartney, graciously extended me opportunity to explore the limits of the problem statement and guided me into penning down my thoughts. His commitment to evidence-based research motivated me throughout the study. My deep appreciation also goes to the PhD Examining Committee for commenting on my work and overall guidance provided to me. To you Kristine, as a researcher, your sense of what required to be done was awesome and no doubts the fountain of new ideas and thoughts. My colleagues', in "We are Solid Waste Group," help, sense of humour and patience was calming even during the most difficult times. My sincere appreciation goes to the Alberta Recycling Management Authority (ARMA) for funding the study, and providing information about tire derived aggregates (TDA) in Alberta. I also appreciate Charles Huck for collecting and delivering TDA to the study site; Salim Abboud and Earl Jenson from Alberta Innovates Technology Futures (AITF) for experimental apparatus design, construction, and operating advice; the City of Edmonton (in particular Christian Felske, Larry Grams, Cam Hailey, Murray Taylor, and Allan Yee) for logistical support and advice on various tasks. To you Wamuyu, Mwai, Wanjiru and Nyawira, your patience and love kept my midnight oil burning; this study could not have been possible without your support and understanding.

Contents

Abstract ii

Acknowledgements v

List of Tables ix

List of Figures xi

List of Symbols and Abbreviations xv

1 Introduction 1

1.1 Problem Definition 1

1.2 Conceptual Framework 2

1.2.1 Performance of LCDS 4
1.2.2 Landfill Type, Geometry, and Operations 5
1.2.3 Clogging Phenomenon 7
1.2.4 Leachate characteristics 10
1.2.5 Media Characteristics 11

1.3 Objectives of the study 12

1.4 Study Research Questions 13

1.5 Organization of the Thesis 13

1.6 Key Findings of the Study, Contributions to Field Applications, and to the Advancement of Scientific Knowledge 14

1.6.1 Field Applications and Engineering Practice 14
1.6.2 Advancement of Scientific Knowledge 15

References 16

2 Composition and Strength of Leachates in Alberta's Sanitary Landfills and its implications on the performance of leachate collection and drainage systems 20

2.1 Introduction 20

2.2 Materials and Methods 31

2.2.1 Description of the Study Area 31
2.2.2 Physico-Chemical Parameters 33
2.2.3 Statistical Analysis 33

2.3 Results and Discussions 33

2.3.1 General Characteristics of Leachates in Alberta Landfills 33

2.4 Spatial variation of leachate chemistries 42

2.5 Implications of the leachate composition and strengths on susceptibility of Alberta's LCDS to clogging 46

References 49

3 Compressibility of tire-derived aggregates: effects on hydraulic performance and on long-term thickness of leachate collection and drainage systems 54

3.1 Introduction 54

3.2 Materials and methods 59

3.2.1 Materials 59
3.2.2 Apparatus and test procedures 59

3.3 Results and Discussions 64

3.3.1 Particle size distributions 64
3.3.2 Specific Gravities of TDA 65
3.3.3 Uni-axial compression behavior of TDA 65
3.3.4 Changes in drainable porosity 68
3.3.5 Hydraulic conductivity of TDA 69

3.4 A Criterion for determing as spread-thickness of a TDA-based drainage layer 72

4 An Experimental Investigation of Clogging Behavior of TDA 84

4.1 Introduction 84

4.2 Experimental Set-up, Material and Methods 91

4.2.1 The experimental set-up 91
4.2.2 Materials 92
4.2.3 Methods 96

4.3 Results and Discussions 107

pH 107
4.3.2 COD 112
4.3.3 TSS 118
4.3.4 Calcium 126
4.3.5 Magnesium 133
4.3.6 Drainable Porosity 138
4.3.7 Hydraulic Conductivity 143
4.3.8 Clog Material 145
4.3.9 Chemical Stability of TDA Materials 149

4.4 Practical Implications of the Clogging Study on the Long-Term Performance of TDA as Media for LCDS 150

4.4.1 Limitations of the Clogging Study 151
4.4.2 Comparison of media performances 153

References 156

5 Conclusions and Recommendations 160

5.1 Composition and Strength of Leachates in Alberta Landfills and Its Implications on Performance of LCDS 160

5.2 Characterization of TDA Processed in Alberta 161

5.3 Long-term Clogging Tests 162

Appendix A: Landfills operating in Alberta 164

Appendix B: Physical characteristics of TDA 225

Appendix B1. Raw Data for particle specific gravity 226
Appendix B2. Conversion of overburden to sanitary landfill height 228
Appendix B4. Raw data for porosity of TDA 238
Appendix B5. Linear regression for Compression index of TDA 239
Appendix B6. Raw data for porosity of TDA 242
Appendix B7. Linear regression for Coefficient Compression 245
Appendix B8: Hydraulic conductivity data 251

Appendic C: Long-term Clogging Study 300

Appendix C1- Changes in Leachate Chemistry – Day 0-127 300
Appendix C2- Changes in Leachate Chemistry – Day 127-427 312
Appendix C3- Mass Balance Analysis 324
Appendix C4: Drainable porosity 336
Appendix C5: Hydraulic conductivities of clogged media 339
Appendix C6: Mineral Phases 342
Appendix C7: Photographic Records 349

List of Tables

Table 2-1. Composition of sanitary landfill leachates reported in literature 21
Table 2-2. Summary of the previous leachate characterization studies, focus and key findings . 26
Table 2-3. Summary of Bio- Geochemical Processes Associated with Clogging Phenomenon .. 29
Table 2-4. Classification of sanitary landfills in Alberta and the type of materials deposited. 32
Table 2-5. Descriptive statistics for various leachate parameters as sampled from twelve Class II municipal sanitary landfills. 34
Table 2-6. Descriptive statistics for various leachate parameters as sampled from eleven Class II industrial landfills 35
Table 2-7. Geographic locations and typical annual precipitation for the 12 municipal landfill sites... 43
Table 3-1. Overview of properties of TDA based on previous studies 56
Table 3-2. Specific gravity of TDA products and gravel. Values are averages based on 3 samples 65
Table 3-3. Showing the strains achieved at compression pressures of 22 and 153 kPa for various samples of the TDA materials. 67
Table 3-4. Values of coefficient of compression, Cc, and e_o values applicable for equation [3-8]. The Cc values are the gradients of the void ratio-$\log_e$ pressure plots. 75
Table 3-5. Hyperbolic parameters for different compaction effort and amount of soil cover as recommended by Zekkos *et al.* (2006).. 77
Table 3-6. Values of initial media thickness based on safety factors for media compression and clogging for a 20 m landfill with PLTT as media for drainage 80
Table 3-7. Values of initial media thickness based on safety factors for media compression and clogging for 20 m landfill with OTR as media for drainage.................................... 80
Table 4-1. Summary of the previous studies involving clogging phenomenon. 86
Table 4-2. Sources of TDA and gravel test materials as applied in the study 94
Table 4-3. Leachate characteristics based on an Alberta leachate characterization study (means ± standard error). 96
Table 4-4. Flow conditions adopted for the study 98
Table 4-5. Parameters for hydraulic conductivity as determined from clean media. 103

Table 4-6. Average loss in drainable porosity in different media columns, compared to initial porosities, after leachate was run through the columns between 168 and 427 days. 141
Table 4-7. Comparison between drainable porosity at the end of clogging tests and drainable porosity after column flushing. Values presented are averages for the whole column. 142
Table 4-8. Measured and predicted hydraulic conductivity (K) values for TDA and gravel drainage media at the end of the clogging experiment. 144
Table 4-9. Mineral phases forming the clog cake and suspended solids (removed during column flushing), as determined by XRD analysis. 148
Table 4-10. Comparison between key clogging parameters in leachate influent to the columns in this study and in 12 Alberta Class II municipal solid waste landfills. 151
Table 4-11. Performance of the drainage media based on ANOVA. The parameters shown are those associated with significant differences with $p < 0.05$ and as discussed in section 4.3 (pH, COD, TSS, Ca^{2+} and drainable porosity). 154

List of Figures

Figure 1-1. Conceptual framework indicating the inter-relationships between factors that influence performance of LCDS 3
Figure 1-2. Configuration of LCDS typically adopted for landfill liner and LCDS. The vertical scale is exaggerated relative to horizontal scale for purposes of clarity. The configuration presented is applicable for active landfills, where top covers have not been installed.......... 6
Figure 1-3. Typical LCDs sections modelled in previous studies 8
Figure 2-1. Variability of pH in Class II municipal landfills of Alberta 37
Figure 2-2. Variability of COD in municipal landfills of Alberta, Canada. 38
Figure 2-3. Temporal variability of leachates COD in typical municipal landfill (Landfill 4) 39
Figure 2-4. Variability of TSS in Class II landfills of Alberta, Canada 41
Figure 2-5. Variability of Ca2+ in Class II landfills of Alberta, Canada.......... 42
Figure 2-6. Correlation between annual rainfall and mean COD concentrations in Alberta's municipal landfills.......... 44
Figure 2-7. Correlation between annual rainfall and mean TSS concentrations in Alberta's municipal landfills.......... 44
Figure 2-8. Correlation between annual rainfall and mean Ca2+ concentrations in Alberta's municipal landfills.......... 45
Figure 2-9. Mean, maximum and minimum concentration of COD for the 12 municipal landfills shown against clogging range as observed by (Fleming et al., 1999). 48
Figure 2-10. Mean, maximum and minimum concentrations of COD for the 12 municipal landfills shown against clogging range as observed by (Fleming et al., 1999). 49
Figure 3-1. Photographs of the test materials: a) PLTT-flat and elongated shape and clean cut edges, b) OTR-block shape and roughly cut edges, c) OTR+PLTT -a mixture of OTR and PLTT on 50:50 by weight basis, d) gravel (clean river bed gravel), e) MTT-flat and elongated shape and clean cut edges. 60
Figure 3-2. Assembly for compressibility tests column 62

Figure 3-3. TDA distribution curves showing percentage of: (a) MTT, (b) OTR, (c) OTR+PLTT, (d) PLTT, and (e) gravel passing different sieve sizes. 64
Figure 3-4. Showing strains against vertical stresses in case of PLTT, OTR, MTT and OTR+PLTT. 66
Figure 3-5. Showing unit weights against vertical stresses in case of PLTT, OTR, MTT and OTR+PLTT. 68
Figure 3-6. Lines of best fit showing variation of drainable porosities with overburden pressures. The corresponding landfill heights were based on the model recommended by Zekkos et al. (2006), assuming initial unit weight of waste as 10 kN.m-3. 69
Figure 3-7. Lines of best fit showing variation of hydraulic conductivity with porosity of TDA 70
Figure 3-8. Variation of hydraulic conductivity data when combined for all TDA media types processed in Alberta. 71
Figure 3-9. Relationship between thickness of TDA and log10 Pressure 72
Figure 3-10. Relationship between void ratio of TDA and loge Pressure 73
Figure 3-11. Relationship between thickness of PLTT and OTR layer and the landfill heights. The initial unit weight refers to the near surface weight density of MSW. 78
Figure 4-1. Typical cross-section for a LCDS 85
Figure 4-2. Schematic diagram showing apparatus set-up, sampling ports, leachate tank, inflow, and effluent flow directions. 93
Figure 4-3. Showing leachate inflow port at the base of the columns 97
Figure 4-4. Annual rainfall data for the period between 1975 and 2009 as recorded at the Edmonton International Airport. 97
Figure 4-5. Leachate effluent arrangement showing position of air bubbles within the fluent lines. 105
Figure 4-6. Leachate effluent arrangement consisting of effluent pipe, pressure break-up cups and drain pipe. 106
Figure 4-7. (a) Average and (b) normalized average pH values as leachate permeated through TDA and gravel media for the period between day 0 and 168. 109
Figure 4-8. (a) Average and (b) normalized average pH for the period from day 168 to 427 as leachate permeated through TDA and gravel media. 110

Figure 4-9. Variation of pH on day 420 as leachate permeated through TDA and gravel media. 110
Figure 4-10. (a) Average and (b) normalized average COD levels as leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, for the period between days 0 and 168........ 113
Figure 4-11. Temporal variation of COD as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, based on the COD influent concentrations at sampling level 0.625 m........ 113
Figure 4-12. (a) Average and (b) normalized average COD concentrations for the period from day 168 to day 427 as leachate permeated through TDA and gravel media........... 115
Figure 4-13.Temporal variations in normalized COD for TDA and gravel media columns. Data shown is for days 234, 301, 364, and 407........ 117
Figure 4-14. (a) Average and (b) normalized average TSS concentrations for the period between days 0 and 168 as leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns. 119
Figure 4-15. Temporal variations in TSS in PLTT, OTR, gravel and OTR+PLTT columns, for day 27, 83, 140 and 168. 121
Figure 4-16. (a) Average and (b) normalized average TSS concentrations for the period from day 168 to day 427 as leachate permeated through TDA and gravel media. 123
Figure 4-17. Temporal variations in TSS (normalized to column influent concentration) as leachate flowed through PLTT, OTR, gravel and OTR+PLTT columns. Data is shown for days 260, 308, 342, 385 and 414. 124
Figure 4-18. (a) Average and (b) normalized average calcium concentrations in PLTT, OTR, gravel and OTR+PLTT columns for the period between days 0 and 168. 127
Figure 4-19. Temporal variation of calcium as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, based on the calcium concentrations on days 13, 41, 153 and 167........ 128
Figure 4-20. (a) Average and (b) normalized average calcium concentrations for the period between day 168 and day 427 as leachate permeated through TDA and gravel media. 131

Figure 4-21. Temporal variations in normalized calcium concentrations as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns on days 308, 343, 371, 385, and 414. 132
Figure 4-22. (a) Average and (b) normalized average magnesium concentrations as leachate permeated through the gravel and TDA columns, for the period between days 0 and 168. 135
Figure 4-23. Variation of magnesium with depth for PLTT, OTR, Gravel and OTR+PLTT columns, based on the magnesium concentrations on day 167. 135
Figure 4-24. (a) Average and (b) normalized average magnesium concentrations for the period from days 168 to 427 as leachate permeated through TDA and gravel drainage media. 136
Figure 4-25. Temporal variations in normalized magnesium concentrations as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns on days 308, 371, 385 and 414. 137
Figure 4-26. Loss in drainable porosity as determined in each of the media columns on day 168. The percentage loss in porosity was determined by dividing the drainable porosity in each segment of the column on day 168 by the initial drainable porosity (≈ 0.4) in each of the columns and subtracting from 100%. 139
Figure 4-27. Drainable porosity losses in PLTT, OTR, gravel and OTR+PLTT columns by day 427, as a percentage of the initial drainable porosity of about 0.4. 140
Figure 4-28. Visual examination of clogging in the PLTT column: a) top of the media, b) middle of the media and c) bottom of the media. 146

List of Symbols and Abbreviations

A	a coefficient	
ANOVA	analysis of variance	
ASTM	American Standard and Test Methods	
B	a coefficient	
BOD	biochemical oxygen demand	mgL^{-1}
Cc	coefficient of compression	
CI	compression index	
COD	chemical oxygen demand	mgL^{-1}
d	depth: depth of TDA layer	m
D	diameter (e.g. internal diameter of pipe)	m
D_{10}	particle size corresponding to which 10% particles are finer	m
D_{50}	particle size in which 50% is finer	m
D_{60}	particle size in which 60% is finer	m
dh	change in depth	m
$D_{initial}$	initial depth	m
e	void ratio	
e_o	initial void ratio	
g	acceleration due to gravity ($9.81ms^{-2}$)	$m\cdot s^{-2}$
Gs	specific gravity	
Ho	initial depth	m
hr	Hour	
i	hydraulic gradient	
Ky	Vertical hydraulic conductivity	$m\cdot s^{-1}$
kN	kilonewtons	
kPa	Kilopascal	

L	litre	-
LCDS	leachate collection and drainage system	
$\log_{10}$	common log	
Ls	Length of flow	m
M	mass	kg
$mass_{TDA}$	mass of TDA	kg
mg	milligram	
mm	millimeter	
MNm^{-2}	million newtons per square metre	
MTT	medium truck tires	
n	porosity	-
OTR	off-the road Tires	
P	overburden pressure	kPa
PLTT	passenger and light truck tires	
P_o	initial pressure	kPa
R	regression coefficient	
Re	Reynolds's number	
TDA	tire derived aggregates	
TSS	total suspended solids	$mg\ L^{-1}$
V	velocity; superficial velocity	$m\ s^{-1}$
v	kinematic viscosity	m^2s^{-1}
V_{water}	volume of water	m^3
XRD	x-ray diffraction	
z_w	depth of at which unit waste is to be estimated,	m
α_w	model parameter for unit weight of waste	$m^4\ kN^{-1}$.
β	angle	radians
β_w	model parameter for unit weight of waste	$m^3\ kN^{-1}$
γ_i	near-surface in-place unit weight	$kN\ m^{-3}$

γ_{water}	unit weight of water	kN m^{-3}
γ_z	unit weight of waste at depth z_w	kN m^{-3}
ε	drainable porosity	
η	Dynamic Viscosity	$N \cdot s\ m^{-2}$
θ	Temperature	^{o}C
ρ	density of water	kg m^{-3}
ρ_{TDA}	density of TDA	kg m^{-3}
τ	Strain	
υ	poisson's ratio	

1 Introduction

1.1 Problem Definition

Some of the solid wastes that are most difficult to manage are waste tires. Waste tires are mostly stockpiled in open spaces, which causes pollution and wastes space (Drescher et al., 1999). Several options for re-use and recycling of waste tires have been proposed. They include burning waste tires as fuel and incorporation in making of rubber modified asphalt (Drescher et al., 1999). Waste tires have also been shredded into smaller pieces and used as fill material for embankments or as a drainage medium in leachate collection and drainage systems (LCDS). The shredded waste tires are commonly referred to as tire chips, if particle sizes are between 12 and 50 mm, and tire shreds if particles sizes are between 50 and 305 mm. Combined chips and shreds of sizes ranging from 12 to 305 mm are generally referred to as Tire-Derived Aggregate (TDA)(ASTM 2009). The acronym TDA is used in this thesis to refer to shredded waste tires applied as drainage media in LCDS.

Application of TDA in LCDS has formed a significant component of waste tire recycling efforts (Aydilek et al., 2006; EWMCE, 2009; Hudson et al., 2007). However, there have been concerns that TDA may not perform adequately, because of: i) leaching of toxic substances used in the manufacture of tires, and ii) potential for rapid clogging due to compression and the size and shape of the particles. Aydilek et al. (2006) investigated leachability of TDA under landfill conditions and concluded that concentrations of inorganic compounds, dissolved metals and volatile organic compounds (VOCs) were not significantly different from those of gravel media. The findings may be attributed to attenuation of pollutants by the LCDS through precipitation and adsorption processes. Therefore, the contribution of toxic substances by leachate is not a major issue (Aydilek et al., 2006). The problem of clogging is more complicated. McIsaac and Rowe (2005) found that TDA may perform poorly and that its lifespan may be three times less than that of gravel. In contrast, Aydilek et al. (2006) demonstrated that clogging was not a major issue for TDA and adequate drainage conditions could be maintained. Hudson et al. (2008) found that tire shreds performed similarly to gravel. They also explained that the leachates applied by McIsaac and Rowe (2005) were of much higher strength than those in the field. The strength of leachates notwithstanding, the gravel and TDA were subjected to similar leachates in the McIsaac and Rowe (2005) study and yet showed distinct levels of clogging. These observations raise fundamental questions of how the TDA that are compressible would perform as drainage media considering that LCDS are subjected to high overburden pressures and severe chemical and biological conditions

Several authors (e.g. EWMCE, 2009; Hudson et al., 2007) recommended that for proper design of TDA-based LCDS, characterization of leachates should be conducted on site by site basis. The specifications of TDA should also be matched with properties of TDA that are commercially available and that are typically used in LCDS. A study was therefore commissioned in 2009 to evaluate performance of TDA processed in Alberta, Canada. The background information, experimental programs, and findings of the study form the basis of this thesis. Below is a discussion of the conceptual framework that guided the study.

1.2 Conceptual Framework

Previous studies on long-term performance of LCDS (Drescher et al., 1999; EWMCE, 2009; Hudson et al., 2007; Rowe, 2005) suggested that they may be influenced by the following four factors:

i) Physical and mechanical properties of drainage media,

ii) Leachate characteristics

iii) Clogging phenomena

iv) Landfill type and geometry

Figure 1-1 depicts the inter-relationships between these factors, which form the overall conceptual framework for the study.

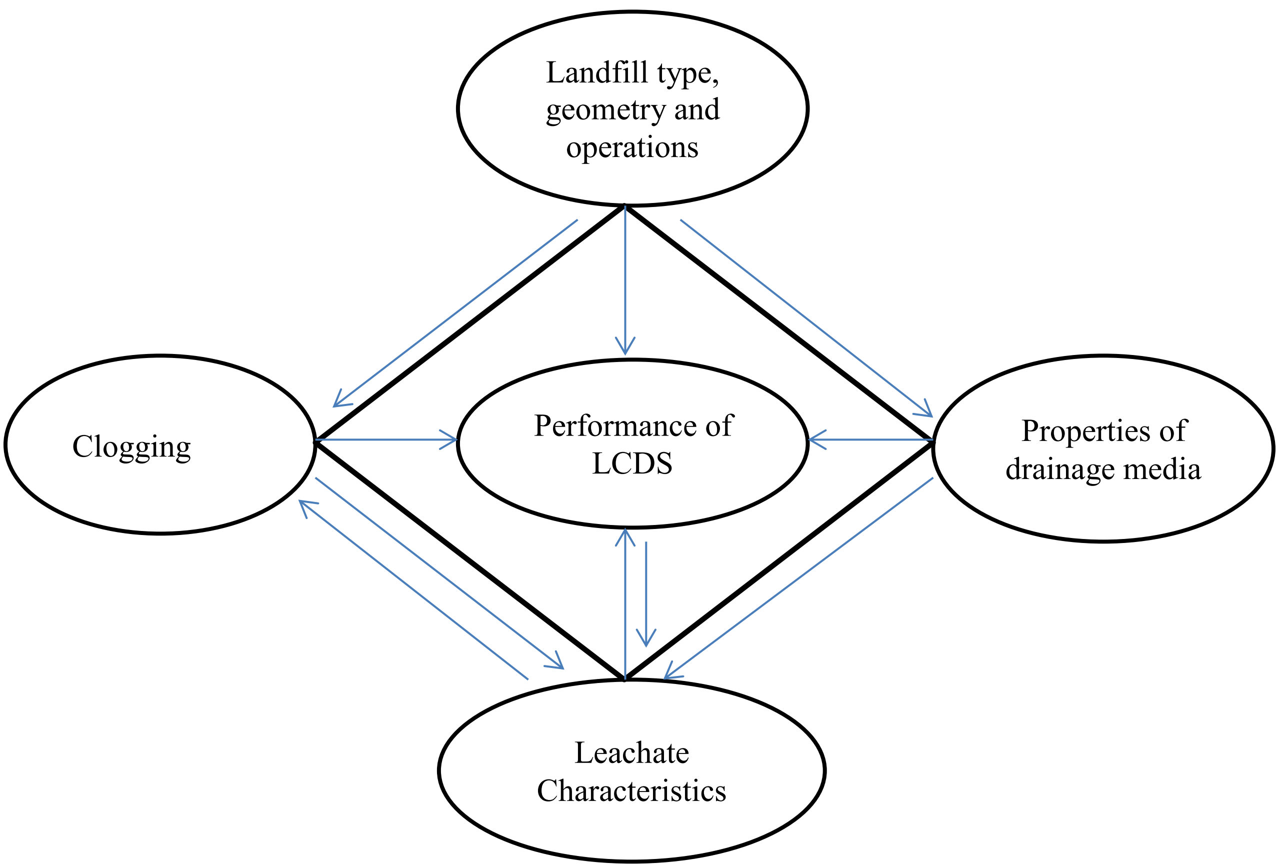


Figure 1-1. Conceptual framework indicating the inter-relationships between factors that influence performance of LCDS

Figure 1-1 shows that drainage media, landfill type and geometry, leachate characteristics and clogging not only influence performance of LCDS directly but also each other. Landfill type and operations may also affect the clogging processes through organic loading and drainage media properties such as compression. Leachate characteristics that include composition and strengths influence the rate of clogging. Performance of LCDS may influence leachate characteristics; for example, through leachate mounding. Climatic conditions and geology are not explicitly shown in the framework because they are considered to relate more to leachate characteristics and the clogging process. The various components of the conceptual framework (Figure 1-1) are discussed in the following sections.

1.2.1 Performance of LCDS

The primary function of LCDs is to control movement of leachates and ensure there are negligible environmental impacts associated with landfills. The long-term performance of LCDS is critical because LCDS are commonly subjected to high overburden pressures and adverse chemical and biological conditions (Rowe, 2005). The criterion for evaluating performance of LCDS is the 'maximum acceptable leachate head' above the impermeable liner (Alberta Environment, 2010; McBean et al., 1995). To facilitate the evaluation, mathematical formulations that approximate maximum leachate mound over a liner have been proposed. The most commonly used formulations are:

(1) Moore 1983 (McBean et al., 1995; Qian et al., 2004)

$$y_{\max} = \frac{X}{2}\left[\left(\frac{Rn}{K} + S^2\right)^{0.5} - S\right] \qquad [1\text{-}1]$$

(2) Moore 1980 (McBean et al., 1995; Qian et al., 2004)

$$y_{max} = \frac{X}{2}\left(\frac{Rn}{K}\right)^{0.5}\left[\left(\frac{K\,S^2}{Rn}\right)+1-\left(\frac{K\,S}{Rn}\right)\left(S^2+\frac{Rn}{K}\right)^{0.5}\right] \quad [1\text{-}2]$$

Analytical method that assumes flat slope configuration (Fleming et al., 1999),

$$y_{max} = \frac{X}{2}\left(\frac{Rn}{K}\right)^{0.5} \quad [1\text{-}3]$$

where, for equations 1-1 to 1-3,

y_{max} = maximum liquid head on the landfill liner, mm

X = horizontal drainage distance, mm

Rn = inflow rate, mm s^{-1}

K = hydraulic conductivity, mm s^{-1}

S = slope of the drainage layer, S = tanβ

β = slope of the drainage layer,

All the three equations relate leachate head to landfill geometry, rate of percolation and hydraulic properties of the drainage media.

1.2.2 Landfill Type, Geometry, and Operations

Sanitary landfilling is a key component of solid waste management. Landfills are classified according to the type of the waste that they receive (Alberta Environment, 2010); for example, municipal sanitary landfills accept domestic wastes, while industrial landfills are associated with waste generated by industries. The characteristics of waste deposited, mode of operation and the type of landfill influence the overall performance of LCDS (Rowe, 2005; Zekkos et al., 2006). Furthermore, the type of top covers influences landfill moisture conditions and therefore long-term performance of LCDS (Rowe, 2005).

The geometry commonly adopted for the construction of the landfill containment system and LCDS is that of an inverted V with drains for intercepting leachates at the lowest point of the arms (Figure 1-2). Key factors relating to landfill geometry are the distances, X, between drains, and slope of the bed, β. Typical leachate flow distances are 20 to 65 m (Fleming et al., 1999). LCDS are normally constructed with slopes ranging from 1 to 5% for efficiency of drainage (McBean et al., 1995). In general, the smaller the slope, the greater the leachate head. It is common practice to construct gravel and TDA LCDS in layers of 0.5 m thickness. However, if clogging occurs within LCDS, the head may become excessive and exceed 0.5 m, thereby making leachate mound reach the waste mass. The LCDS also becomes saturated, a condition that enhances clogging processes and therefore performance (Rowe, 2005).

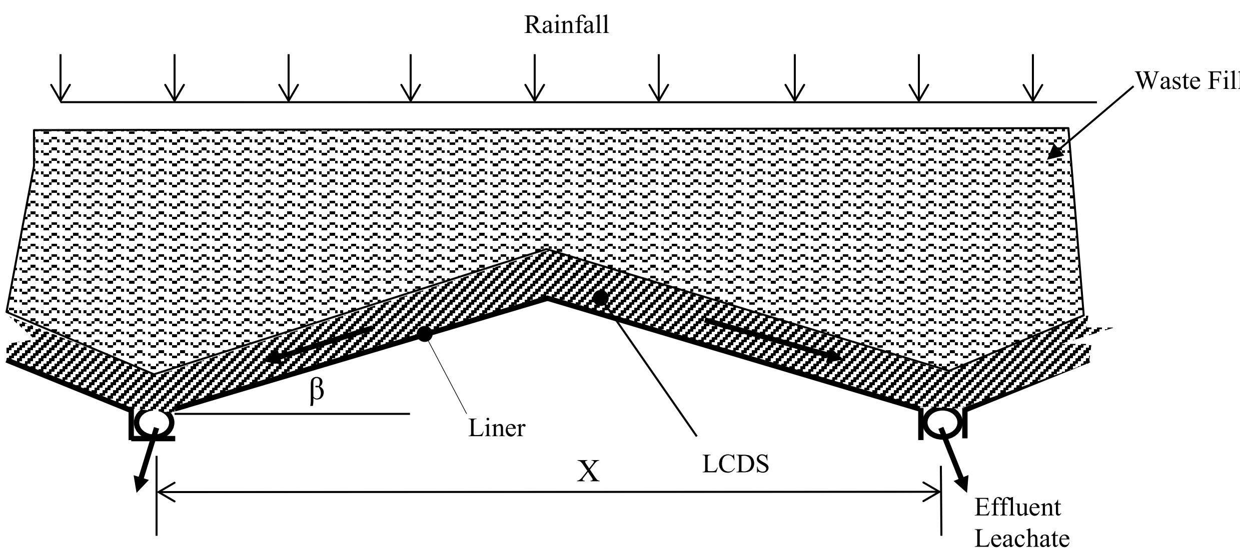


Figure 1-2. Configuration of LCDS typically adopted for landfill liner and LCDS. The vertical scale is exaggerated relative to horizontal scale for purposes of clarity. The configuration presented is applicable for active landfills, where top covers have not been installed.

1.2.3 Clogging Phenomenon

Media clogging has three main components; namely, biological, chemical, and physical (EWMCE, 2009; Mostafa and Van Geel, 2007). The biological component involves growth of micro-organisms that are closely associated with the metabolic processes of acetogenesis and methanogenesis (Cooke et al., 1999). New bacterial cells are formed, thereby encouraging development of biofilms that reduce media porosity (Fleming et al., 1999; McIsaac and Rowe, 2005; Mostafa and Van Geel, 2007). Chemical clogging is associated with precipitation mainly of calcium carbonate, and subsequent formation of stable mineral phases such as calcites (Cooke et al., 2001; McIsaac and Rowe, 2005; VanGulck et al., 2003). These minerals form scales that may reduce pore spaces and therefore affect permeability of drainage media. Physical clogging involves filtration and straining of suspended particles (Cooke and Rowe, 2008; Cooke et al., 2005). The initially trapped particles may act as nucleation sites for further deposition of both organic and inorganic solids resulting in progressive clogging of media. The trapped particles may also enhance sorptive processes thereby causing pre-treatment of leachates (Fleming et al., 1999).

Studies on mechanisms of clogging have typically involved three approaches; namely, 1) field investigations, 2) laboratory experiments, and 3) numerical modelling. Field studies can give a real time picture of landfill conditions; for example, Fleming et al. (1999) examined an existing LCDS and established that clog material comprised of mineral precipitates, fine granular particulates, and biofilms growing under anaerobic conditions. Nevertheless, field the studies are not only rare but problematic because of potential of damaging landfill containment system (EWMCE, 2009; Fleming et al., 1999).

Laboratory studies involve bench-scale experiments that simulate landfill conditions in the field (Fleming and Rowe, 2004; McIsaac and Rowe, 2005). Figure 1-3 shows a section of LCDS that are typically used to simulate clogging phenomenon under laboratory conditions. Some of the assumptions commonly made for the modeled section are saturated flow conditions, and vertical flow regimes. However, LCDS in the field usually experience both saturated and unsaturated flow conditions. Unsaturated flow conditions dominates as long as the drainage medium has not clogged substantially. Further, flow regimes tend to be both horizontal and vertical; with horizontal flow probably dominating (Hudson et al., 2007). The modeled sections and bench-scale experiments may therefore oversimplify LCDS.

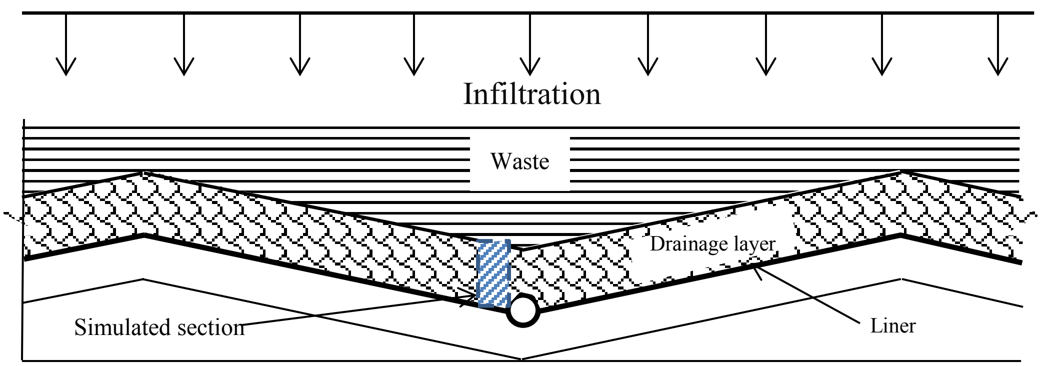


Figure 1-3. Typical LCDs sections modelled in previous studies

Laboratory studies may also be difficult to generalize due to different experimental procedures and assumptions among researchers (McIsaac and Rowe, 2005). Such studies may also not account for climatic conditions and materials typically available in different geographical regions. In general, however, laboratory studies have helped with conceptual understanding of clogging phenomenon. One way to reduce difficulties and uncertainties associated with laboratory investigations is to conduct case dependent or site specific studies taking into account materials typically used for drainage, the prevailing climatic conditions and waste management practices (Rowe, 2005).

Numerical modeling has proven to be a useful tool for simulating aspects of sanitary landfilling that may be difficult to recreate under laboratory conditions (Cooke and Rowe, 2008). Such aspects include time scale (lifetime of landfill may be greater than100 years; (Fleming et al., 1999)), landfill geometry, and leachate characteristics. The most common numerical model is BioClog that evolved from 1-D model to 2-D model (Cooke and Rowe (2008); and Cooke et al. (1999). BioClog is essentially a finite element transport model coupled with biogeochemical processes such as biological growth, biodegradation, precipitation, particle attachment and detachment (Cooke and Rowe, 2008). The model uses geometrical relationships to establish porosity from the computed thickness of accumulated clog matter and a relationship between porosity and hydraulic conductivity. However, the model has not incorporated loss in porosity for media such as TDA that can lose up to 50% of porosity through compression (Warith and Sudhakar, 2006). The parameters for running the numerical models are typically obtained from laboratory studies (McIsaac and Rowe, 2005). In some cases (e.g. in BioClog model), model parameters are based on artificial leachates, which raises questions on the practicality of the models in evaluating TDA-based LCDSs. In general, there is a need for further development of numerical models in case of TDA-based systems (EWMCE, 2009).

1.2.4 Leachate characteristics

Leachate is the liquid formed when precipitation water percolates through a sanitary landfill, thereby absorbing substances that may contain organic and inorganic ions, including heavy metals. If uncontrolled, leachates pose a great risk to both the environment and human health (Agdag, 2010; Amaral et al., 2009; Bernard et al., 1997; Bolton and Evans, 1991). The traditional approach for controlling movement of leachates and therefore ensuring its safe disposal is by installing LCDS (Alberta Environment, 2010). However, LCDS just like other permeable systems that are loaded with organic matter are affected by clogging. A relationship therefore exists between leachate characteristics and clogging (EWMCE, 2009; Hudson et al., 2008; McIsaac and Rowe, 2005; Mostafa and Van Geel, 2007).

Leachate species closely associated with clogging are chemical oxygen demand (COD), calcium (Ca^{2+}) ion concentration, and total suspended solid (TSS) (Calice and Petronio, 1997; Cooke et al., 2001; Fleming et al., 1999; McIsaac and Rowe, 2005). The greater the concentration of these components, the faster the rate of media clogging (Hudson et al., 2008). However, a major uncertainty arises from the fact that by the time leachates are sampled, clogging processes may have been established within a LCDS. Pre-treatment of leachates may also have taken place especially considering that drainage media acts as a fixed bed reactor (Fleming et al., 1999). Therefore, sampled leachates are of lower strength than the leachates causing clogging in the LCDS. To compensate for the lower strength, some researchers have augmented raw leachates with volatile fatty acids and minerals that are assumed to have been removed in the pre-treatment process (e.g. McIsaac and Rowe, 2005). However, this approach presents uncertainties because there is yet no clear criterion to guide augmentation. Furthermore, leachates are highly variable

(Chu et al., 1994; Fan et al., 2006; Fatta et al., 1998), which is associated with the different phases of digestion; (i) aerobic, (ii) acetogenesis, and (iii) methanogenesis that take place during life cycle of a landfill. The evolvement and transition of these phases from one to another depend on several factors including the age of the landfill, type of drainage media, waste management practices, type of landfill, and local climatic conditions (Fatta et al., 1998). This variability makes leachate characteristics as well as actual media clogging site specific. Dependence of leachates characteristics on local climatic conditions and prevailing waste management practices also imply that there is need to assess potential of leachates to stimulate physical, chemical and biological processes and therefore susceptibility of LCDS to clogging.

1.2.5 Media Characteristics

Gravel has traditionally been used as the medium for drainage in LCDS. More recently, TDA has been applied in LCDS, mainly to provide an alternative use for tires once they are discarded (Reddy and Marella, 2001). Knowledge of engineering properties such as hydraulic conductivity, compressibility, and particle size distribution is important for the design of TDA-based LCDS (Reddy and Marella, 2001). Hydraulic conductivity of TDA may vary from 1.4×10^{-2} to 5.9×10^{-1} m s^{-1} at dry density of about 470 kg m^{-3}. Hydraulic conductivity drops to about 5.8×10^{-3} m s^{-1} when dry density reaches about 650 kg m^{-3} (ASTM 2009). In comparison, the hydraulic conductivity of gravel is about 7.8×10^{-3} m s^{-1} (Qian et al., 2004), implying that the initial hydraulic conductivity of TDA may be beneficial compared to that of gravel. However, this benefit may not last long because of the compression behavior of TDA (Hudson et al., 2007). For example, Didier et al (2007) demonstrated that tire shreds from passenger cars can compress by over 50% when subjected to pressures such as would occur at the base of a 50 m high landfill.

Because, compression of porous media reduces the pore volume, it follows that permeability would be impaired if overburden pressures are excessive, which would lead to build up of leachate head and therefore affect the performance of LCDS. Hudson et al. (2007) assessed the suitability of different shred sizes when used as media for drainage and found that tire shreds with larger particle sizes had higher hydraulic conductivities compared to small size tire shreds. This would also imply that TDA of different sizes and shapes may be affected differently by clogging phenomenon. In general, there are concerns that service life of tire shred based LCDS may be shorter than for gravel-based LCDS (Rowe et al., 2000; Rowe and Babcock, 2007).

Compression of TDA media in LCDS not only reduces permeability but also the thickness of the drainage layer. If reduction of media thickness is excessive, leachate head may extend into waste mass. The reduction may accelerate clogging phenomenon and therefore affect performance of LCDS. Besides, there is lack of technical data such as applicable values for hydraulic conductivity that may be used for the design of TDA-based LCDS. The lack of technical data is especially the case in Alberta, Canada, where different types of TDA exist (Meles et al., 2013) and have frequently been used as drainage media in LCDS. Therefore, there is need for a study to evaluate characteristics of TDA processed in Alberta, as part of the overall goal of evaluating long-term performance of TDA-based LCDS.

1.3 Objectives of the study

The main objective of the study was to evaluate the performance of TDA products processed in Alberta, Canada when used as drainage media in LCDS. The specific objectives were to:

i. evaluate the characteristics of leachates from Alberta's sanitary landfills based on historical leachate data and comparing to the existing literature;

ii. investigate the effects of media compression on the performance of TDA-based LCDS; and
iii. compare the short- and long-term clogging behavior of TDA and gravel when permeated with real landfill leachates.

1.4 Study Research Questions

To guide the study activities, the following specific research questions were formulated:

i. How do the composition and strength of leachates vary in Alberta landfills and what does the variation imply to the performance of LCDS?
ii. How would compression of TDA influence the performance of TDA-based LCDS?
iii. How would different types of TDA and gravel media compare when permeated with raw landfill leachates?

1.5 Organization of the Thesis

The problem statement, objectives of the study, specific objectives, and research questions are presented in Chapter 1. The relevant bio-geochemical characteristics of historical leachate data in Alberta landfills are compared to other published leachate data in Chapter 2. Also presented in Chapter 2 is a qualitative assessment of the susceptibility of Alberta's landfills to clogging. In Chapter 3, the physical and mechanical properties of TDA media are presented and discussed, while in Chapter 4 investigation into clogging behavior of TDA media is presented. A summary of the work and conclusions drawn are presented in Chapter 5.

1.6 Key Findings of the Study, Contributions to Field Applications, and to the Advancement of Scientific Knowledge

1.6.1 Field Applications and Engineering Practice

a) Prior to this study, the hydraulic conductivities of the TDA processed in Alberta were not documented; yet hydraulic conductivity is a key input parameter in the equations 1-1 to 1-3 (Section 1.2.1), which are normally used for calculating leachate heads in the field. In this study, a chart (Figure 3-7) that shows how hydraulic conductivities of TDA may vary with media porosity and therefore media compression, has been provided. The chart makes it feasible for landfill designers to apply the appropriate values of hydraulic conductivity for the TDA material used and the height of landfill.

b) The compression behaviour of TDA that are commercially available in Alberta was not previously known. There were also no criteria on how to specify the initial media thickness to avoid the leachate mound extending above the drainage layer. From this study, a design chart (Figure 3-8) that shows the relationship between media compression and height of landfill is provided. This chart is a design tool that may guide landfill designers and engineers in determining the appropriate media thickness for different landfill heights.

c) A key challenge facing operations and management of sanitary landfills is clogging phenomenon. Prior to the current study, the susceptabilty of Alberta landfills to clogging was not known. This study shows that the majority of the Class II municipal landfills investigated were susceptible to clogging. The result allows appropriate measures to be taken by respective landfill operators to ensure landfill operations do not encourage excessive leachate mounding.

1.6.2 Advancement of Scientific Knowledge

a) At the commencement of the current study, it was hypothesized that hydraulic performance of LCDS would improve if different types of TDA are mixed. This study showed that no significant improvement in hydraulic conductivity would be attained by mixing TDA sourced from passenger and light trucks with that from off-road vehicles.

b) Previous studies for simulating clogging phenomenon applied leachates in upward direction, ostensibly to keep the media saturated. The approach was considered inappropriate because flow in the field is by gravity. However, it was not detailed in the available literature how downward flow could be achieved and at the same time keep a highly porous media saturated. In this study, it was demonstrated and detailed that by installing pressure break cups, it is possible to keep the flow downwards and also have the media saturated.

c) The experimental set-up and process controls for the long-term clogging study were faced by unforeseen challenges that had not been reported previously. In this study, the limitations of the experimental set-up have been documented and specific corrective measures proposed.

References

Agdag, O. N. (2010). Characterization and treatment of Denizli landfill leachate using anaerobic hybrid/ aerobic CSTR systems. *Environmental Technology* **32:** 699-711.

Alberta Environment (2010). Standards for Landfills in Alberta. Government of Alberta. Alberta, Canada.

Amaral, M. C. S., Ferreira, C. F. A., Lange, L. C. and Aquino, S. F. (2009). Characterization of Landfill Leachates by Molecular Size Distribution, Biodegradability, and Inert Chemical Oxygen Demand. *Water Environment Research* **81:** 499-505.

ASTM (2009). D6270-08: Standard Practice for use of scrap tires in civil engineering. ASTM International, West Conshohocken, PA, USA.

Aydilek, A. H., Madden, E. T. and Demirkan, M. M. (2006). Field evaluation of a leachate collection system constructed with scrap tires. *Journal of Geotechnical and Geoenvironmental Engineering* **132:** 990-1000.

Bernard, C., Colin, J. R. and Anne, L.-D. D. (1997). Estimation of the hazard of landfills through toxicity testing of leachates. *Chemosphere* **35:** 2783-2796.

Bolton, K. A. and Evans, L. J. (1991). Elemental composition and speciation of some landfill leachates with particular reference to cadmium. *Water, Air and Soil Pollution* **60:** 43-53.

Calice, N. and Petronio, B. M. (1997). Characterisation of high molecular weight organic compounds in landfill leachate: Humic substances. *Journal of Environmental Science and Health* **32:** 2229-2244.

Chu, L. M., Cheung, K. C. and Wong, M. H. (1994). Variations in the Chemical Landfill Leachate. *Environmental Management* **18:** 105-117.

Cooke, A. J. and Rowe, R. K. (2008). 2D modelling of clogging in landfill leachate collection systems. *Canadian Geotechnical Journal* **45:** 1393-1409.

Cooke, A. J., Rowe, R. K., Rittimann, B. E., et al. (2001). Biofilm growth and mineral precipitation in synthetic leachate columns. *Journal of Geotechnical and Geoenviornmental Engineering* **127:** 849-856.

Cooke, A. J., Rowe, R. K. and Rittmann, B. E. (2005). Modelling species fate and porous media effects for landfill leachate flow. *Canadian Geotechnical Journal* **42:** 116-1132.

Cooke, A. J., Rowe, R. K., Rittmann, B. E. and Fleming, I. R. (1999). Modeling Biochemically Driven Mineral Precipitation in Anaerobic Films. *Water Science Technology* **39:** 57-64.

Didier, G., Moretto, R., Budca, A. and Cazenove, A. D. (2007). Use of shredded end of life tyres for drainage in leachate recirculation trenches, biogas drainage and drainage of water under cover in MSW landfills Proceedings Sardinia 2007, eleventh international waste management and landfill symposium. Cagliari, Italy.

Drescher, A., Newcomb, D. and Heimdahl, T. (1999). Deformability of shredded tires, University of Minnesota, Department of Civil Engineering.

EWMCE (2009). Implications of Using Tire Derived Aggregate for Landfill Leachate Collection Systems – Literature Review. Edmonton, Alberta Recycling Management Authority (ARMA).

Fan, H., Shu, H. Y., Yang, H. S. and Chen, W. C. (2006). Characteristics of landfill leachates in central Taiwan. *Science of the Total Environment* **361:** 25-37.

Fatta, D., Voscos, C., Papadopoulos, A. and Loizidou, M. (1998). Leachate Quality of a MSW landfill. *Journal of Environmental Science and Health* **A33:** 749-763.

Fleming, I. R. and Rowe, R. K. (2004). Laboratory studies of clogging of landfill leachate collection and drainage systems. *Canadian Geotechnical Journal* **41:** 134-153.

Fleming, I. R., Rowe, R. K. and Cullimore, D. R. (1999). Field observations of clogging in a landfill leachate collection system. *Canadian Geotechnical Journal* **36:** 685-707.

Hudson, A. P., Beaven, R. P., Powrie, W., et al. (2008). Clogging potential of methanogenic leachate on tyre and aggregate drainage layers. Proceedings Waste 2008: Waste and Resource Management- a Shared Reponsibility. Stratford-upon-Avon, Warkwickshire, England,**:** pp. 16-17.

Hudson, A. P., Beaven, R. P., Powrie, W. and Parkes, D. (2007). Hydraulic conductivity of tyres in landfill drainage syatems. *Waste and Resource Management* **160:** 63-70.

McBean, E. A., Rovers, F. A. and Farquhar, G. J. (1995). Solid waste landfill engineering and design. Prentice Hall PTR, Upper Saddle River, Toronto.

McIsaac, R. and Rowe, R. K. (2005). Change in leachate chemistry and porosity as leachate permeates through tire shreds and gravel. *Canadian Geotechnical Journal* **42:** 1173-1188.

Meles, D., Bayat, A. and Soleymani, H. (2013). Compression Behaviour of Large-Sized Tire-Derived Aggregate for Embankment Application. *Journal of Materials in Civil Engineering* **25:** 1285-1290.

Mostafa, M. and Van Geel, P. J. (2007). Conceptual Models and Simulations for Biological Clogging in Unsaturated Soils. *Vadose Zone Journal* **6:** 175-185.

Qian, X., Gray, D. H. and Koerner, R. M. (2004). Estimation of Maximum Liquid Head over Landfill Barriers *Journal of Geotechnical and Geoenviornmental Engineering* **130:** 488-497.

Reddy, K. R. and Marella, A. (2001). Properties of different size scrap tire shreds: Implications on using as drainage material in landfill cover systems. The Seventeen International Conference on Solid Waste Technology and Management. Philadelphia, PA, USA.

Rowe, R. K. (2005). Long-term performance of contaminant barrier systems. *Geotechnique* **55:** 631-678.

Rowe, R. K., Armstrong, M. D. and Cullimore, D. R. (2000). Mass loading and the rate of clogging due to municipal solid waste leachate. *Can. Geotech. J.* **37:** 355-370.

Rowe, R. K. and Babcock, D. (2007). Modelling the clogging of course gravel and tire shreds in column tests. *Can. Geotech. J.* **44:** 1273-1285.

VanGulck, J. F., Rowe, R. K., Ritmann, B. E. and Cooke, A. J. (2003). Predicting biogeochemical calcium precipitation in landfill leachate collection systems. *Biodegradation* **14:** 331-346.

Warith, M. and Sudhakar, M. R. (2006). Predicting the compressibility behaviour of tire shred samples for landfill applications. *Waste Management* **26:** 268-276.

Zekkos, D., Bray, J. D., Jr., E. K., et al. (2006). Unit weight of Municipal Solid Waste. *Journal of Geotechnical and Geoenvironmental Engineering* **132:** 1250-1261.

2 Composition and Strength of Leachates in Alberta's Sanitary Landfills and its implications on the performance of leachate collection and drainage systems

Materials in this chapter to be submitted as:

a. Mwai, K.M., Kristine, W., & McCartney, D. 2015. Composition and strength of leachates in Alberta landfills and its implications on the long-term performance of leachate collection and drainage systems

2.1 Introduction

A major concern with sanitary landfilling as a technology for solid waste management is the long-term polluting potential of landfill leachates (Rowe, 2005). Leachates refer to the liquid formed when water percolates through deposited waste and that are released or contained within a landfill (Gálvez et al., 2008). During percolation, leachates cause dissolution of various substances, pick up particulate matter, and transport the dissolved and suspended materials through the waste (Calace and Petronio 1997; Fan et al. 2006). Leachates therefore contain complex pollutants such as dissolved organic and inorganic matter, heavy metals and xenobiotic organic compounds (Amaral et al., 2009; Bernard et al., 1997; Emenike et al., 2012; Gálvez et al., 2008). The concentration of these species defines the strength of the leachates and therefore pollution potential of landfill leachates.

Table 2-1 gives a summary of parameters and key species associated with landfill leachates. Also indicated are concentrations of various leachate species as reported in the literature. Leachate pH is the master variable indicating the balance between acid and base producing processes such as the acetogenesis and methanogenesis.

Table 2-1. Composition of sanitary landfill leachates reported in literature

Reference/ Parameter	pH	BOD	COD	BOD/ COD Ratio	alkalinity ($CaCO_3$)	SO_4^{2-}	Cl^-	PO_4^{3-}	TDS	TSS	NH_4^+	TKN	Na^+	Ca^{2+}	Fe^{3+}	Mg^{2+}	Pb^{2+}
Units	-	mg L^{-1}	mg L^{-1}	-	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}	mg L^{-1}
(Emenike et al., 2012)	8.2	3,500	10,234	-	9,000	37.1	4,150	70.2	830	97	880	31.8	48.6	25.6	3.1	20.3	<0.0001
(Fan et al., 2006)	8.38	1,270	5,050	-	-	225	3,130	18.1	-	-	1,330	1,670	-	-	4.9	-	-
(VanGulck et al., 2003)	6.8	-	12,200	-	-	-	770	6.1	-	1,000	-	1,180	2,150	460	171	487	0.028
(Frascari et al., 2004)	8.3-8.5	850-1,700	5,500-7,000	0.5-0.18	-	100-500	2,400-3,800	10-25	-	-	900-1,900	1,280-2,530	-	-	-	-	0.03-0.06
(Kim and Lee, 2008)	-	7.5-11.6	139.6-218.0	0.05-0.07	-	-	-	-	-	-	-	-	-	-	-	-	-
(Bolton and Evans, 1991)	5.44-7.65	-	-	-	-	<10-260	100-2,460	n.d.-1.4	-	-	-	-	40-780	170-820	0.22-38	30-540	n.d.
(Calice and Petronio, 1997)	(6.44)-8.30	-	2422-(9,155)	-	-	13.8-(81)	(566)-2,873	(8.2)-n.d	-	-	-	-	(225)-905	8-(808)	2.0-(5.4)	39-(144)	(0.016)-0.032
(Bernard et al., 1997)	7.8-8.6	-	0.4-8.0	-	585-6,950	0-148	750-2,185	-	-	-	103-1,231	-	519-2,957	15-119	0.0-7.0	51-295	-
(Fleming et al., 1999)	5.8-7.7	-	3,000-2,0000	0.18-1.1	-	-	500-3,400	-	-	-	-	-	-	280-2,100	-	-	-
(Khattabi et al., 2002)	5.1-8.2	25-187	313-1,550	0.01-0.17	-	93-233	150-839	-	-	-	112-218	-	-	-	0.2-11.3	-	-

Reference/ Parameter	pH	BOD	COD	BOD/ COD Ratio	alkalinity ($CaCO_3$)	SO_4^{2-}	Cl^-	PO_4^{3-}	TDS	TSS	NH_4^+	TKN	Na^+	Ca^{2+}	Fe^{3+}	Mg^{2+}	Pb^{2+}
(Mor et al., 2006)	6.9	19,000	27,200	-	-	-	-	-	27956	-	2,675	-	545		70.62		1.54
(Kulikowska and Klimiuk, 2008)	7.29-8.61	76-701	580-1,821	-	-	98-374	490-1,190	1.4-15.7	2,969-6,823	191-740	66-364	-	-	192-430		126-419	n.d.-1.84
(Amaral et al., 2009)	(7.5)-7.8	(168)-76	2,783-1,352	(0.05)-0.06	2,797-(6,092)	-	1,708-(2,973)	7-(11)	-	(37)-321	451-(1240)	-	-	-	-	-	-
(Aziz et al., 2010)	6.93-8.26	135-476	630-2,860	0.088-0.35	-	-	-	8-40	-	232-1374	130-1,039	-	-	-	0.6-11.4	-	-

n.d. = below detection limits; values in bracket are for young leachates

The BOD and COD of the leachate refer to its biochemical and chemical oxygen demand, respectively. The BOD/COD ratios indicate biodegradability of leachates and therefore its relative biological strength (Amaral et al., 2009; Aziz et al., 2010; Frascari et al., 2004). About 90% of the total nitrogen concentrations in landfill leachates is ammoniac nitrogen (Gálvez et al., 2008), which may be explained by reduction of nitrates and other nitrogen containing compounds such as proteins and amino acids to ammonia as anaerobic conditions develop (Fatta et al., 1998). The sulfate (SO_4^{2-}) species also originate from organic matter and are required for microbial growth. However, sulfates are less favorable substrates compared to nitrates and nitrites and, therefore, tend to leach to the bottom of the landfill. Thus, the bottom zone is dominated by sulfate reducing bacteria and methanogens (Hunter et al., 1998; Konhauser, 2007). Compared to other organic materials, landfill leachates exhibit low concentrations of phosphates (Aziz et al., 2010), which imply that it could be a limiting nutrient for microbial cell development (Chu et al., 1994).

Fan et al. (2006) pointed out that concentration of solids in leachates is positively correlated to COD, BOD, VSS and TDS. This observation implies the solids in leachates may contribute to BOD, COD and VSS concentration of leachates and, therefore support microbial growth including development of biofilms. Solids may also contribute to physical clogging of LCDS if they are intercepted within the media pores (VanGulck and Rowe, 2004).

Inorganics in leachates are associated with ions from alkali (Na^+, K^+), alkaline-earth (Mg^{2+}, Ca^{2+}) and transition metals (Fe^{3+}, Zn^{2+}, Mn^{3+}, Ni^{2+}, Cd^{2+}, Pb^{2+}). Fleming et al.

(1999) found Mg^{2+} and Ca^{2+} based precipitates that may contribute significantly to physical-chemical clogging of the LCDS. Trace heavy metals in typical landfill leachates occur in low concentration (e.g. Bolton and Evans, 1991; Chu et al., 1994; Fatta et al., 1998; Inanc et al., 2000). Mor et al. (2006) attributed the low concentrations to binding of the metals onto the solid matrix within LCDS. Although heavy metals in landfill leachates are expected to check microbial growth, including development of biofilms (Bolton and Evans, 1991), they may be largely unavailable.

Table 2-1 shows that leachate composition and strength tend to vary greatly as observed by several researchers (e.g. Bernard et al., 1997; EWMCE, 2009; Mor et al., 2006). This variability has been associated with age of the landfill, prevailing waste management practices such as diversion targets for organic waste, and climatic conditions (Gettinby et al., 1996; Kalcikova et al., 2012; Khattabi et al., 2002). These factors vary from place to place, making generalization of leachate characteristics impracticable.

To ensure that landfill leachates are managed appropriately, most jurisdictions require elaborate leachate monitoring programs during the life of a sanitary landfill (Alberta Environment, 2010). A number of studies have also been conducted focusing on various aspects of leachate characteristics and management (Table 2-2). These studies can be categorized into four main subjects; namely, i) leachate composition and strength, ii) toxicity, iii) treatment and disposal, and iv) potential to cause clogging in LCDS. Clogging is directly associated with malfunctioning of leachate containment and control systems (EWMCE, 2009; Fleming et al., 1999). The malfunctioning not only enhances potential for pollution, but it complicates drainage, treatment and final disposal of leachates.

The traditional approach for draining and collecting leachates is by installing LCDS at the base of sanitary landfills (Figure 1-2). The performance criterion for LCDS is such that leachate mounding over the liner should not exceed a specified maximum value, usually 300 mm (Koerner and Koerner, 2004; Qian et al., 2004), beyond which the drainage media are deemed clogged (McBean et al., 1995; Warith and Rao, 2004).

Clogging may be defined as the accumulation of biofilms, mineral species, and biodegradation products within voids of a drainage medium (Fleming et al., 1999; McIsaac and Rowe, 2005). Table 2-3 gives a summary of the various processes associated with clogging mechanism and how they affect performance of LCDS. There is a direct relationship between leachate characteristics and how clogging develops in drainage media (EWMCE, 2009; Hudson et al., 2008; McIsaac and Rowe, 2005). Table 2-3 lists leachate parameters associated with clogging, and, therefore, critical for assessing clogging potential of leachates. These parameters are COD, BOD, VSS, cations (e.g. Ca^{2+} and Mg^{2+}) and TSS.

Whether the processes indicated in Table 2-3 cause clogging or not depends on mass loading of various leachate species in the LCDS (Cooke et al., 2001; McIsaac and Rowe, 2005; VanGulck et al., 2003). High strength leachates would therefore be expected to cause rapid clogging as compared to those of lower strength (Hudson et al., 2008).

Table 2-2. Summary of the previous leachate characterization studies, focus and key findings

No	Reference	Type of landfill	Focus of the study	Key findings
1	Frascari et al. (2004)	Active landfill in Northern Italy	Long-term characterization and migration potential of landfill leachates	• pH ranged between 8.3 and 8.5 indicating methanogenic conditions • BOD/ COD ratio decreased from 0.5 to 0.18 in 10 years, indicating decreasing leachate strengths • fluctuation in leachate strengths associated with fluctuations in leachate flow • Lagoon treatment may be suitable due to high fluctuations in leachate strength
2	Kim and Lee (2008)	old landfill with no final cover and a young landfill with cover	Comparative study on leachate in closed landfill sites: focusing on seasonal variations	• higher fluctuations in concentration of organic matter and nitrogen at the younger landfill • High precipitation results in low strength leachates
3	Bolton and Evans (1991)	Four municipal solid waste landfills in southern Ontario	Composition of cations and anions and trace heavy metals (e.g. Cd, Cu, Fe, Mn)	• Alkali and alkaline earth metals exist mainly as un complexed ions • Speciation of metals dependent on pH (uncomplexed with pH 3-4.8) and complexed with pH > 4.8
4	Calace and Petronio (1997)	Two municipal landfills in Italy,	Characterization of high molecular weight substances in landfill leachates	• Old leachates contain more humic fulvic compared to younger leachates; hence low strength leachates for older landfills • Concentration of low molecular weight organic compounds decreases with refuse age
5	Bernard et al. (1997)	municipal and industrial waste dumping sites	Estimating effects of leachate strengths (toxicity) on aquatic organisms.	• High concentration of leachates constituents imply high strength leachates • Industrial wastes contained higher calcium content • Concentration of various species distributed according

No	Reference	Type of landfill	Focus of the study	Key findings
				to the type of landfill
6	Fleming et al. (1999)	Municipal landfill in Ontario, Canada	Field observations of clogging of leachate collection system	• within 1–4 years, the drainage stone covered with clog mass • clog mass contained mineral precipitates, biofilms, particulate matter • drainage system characterized by anaerobic conditions • rate of clogging closely associated with moisture content • leachate strength associated more with stabilization processes rather that seasonal dilution • biofilms were soft and black, typical of microbial consortia in an anaerobic system
7	Khattabi et al. (2002)	Etueffont landfill (Belfort, France) Closed landfill in France-established in 1974	Changes in quality of landfill leachates from recent and aged municipal solid waste	• leachate strength decreased with increasing leachate flow rates • leachate strength decreased with increasing landfill/ waste age
8	Al-Yaqout and Hamoda (2003)	Two unlined landfill for municipal solid waste in Kuwait	chemical characterization of leachates	• low strength of leachates caused by decomposition processes and landfill operations (e.g. gas flaring). • low strength of leachates associated with dilution effects
9	VanGulck et al. (2003)	Municipal sanitary landfill, Ontario, Canada	Predicting biogeochemical calcium precipitation	• clogging caused by calcium carbonate precipitation • formation of CaCO3(s) associated with fermentation of acetate
10	VanGulck and Rowe (2004)	Municipal sanitary landfill, Ontario, Canada; laboratory study	Evolution of clog material due to synthetic landfill leachates	• Decrease in drainable porosity prior to steady state COD removal associated with growth of biofilms • Loss in drainable porosity after steady state COD removal associated to both biofilms and calcium carbonate precipitation

No	Reference	Type of landfill	Focus of the study	Key findings
				• Clog composition showed most carbonate (99%) was bound to calcium
11	Fleming and Rowe (2004)	Municipal sanitary landfill in Ontario, Canada	Laboratory studies to investigate clogging of LCDS	• Calcite dominant mineral in clog material • Precipitation and biological consumption of organic acids linked to rise in pH • Short-term fluctuations in leachate strength associated with stormwater drainage conditions • Increased hydraulic retention time increased levels of precipitation
12	McIsaac and Rowe (2005)	Municipal sanitary landfill in Ontario, Canada	Spatial and temporal changes in leachate chemistry after passing through tire shreds and gravel	• COD and calcium concentration reduced with time until steady state conditions were reached • More clogging observed in areas with high mass loading in case of tire shreds • More uniform development of clog material observed in gravel columns • The gravel may have a service life three times greater than compressed (at 150 kPa) tire shred
13	Kulikowska and Klimiuk (2008)	Landfill with mixed municipal and industrial wastes	The effect of landfill age on leachate composition	• decreased from 1800 in 2nd year to 610 mgL^{-1} in 6th year • concentration of alkali and alkaline earth metals depended more on seasons of the year rather than landfill age • pH of 7.84, low COD concentration (< 2000 mgL^{-1}), low BOD/COD ratio (< 0.4) indicated landfill characterized by methanogenic conditions

Table 2-3. Summary of Bio- Geochemical Processes Associated with Clogging Phenomenon

Process	Relevance to clogging of a drainage media
Biofouling	Availability of degradable material enhances formation of biofilms which can accumulate in LCDS (Bear and Verruijt, 1987). Main leachate species are COD, BOD and VSS.
Dissolution	Causes formation of dissolved leachate species (e.g. Ca^{2+}). Dissolved species can precipitate out and cause plugging of media pores (McBride, 1994).
Precipitation	Involves formation of minerals species that can accumulate within the LCDS and plug the media pores(VanGulck et al., 2003). Main ions are Ca^{2+}, Mn^{2+}, Mg^{2+} and Fe^{3+} (Fleming et al., 1999).
Sorption	Leachate species may attach on the surface of drainage media, forming nucleation sites upon which TSS and VSS can accumulate (Yong and Mulligan, 2004).
Straining /filtration	Traps suspended leachate species (e.g. TSS, VSS) within media pores (McBean et al., 1995). This may reduce porosity and hence hydraulic function of LCDS (VanGulck et al., 2003)

The strength of leachates is not constant (Table 2-1) but is linked to the different phases of the biochemical reactions that take place during the life cycle of the landfill (Al-Yaqout and Hamoda, 2003; Hudson et al., 2008; Khattabi et al., 2002). At the beginning of landfill operations, aerobic digestion takes place, but it lasts for only a short period as oxygen is depleted rapidly. The next phase, acetogenic phase, is marked by a high concentration of soluble biodegradable organic compounds, especially volatile fatty acids (Calace and Petronio, 1997; EWMCE, 2009). Typically, the acetogenic phase lasts for about 5 to 10 years (Kalcikova et al., 2012), depending on the waste management practices, such as diversion targets for organic wastes. The last phase, methanogenic phase, gets established following emergence of methanogenic bacteria (EWMCE, 2009;

Kalcikova et al., 2012). In this phase, volatile fatty acids produced during acetogenic phase are consumed, producing methane and carbon dioxide. This process makes landfill leachates neutral or slightly alkaline and less biodegradable (Kulikowska and Klimiuk, 2008). The activities of methanogenic bacteria continue with time, ultimately yielding mature leachates that are characterized by high pH and organic macromolecular compounds, mainly humic and fulvic-like acids (Amaral et al., 2009; Calice and Petronio, 1997). According to Ziyang et al. (2009), the transition between acetogenic and methanogenic phases is the most biologically active stage in a landfill. Because biofouling and precipitation of calcium carbonate are directly linked to microbial activities the LCDS, these and other clogging processes are intensified during this period.

A direct indicator for biodegradability of leachates is BOD_5/COD ratio (Amaral et al., 2009; Kulikowska and Klimiuk, 2008). Young or acetogenic leachates are characterized by BOD_5/COD value of about 0.4. For old or methanogenic leachates, values of about 0.1 have been reported (e.g. by Aziz et al., 2010; Frascari et al., 2004; Kulikowska and Klimiuk, 2008). Aziz et al. (2010) pointed out that mature leachates exhibit lower COD values of between 500 and 4,500 mgL^{-1} compared to 9155 mgL^{-1} for acetogenic leachates (Calice and Petronio, 1997). Typical ranges for TSS in young and mature landfills are 200 - 2000 and 100 - 400 mgL^{-1}, respectively (Aziz et al., 2010). The lower strength of the mature leachate suggests that low clogging levels are expected during methanogenic phase. Therefore, evaluating clogging phenomenon on basis of methanogenic leachates alone may underestimate potential for clogging. Conversely, focusing solely on acetogenic leachates may overestimate susceptibility of LCDS to clogging.

Although the acetogenic phase takes only a few years relative to methanogenic phase (Kulikowska and Klimiuk, 2008), the actual time scale may vary from site to site depending on the type and amount of waste deposited and climatic conditions. On the other hand, the overall mass loading during methanogenic phase that dominate the life of a sanitary landfill may be significant despite the low rate of nutrient loading. The different yet unknown time scales for landfill phases raise the question of how susceptibility to clogging can be evaluated. The reviewed literature (Table 2-2) did not address susceptibility of landfills to clogging given actual leachate characteristics yet it is crucial in developing mitigation measures against media clogging. Understanding the effect of leachate composition and strength on media clogging requires characterization of landfill leachates. Accordingly, the objectives of this chapter are to:

i) present historical leachate characteristics data from sanitary landfills in Alberta, Canada;
ii) discuss leachate composition and strength in Alberta landfills and its implications on clogging of LCDS.

2.2 Materials and Methods

2.2.1 Description of the Study Area

The study involved sanitary landfills located in the Province of Alberta, Canada. Alberta has an area of 661,848 km^2 extending for 1,200 km from north to south. It is one of the three provinces of Canada together with Manitoba and Saskatchewan that lie in the Canadian prairies, a region with diverse climatic conditions. Annual precipitation ranges from 300 mm in the southeast to 450 mm in the north, with some areas near the Rocky Mountains experiencing up to 600 mm of rainfall.

Sanitary landfills in Alberta are classified and licensed depending on the type of the waste to be deposited. Class I landfills are for hazardous waste, Class II landfills receive municipal and industrial wastes, while Class III landfills are for dry wastes. Table 2-3 shows the class, number and types of waste deposited in Alberta landfills. Current Alberta standards for sanitary landfills require Class II landfills to have a liner and a leachate collection system (Alberta Environment 2010). Class III landfills are only required to provide for the containment of the inert wastes and as such, installation of a LCDS is not mandatory (Alberta Environment, 2010). Because the focus of this study was on clogging of leachate collection media, information on leachate quality was obtained from class II landfills. Although operating licenses require landfill owners to submit annual reports to Alberta Environment (Alberta Environment, 2010), some landfills were constructed before the current regulations. Therefore, it was necessary to obtain some results of the leachate analyses directly from the landfills. In total, leachate quality data were obtained from 22 sanitary landfills; 12 municipal and 10 industrial.

Table 2-4. Classification of sanitary landfills in Alberta and the type of materials deposited.

Landfill Class	No. in Alberta	No. sampled	Typical waste deposited (Alberta Environment 2010)
Class I	2	0	Flammable, corrosive, explosive or toxic solid/liquid wastes.
Class II (< 10,000 t y^{-1})	101	0	Paper, organics, textiles, plastics, pop cans, cardboard, tires, soil, ashes.
Class II - Municipal (> 10,000 t y^{-1})	37	12	Paper, organics, textiles, plastics, pop cans, cardboard, tires, soil, ashes.
Class II - Industrial (> 10,000 t y^{-1})	23	10	Paper, textiles, plastics, cardboard, tires, soil, ashes
Class III	18	0	Construction, demolition and renovation materials.
Total	181	22	

2.2.2 Physico-Chemical Parameters

Alberta Standards for sanitary landfills require Class II landfills to have a leachate monitoring program, which covers active, final closure and post-closure stages of a landfill (Alberta Environment, 2010). The program require annual sampling of leachates for parameters including pH, total dissolved solids (TDS), total suspended solids (TSS), ammonia, nitrogen, chloride, sodium, sulfate, metals, and organic pollutants (BTEX, F1, F2 and phenols). Most landfills extend these standard requirements to include parameters such as COD, BOD, alkalinity, nitrates and nitrites. In this study, the leachate parameters studied were pH, BOD, COD, TSS, TDS, Pb, Ca, Cd, Fe, Mg, Mn, Na, Zn, phosphates, nitrates and nitrites and sulfates.

2.2.3 Statistical Analysis

Leachate quality data from the 22 sanitary landfills studied were subjected to statistical analysis. The quality data was restricted to only certified test results and chemical tests conducted by commercial laboratories. The statistical analysis covered computation of means, medians, and range of values. The analysis also tested for differences between municipal and industrial landfills and compared leachate characteristics in Alberta landfills with those of other jurisdictions.

2.3 Results and Discussions

2.3.1 General Characteristics of Leachates in Alberta Landfills

The characteristics of the leachates from Class II municipal and industrial landfills are presented in Tables 2-5 and 2-6, respectively. The physico-chemical parameters presented are those typically used (e.g. by Fleming et al., 1999; Kim and Lee, 2008; Kulikowska and Klimiuk, 2008) to indicate the composition of sanitary landfill leachates. For ease of identification, these parameters are grouped as: i) general indicators pH and alkalinity; ii) organics indicated by BOD and COD, sulfates, nitrogen and phosphates; iii) solids, and iv) inorganics.

Table 2-5. Descriptive statistics for various leachate parameters as sampled from twelve Class II municipal sanitary landfills.

Parameter	Unit	Median	Mean	Max	Min
General Indicators					
pH	-	7.4	7.5	13.0	1.9
Total alkalinity ($CaCO_3$)	mg L^{-1}	2,520	3,140	30,900	0.5
Organics					
Biochemical Oxygen Demand (BOD)	mg L^{-1}	2,250	2,320	56,100	2
Chemical Oxygen Demand (COD)	mg L^{-1}	4,000	5,958	83,000	10
Nitrite and Nitrates (NO_2^- + NO_3^-)	mg L^{-1}	0.13	2.83	165.00	0.01
Ammonium (NH_4)	mg L^{-1}	311.0	347.0	1,900.0	0.1
Total Kjeldahl Nitrogen (TKN)	mg L^{-1}	164.0	693.0	12,000	0.1
Sulfate (SO_4^{2-})	mg L^{-1}	133.0	1,165.9	64,703.0	0.5
Phosphate (PO_4^{3-})	mg L^{-1}	0.21	23.77	885.00	0.01
Solids					
Total dissolved solids (TDS)	mg L^{-1}	5,610	10,095	52,000	1
Total suspended solids (TSS)	mg L^{-1}	675	1743	21,940	3
Inorganics					
Sodium (Na^+)	mg L^{-1}	630.0	1,272.6	13,000.0	0.5
Calcium (Ca^{2+})	mg L^{-1}	277.00	522.00	3,810.00	0.03
Iron (Fe^{3+})	mg L^{-1}	14.10	203.07	7,260.00	0.01
Manganese (Mn^{2+})	mg L^{-1}	0.900	7.730	252.000	0.005
Nickel (Ni^{2+})	mg L^{-1}	0.099	1.190	46.800	0.0001
Cadmium (Cd^{2+})	mg L^{-1}	0.0010	3.2730	255.0000	0.0001
Magnesium (Mg^{2+})	mg L^{-1}	215.00	377.67	7,170.00	0.05
Lead (Pb^{2+})	mg L^{-1}	0.0060	0.0424	0.6740	0.00005

Table 2-6. Descriptive statistics for various leachate parameters as sampled from eleven Class II industrial landfills

Parameter	Unit	Median	Mean	Max	Min
General Indicators					
pH		7.5	7.9	12.6	5.8
Total alkalinity ($CaCO_3$)	mg L^{-1}	470	768	4,078	61
Organics					
Biochemical oxygen demand (BOD)	mg L^{-1}	575	2,322	14,400	1
Chemical oxygen demand (COD)	mg L^{-1}	1,780	4,646	25,500	1
Nitrite and Nitrates (NO_2^- + NO_3^-)	mg L^{-1}	0.590	5.76	91.00	0.03
Ammonium (NH_4)	mg L^{-1}	16.5	64.6	417.0	0.1
Total Kjeldahl Nitrogen (TKN)	mg L^{-1}	15.1	79.9	476.0	0.2
Sulfate (SO_4^{2-})	mg L^{-1}	170.0	348.0	2,130.0	0.5
Phosphate (PO_4^{3-})	mg L^{-1}	0.05	0.06	0.10	0.005
Solids					
Total dissolved solids (TDS)	mg L^{-1}	7,320	11,549	52,200	136
Total suspended solids (TSS)	mg L^{-1}	56	251	4,440	1
Inorganics					
Sodium (Na^+)	mg L^{-1}	1,500	2,981	17,200	13
Calcium (Ca^{2+})	mg L^{-1}	707	985	8,820	30
Iron (Fe^{3+})	mg L^{-1}	5.86	20.48	207.00	0.02
Manganese (Mn^{2+})	mg L^{-1}	1.70	7.60	64.00	0.005
Nickel (Ni^{2+})	mg L^{-1}	0.0380	0.6090	8.3000	0.0010
Cadmium (Cd^{2+})	mg L^{-1}	0.0010	0.0090	0.0580	0.0001
Magnesium (Mg^{2+})	mg L^{-1}	206.00	353.00	6,500.00	4.00
Lead (Pb^{2+})	mg L^{-1}	0.0050	0.0320	0.1660	0.00005

The differences in characteristics of leachates in municipal or industrial landfills were evaluated using a one-way ANOVA on the mean values presented in Tables 2-5 and 2-6. No significant difference was demonstrated at $p > 0.05$ level [(F (1, 36) = 0.16, p = 0.69].

Nevertheless, municipal landfills exhibited higher concentrations of most species with the exception of BOD, nitrates, sodium and calcium. Consequently, it was considered sufficient to carry out further analysis on data from municipal landfills only.

Leachate pH ranged from 1.9 to 13.0 for Class II municipal landfills (Figure 2-1). The lower pH values indicated an environment marked by highly concentrated soluble and biodegradable organic compounds, especially volatile fatty acids (Kalcikova et al., 2012). The higher pH values indicate high alkalinity, which is typical of mature landfill leachates (Al-Yaqout and Hamoda, 2003; Kalcikova et al., 2012). Three municipal landfills exhibited the extreme pH; landfills 1 and 2 had low pH values of 1.9 and 3.4, respectively and landfill 9 had the pH of 13. The other landfills exhibited pH values ranging between 6 and 9, which compares well with pH values of 5 to 9 reported by other researchers (Table 2-1). The cause of the extreme pH values was not established. But, concentrated acids and bases are a concern due to possible chemical attack of drainage media, especially if the media comprise of tire shreds (Aydilek et al., 2006; EWMCE, 2009). Nevertheless, Aydilek et al. (2006) point out that such extreme pH values are rare in sanitary landfills.

Leachate pH values varied from site to site (Figure 2-1) possibly because of landfill age, type of waste, landfill management practices such as diversions of organic wastes and climatic conditions (Aziz et al., 2010; Poulsen et al., 2002; Ziyang et al., 2009). Most landfills exhibited mean pH of between 6.6 and 7.5 indicating a transient environment from slightly acidic, typical of acetogenic phase to slightly alkaline typical of methanogenic conditions. Transient pH values are associated with high strength leachates (Kulikowska and Klimiuk, 2008), implying most landfills represented in Figure 2-1 may have conducive environments for biologically-induced clogging (Cooke et al., 2001; EWMCE, 2009).

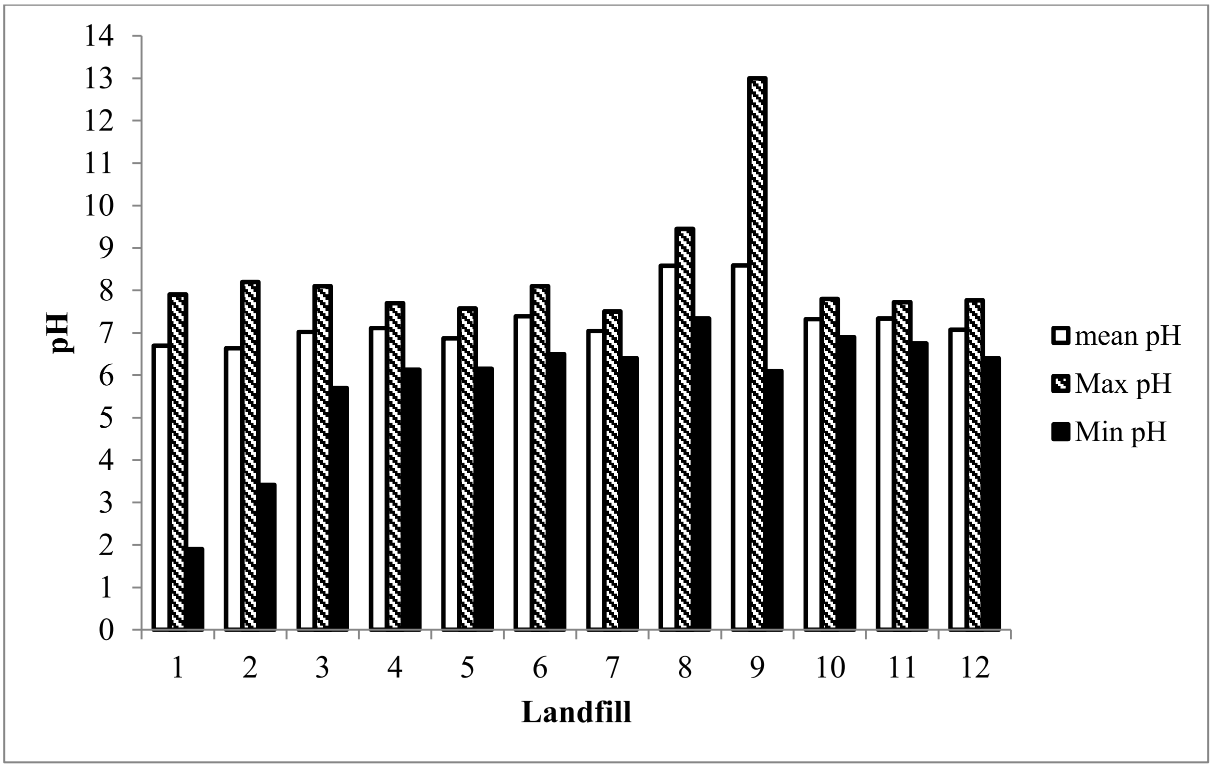


Figure 2-1. Variability of pH in Class II municipal landfills of Alberta

The concentrations of COD ranged from 10 to 83,000 mg L^{-1} (Table 2-5). The mean value of 5,958 mg L^{-1} was close to the value of 5,050 mg L^{-1} reported by Fan et al. (2006) but about half the values reported by VanGulck et al. (2003) and Emenike et al. (2012). Figure 2-2 shows the variability of COD for individual Class II municipal landfills. Considering that COD values greater than 4,500 mg L^{-1} characterize young leachates and values less than 4,500 mg L^{-1} indicate mature leachates (Aziz et al., 2010), 8 out of 12 municipal landfills were considered to have relatively young leachates. These leachates are characterized by volatile fatty acids that are highly biodegradable and therefore of high strength compared to mature leachates (Amaral et al., 2009).

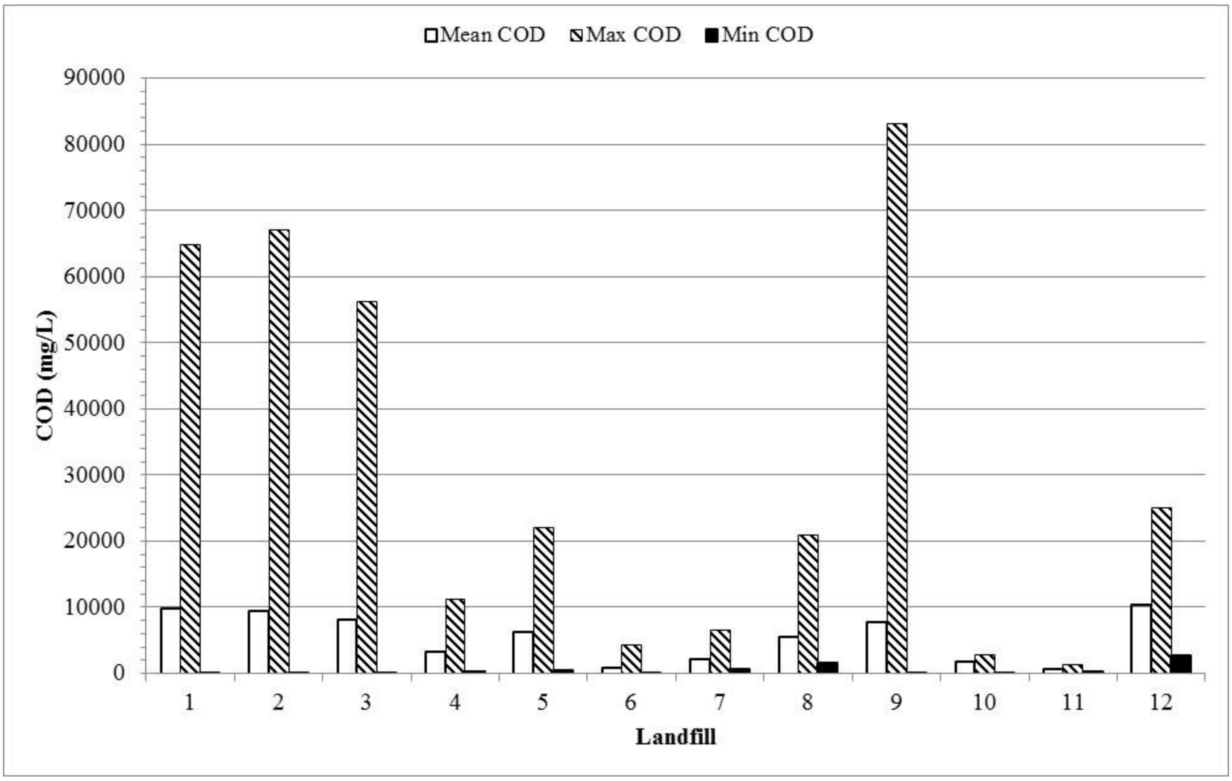


Figure 2-2. Variability of COD in municipal landfills of Alberta, Canada.

In general, COD values showed high variability, similar to the observations of other researchers (Table 2-1). Figure 2-3 shows variation of COD with time for landfill 4. In the early stages, less than 5 years, landfilling process are characterized by high concentrations of COD, which decrease with time as organic matter is stabilized by bacteria (Kulikowska and Klimiuk, 2008). COD fluctuate more in early years compared to later years. The local low points appearing in Figure 2-3 may be associated with rainfall events that tend to dilute leachates (Aziz et al., 2010).

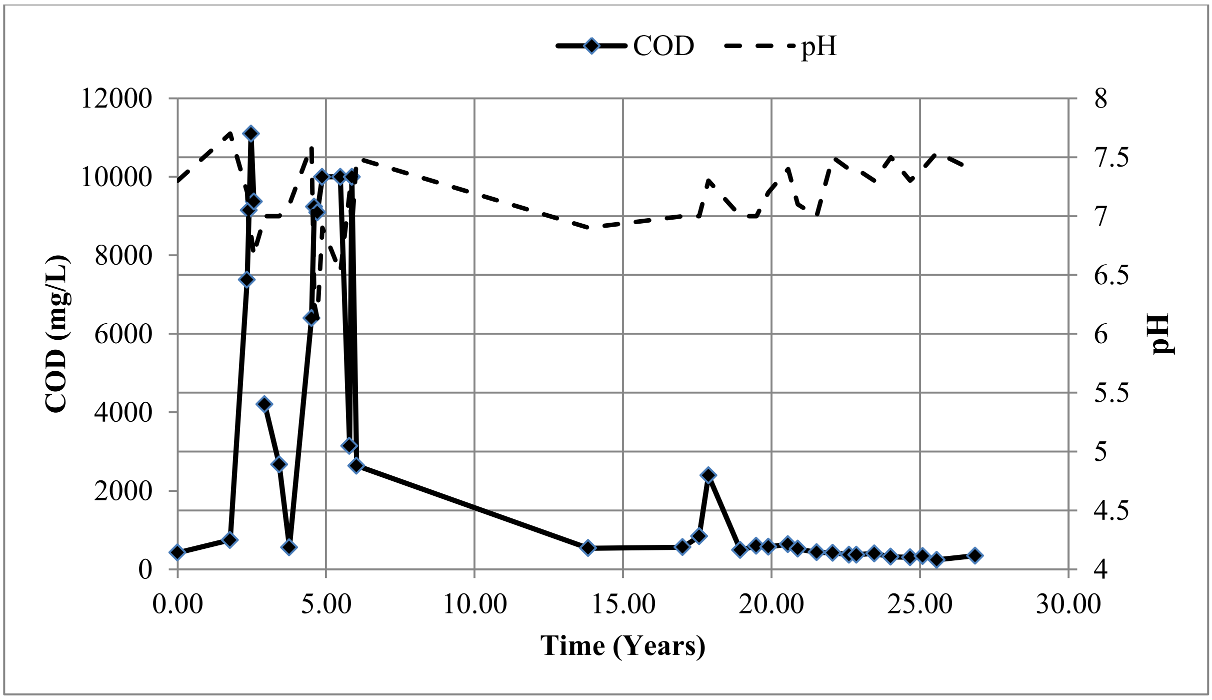


Figure 2-3. Temporal variability of leachates COD in typical municipal landfill (Landfill 4)

High COD values corresponded with pH values that fluctuated from being slightly acidic and slightly alkaline (Figure 2-3). The pH fluctuations occurred at a young age of about 5 years (Figure 2-3). This period may indicate the time scale for acetogenic leachates, consistent with the observations made by Kulikowska and Klimiuk (2008) that acetogenic phase does not last long compared to methanogenic phase. Because transient pH values are associated with active biological processes, it follows that the early stages of landfilling process are critical in evaluating clogging potential of landfill leachates. Fleming et al. (1999) exhumed LCDS at Keele Valley landfill (Ontario) and found that within a period of 1 - 4 years of landfilling, the drainage media had accumulated substantial clog and slime materials. During this period, the concentration of COD in effluent leachates ranged between 4000 and 17,000 mg L^{-1}, implying leachates were relatively young (Aziz et al., 2010). While the observations by Fleming et al. (1999) do not answer the question of relative importance of acetogenic and methanogenic leachates to the clogging processes (Table 2-3), they suggest that clogging phenomenon starts during the early stages of landfilling process. As leachates mature, pH tends to rise and stabilize around 7.5 (Figure 2-3). The corresponding low concentration of COD at this stage makes conditions for biological clogging less favourable. However, the overall mass loading of organic matter may be higher because of relatively long period associated with the methanogenic stage.

Concentration of solids in the leachate is expressed as total dissolved solids (TDS) and total suspended solids (TSS) (Table 2-5). The concentration of TDS ranged from 1 to 52,000 mg L^{-1} for municipal landfills. High TDS values imply high strength leachates and therefore potential to cause rapid clogging. TSS ranged from 3 to 21,940 mg L^{-1} in the case of municipal landfills (Table 2-5). Typical ranges for TSS in young and mature landfills are 200 - 2000 and 100 - 400 mg L^{-1}, respectively. Because of the overlap in concentration, these ranges may not give a clear distinction between high and low strength leachates. However, it can be assumed that leachates with mean concentration of less than 250 mg L^{-1} are low strength leachates with respect to TSS. Accordingly, only municipal landfills 7 and 11 could be associated with low strength leachates (Figure 2-4).

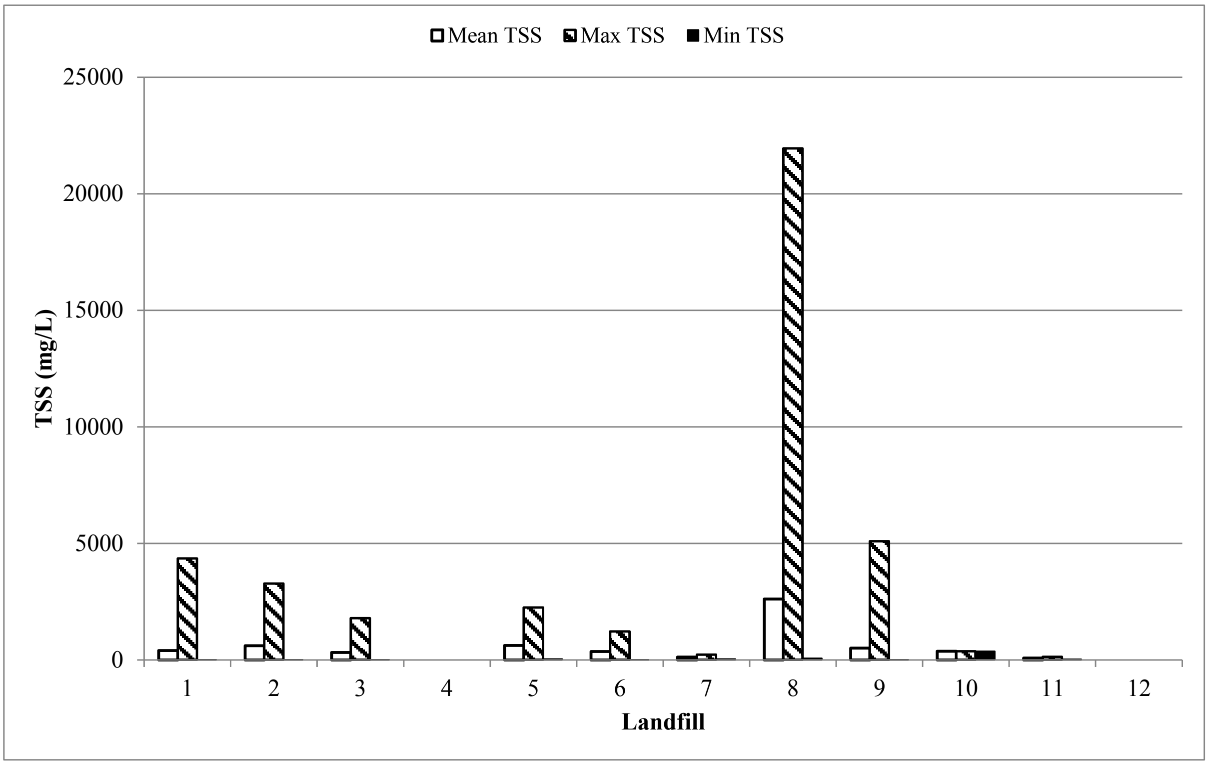


Figure 2-4. Variability of TSS in Class II landfills of Alberta, Canada

Ca^{2+} is closely associated with clogging of LCDS mainly because it precipitates as calcium carbonate (Cooke et al., 1999; Fleming et al., 1999). The concentration of Ca^{2+} ranged from 0.03 to 3,810 mg L^{-1} (Table 2-5). The mean concentration of Ca^{2+} was 522 mg L^{-1} as shown in Table 2-5, which is close to the value of 460 mg L^{-1} observed by VanGulck et al. (2003) (Table 2-1). Fleming et al. (1999) recorded Ca^{2+} values that ranged from less than a 100 to about 2,500 mg L^{-1}, and attributed the result to the formation of mineral deposits, mainly calcites, that were found in the collection system. Out of the 12 Alberta municipal landfills, 4 recorded more than 2,500 mg L^{-1} (Figure 2-5). This observation indicates an ample supply of Ca^{2+} in such landfills and, therefore, potential for clogging due to precipitation of calcium carbonates (Cooke et al., 1999; EWMCE, 2009).

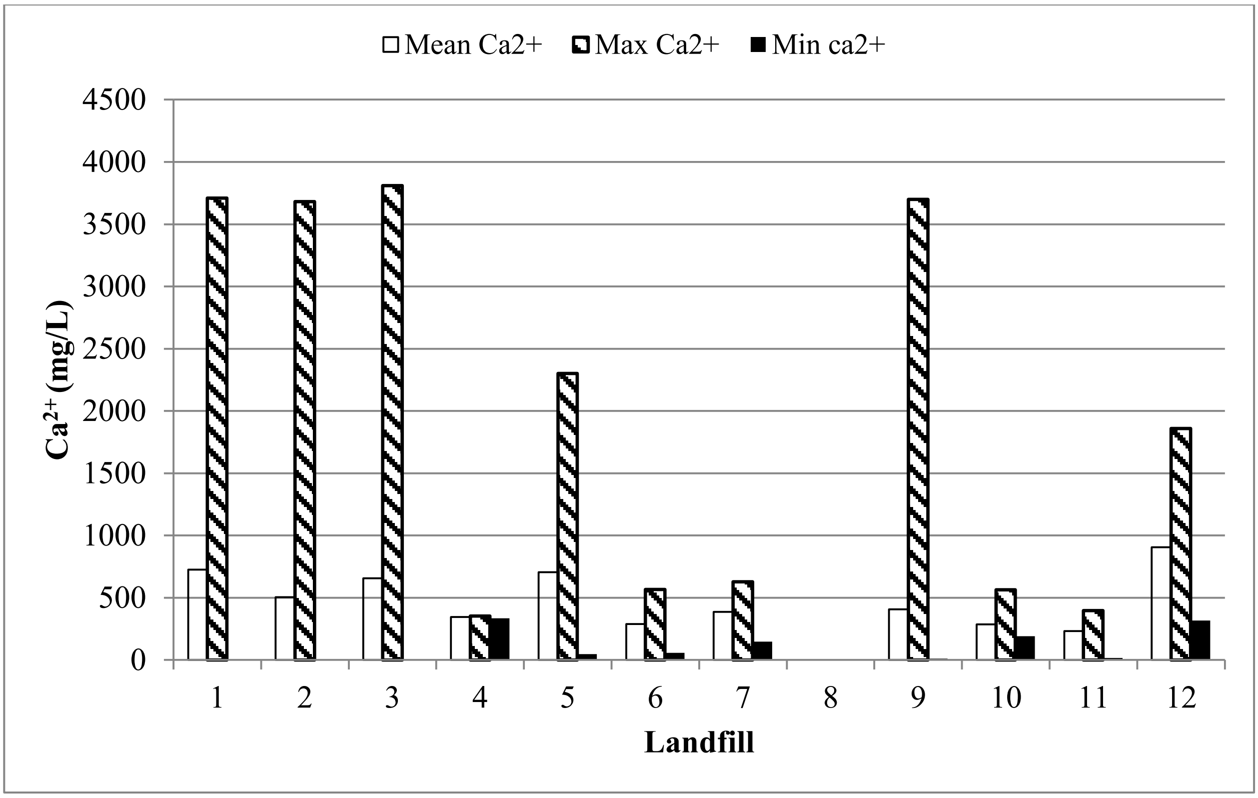


Figure 2-5. Variability of Ca^{2+} in Class II landfills of Alberta, Canada.

2.4 Spatial variation of leachate chemistries

Section 2.3 showed that the concentration of COD, TSS and Ca^{2+} and, therefore, potential to cause clogging, varies from landfill to landfill. The observation is in agreement with findings of other researchers (e.g. Aziz et al., 2010; Kalcikova et al., 2012) that characteristics of landfill leachates is largely site specific. Apart from age (Figure 2-3) and waste management practices, climatic conditions have also been associated with variability of leachates characteristics (Al-Yaqout and Hamoda, 2003; Khattabi et al., 2002). Accordingly, considerable variations in leachate strength are expected among landfill sites with distinctive rainfall amounts or patterns. Table 2-6 shows the geographical locations of the 12 municipal landfills used in this study together with the annual precipitation. The geographical regions represented are Calgary (landfills 1-3) Central Alberta (landfills 4-6), Edmonton Capital Region (landfills 7-10), Southern Alberta (landfill 11) and Mountain region (landfill 12). Figure 2-6 depicts the correlations between rainfall amounts against mean concentrations of COD in Alberta landfills. Corresponding correlations between rainfall amounts and TSS and Ca^{2+} are shown in Figure 2-7 and 2-8, respectively.

Table 2-7. Geographic locations and typical annual precipitation for the 12 municipal landfill sites

Landfill No	Geographical Region	Annual Precipitation (mm)
Landfill 1	Calgary	419
Landfill 2	Calgary	419
Landfill 3	Calgary	419
Landfill 4	Central Alberta	421
Landfill 5	Central Alberta	421
Landfill 6	Central Alberta	421
Landfill 7	Edmonton Capital Region	446
Landfill 8	Edmonton Capital Region	456
Landfill 9	Edmonton Capital Region	456
Landfill 10	Edmonton Capital Region	446
Landfill 11	Southern Alberta	380
Landfill 12	Mountain Region	446

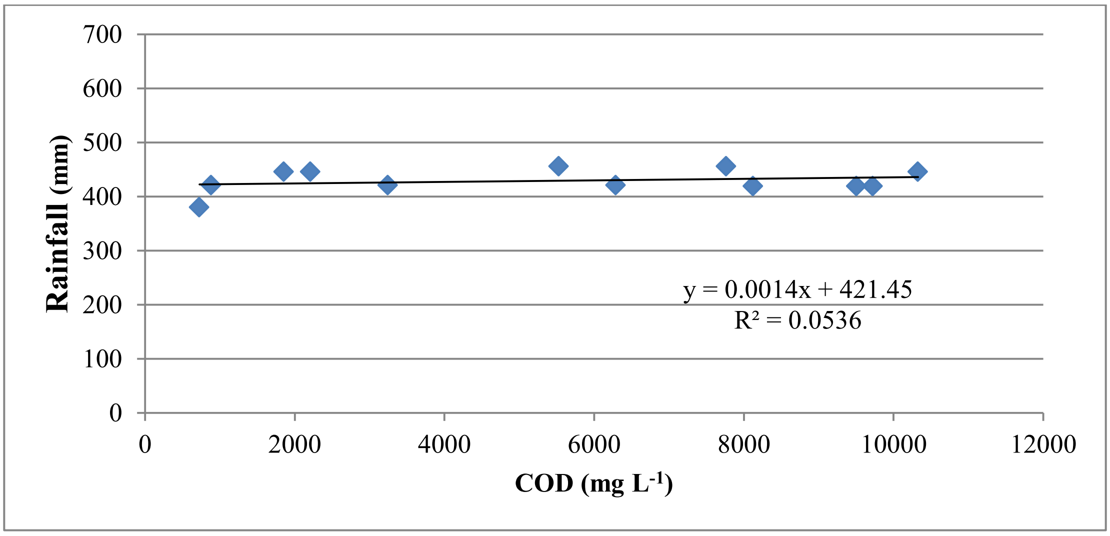


Figure 2-6. Correlation between annual rainfall and mean COD concentrations in Alberta's municipal landfills.

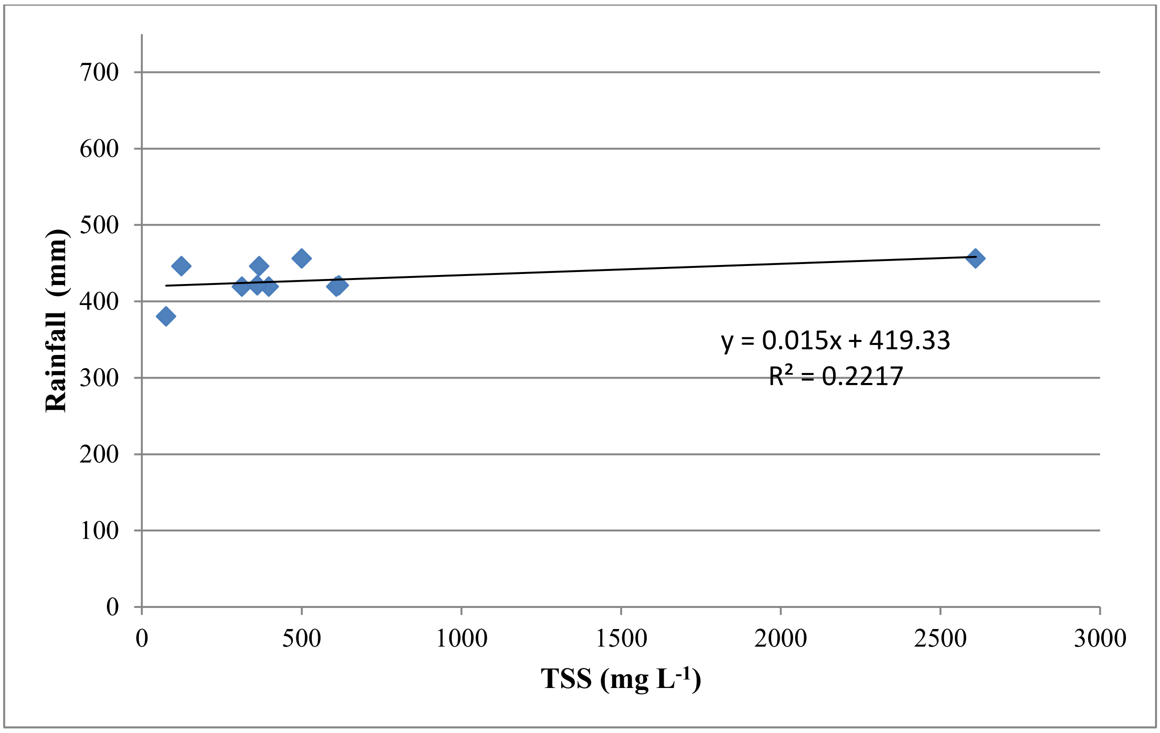


Figure 2-7. Correlation between annual rainfall and mean TSS concentrations in Alberta's municipal landfills.

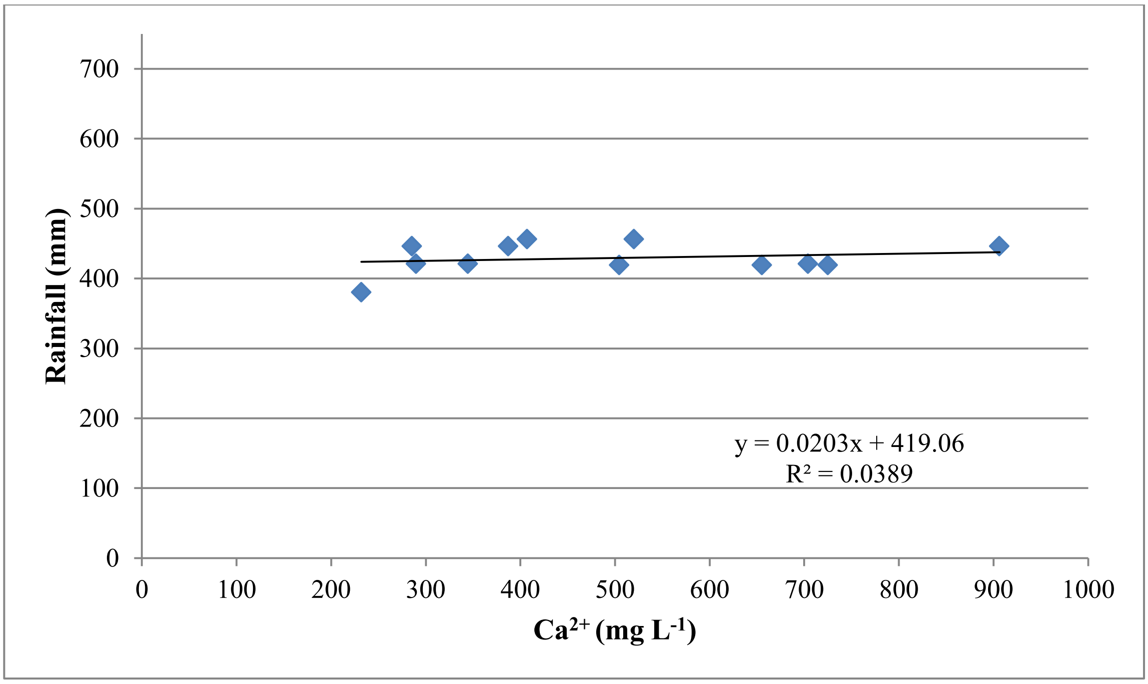


Figure 2-8. Correlation between annual rainfall and mean Ca^{2+} concentrations in Alberta's municipal landfills.

Figures 2-6, 2-7 and 2-8 do not show strong correlations between rainfall amounts and concentrations of COD, TSS and Ca^{2+}, respectively. This observation was surprising since it was expected that low strength leachates correlate strongly with high rainfall conditions due to dilution effects (Fan et al., 2006; Poulsen et al., 2002). This observation may be explained by the fact that rainfall data (Table 2-7) was based on regional information while leachate data (Table 2-5) was specific to landfill sites. There is a need therefore to investigate spatial variability of leachate chemistries based on site rainfall data as opposed to the regional rainfall data.

The chemical characteristics of leachates in Alberta's municipal landfills were compared in with those reported by other researchers (Table 2-1). The mean pH values presented in Figure 2-1 ranges between 6.7 and 8.6. Mean pH values based on published literature (Table 2-1) range between 5.1 and 8.6 implying that general geochemical conditions of Alberta municipal landfills compare well with other jurisdictions. The mean concentrations of COD ranged between 725 and 10,327 mg L^{-1} (Figure 2-2). These values compared well with mean COD values reported by Emenike et al. (2012), VanGulck et al. (2003) and Fan et al. (2006). The mean concentrations of calcium in Alberta's municipal landfills ranged between 231 and 3,810 mg L^{-1} (Figure 2-5). These values compared well with those reported by VanGulck et al. (2003), but they were much higher than those reported by Emenike et al. (2012) (Table 2-1). In general, variability of leachate chemistries occurs within landfills (Figure 2-5) and between regions (Table 2-1).

Therefore, generalization of leachate characterization data, even for sites within the same region would be inappropriate.

2.5 Implications of the leachate composition and strengths on susceptibility of Alberta's LCDS to clogging

The presence of organic and inorganic constituents in landfill leachates is indicative of an environment that is conducive for microbial activities and geochemical reactions and, therefore, development of clog particles. It was discussed previously that municipal landfills exhibited leachates of higher strength compared to industrial landfills and, therefore, have a higher potential for clogging. It was also discussed that leachates evolve over two main phases; namely, young and mature phases. Young leachates may cause more clogging than old leachates, but their timespan is relatively short compared to that of mature leachates (Beaven et al., 2013; Hudson et al., 2008). Of interest then is the susceptibility of municipal landfills to clogging, given leachates chemistries presented in Table 2-5.

Establishing the susceptibility of landfills to clogging is difficult as effluent leachates are of lower strength than those entering the LCDS because of pre-treatment within the media (Ham and Bookter, 1982; Rowe, 2005). The field study by Fleming et al. (1999) focused on field clogging profiles and the end-of-pipe raw leachates. Figure 2-9 shows the minimum, mean and maximum concentrations of COD values reported for the 12 municipal landfills together with the range of COD values recorded by Fleming et al. (1999). The corresponding values for Ca^{2+} are shown in Figure 2-10. However, comparisons based on composition and strength of leachates alone, are not a sufficient check for susceptiblity of media to clogging. Beaven et al. (2013) pointed out that the relative duration and pollutant flux of acidogenic and methanogenic leachates experienced by a LCDS during its active life are important factors for evaluating potential of drainage media to clogging. Regarding pollutant flux, Beaven et al. (2013) considered both volumetric and organic loading. For this study, site specific volumetric loads were not determined. Beaven et al. (2013) proposed that a 25 m deep landfill would require the passage of 70 m^3 of water per m^2 surface area over its lifetime. The corresponding organic load for a 25 m deep landfill was estimated as 15 kg of total organic carbon per m^2 area (Beaven et al., 2013). However, the actual fluxes into the drainage layer may be very low considering that typical landfill operations take many decades (Beaven et al., 2013).

In most landfills acidogenic conditions exist for a few months before methanogenic conditions become established, implying the majority of leachates reaching LCDS are methanogenic (Beaven et al., 2013). Ham and Bookter (1982) demonstrated that placing refuse over a relatively stabilised waste resulted in 75 to 99% reduction in COD produced by the upper layer. Therefore the minimum and maximum concentrations of leachate species shown in Figures 2-9 and 2-10 may be associated with heavy rainfall events and short circuiting, and may not necessarily cause drainage media to clog (Beaven et al., 2013). This is corroborated by findings of Fleming et al. (1999) that although some clogging had developed within a period of 1-4 years, the hydraulic conductivity of the 50 mm gravel was still sufficient to transmit leachate without development of leachate mound (Rowe, 2005). Lack of clogging in a real LCDS is consistent with observations made on basal drainage sand excavated from Landgraaf test cell as described by Beaven et al. (2013). In this case there was also no physical evidence of significant accumulation of clog material, a condition attributed to methanogenic leachates reaching the sand drainage layer. Based on this qualitative assessment, and considering that gravel and tire shred drainage media have higher porosities than sand, it is unlikely that municipal landfills investigated are susceptible to clogging. However, there is need to conduct further studies to ascertain that municipal landfills in Alberta are indeed not susceptible to clogging.

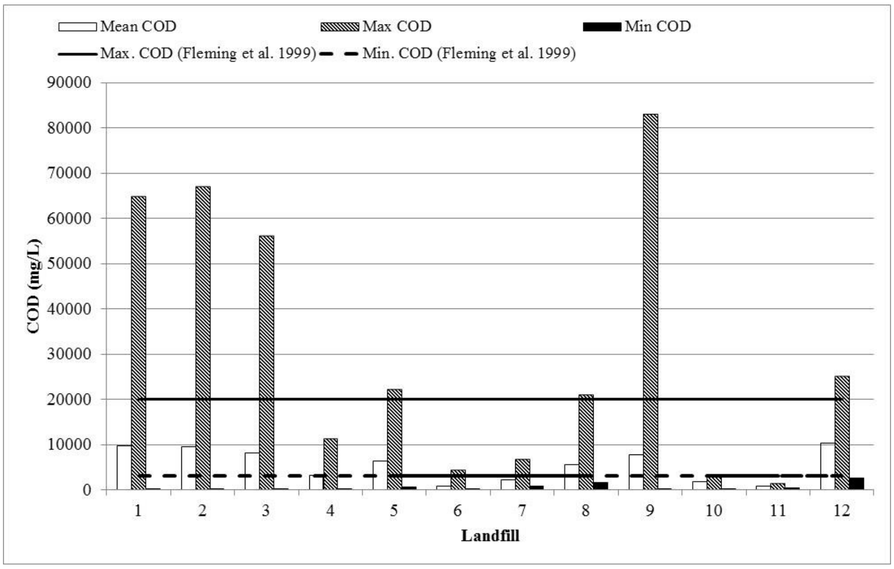


Figure 2-9. Mean, maximum and minimum concentration of COD for the 12 municipal landfills shown against clogging range as observed by (Fleming et al., 1999).

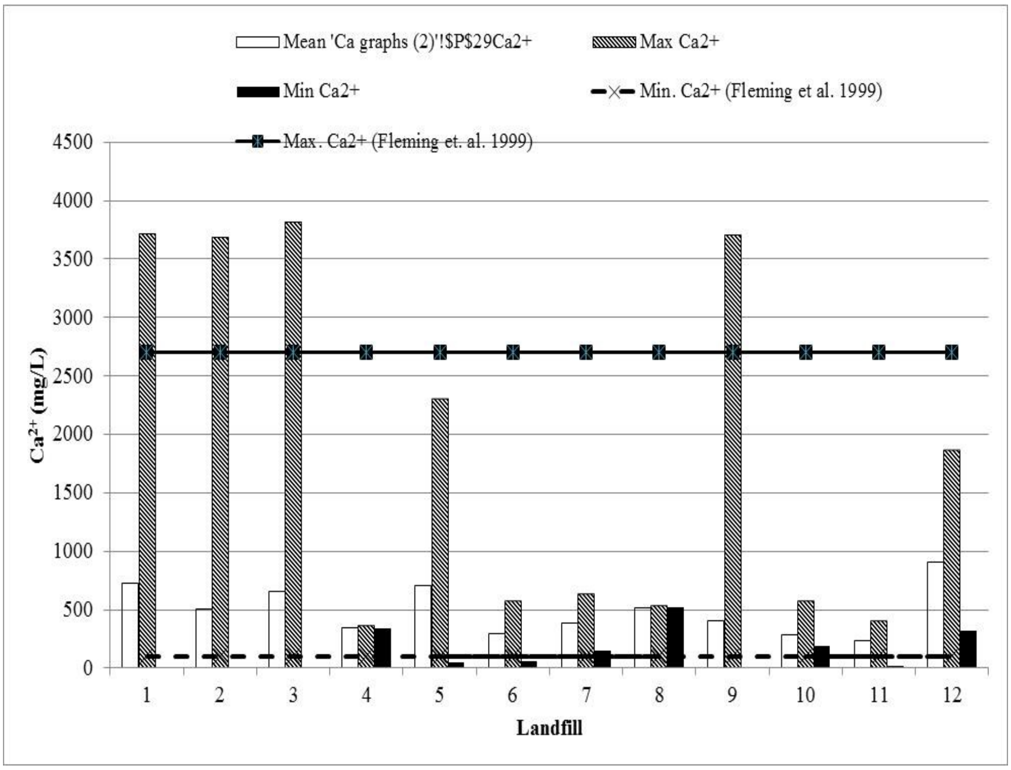


Figure 2-10. Mean, maximum and minimum concentrations of COD for the 12 municipal landfills shown against clogging range as observed by (Fleming et al., 1999).

References

Al-Yaqout, A. F. and Hamoda, M. F. (2003). Evaluation of landfill leachate in arid climate—a case study. *Environment International* **29:** 593-600.

Alberta Environment (2010). Standards for Landfills in Alberta. Government of Alberta. Alberta, Canada.

Amaral, M. C. S., Cynthia F. A. Ferreira, Lise´ te Celina, L. and Aquino, S. F. (2009). Characterization of Landfill Leachates by Molecular Size Distribution, Biodegradability, and Inert Chemical Oxygen Demand. *Water Enviroment Research* **81:** 499-505.

Aydilek, A. H., Madden, E. T. and Demirkan, M. M. (2006). Field evaluation of a leachate collection system constructed with scrap tires. *Journal of Geotechnical and Geoenvironmental Engineering* **132:** 990-1000.

Aziz, S. Q., Aziz, H. A., Yusoff, M. S., et al. (2010). Leachate characterization in semi-aerobic and anaerobic sanitary landfills: A comparative study. *Journal of Environmental Management* **91:** 2608-2614.

Bear, J. and Verruijt, A. (1987). *Modeling groundwater flow and pollution*. D. Reidel Publishing Company, Dordrecht.

Beaven, R. P., Hudson, A. P., Knox, K., et al. (2013). Clogging of landfill tyre and aggregate drainage layers by methanogenic leachate and implications for practice. *Waste Management* **33:** 431-444.

Bernard, C., Colin, J. R. and Anne, L.-D. D. (1997). Estimation of the hazard of landfills through toxicity testing of leachates. *Chemosphere* **35:** 2783-2796.

Bolton, K. A. and Evans, L. J. (1991). Elemental composition and speciation of some landfill leachates with particular reference to Cadmium. *Water, Air abd Soil Pollution* **60:** 43-53.

Calace, N. and Petronio, B. (1997). Characterization of high molecular weightorganic compounds in landfill leachate:humic substances. *Journal of Environmental Science and Health* **32:** 2229-2244.

Chu, L. M., Cheung, K. C. and Wong, M. H. (1994). Variations in the Chemical Landfill Leachate. *Environmental Management* **18:** 105-117.

Cooke, A. J., Rowe, R. K., Rittimann, B. E., et al. (2001). Biofilm growth and mineral precipitation in synthetic leachate columns. *Journal of Geotechnical and Geoenviornmental Engineering* **127:** 849-856.

Cooke, A. J., Rowe, R. K., Rittmann, B. E. and Fleming, I. R. (1999). Modeling Biochemically Driven Mineral Precipitation in Anaerobic Films. *Water Science Technology* **39:** 57-64.

Emenike, C. U., Fauziah, S. H. and Agamuthu, P. (2012). Characterization and toxicological evaluation of leachate from closed sanitary landfill. *Waste Management & Research* **30:** 888-897.

EWMCE (2009). Implications of Using Tire Derived Aggregate for Landfill Leachate Collection Systems – Literature Review. Edmonton, Alberta Recycling Management Authority (ARMA).

Fan, H., Shu, H. Y., Yang, H. S. and Chen, W. C. (2006). Characteristics of landfill leachates in central Taiwan. *Science of the Total Environment* **361:** 25-37.

Fatta, D., Voscos, C., Papadopoulos, A. and Loizidou, M. (1998). Leachate Quality of a MSW landfill. *Journal of Environmental Science and Health* **A33:** 749-763.

Fleming, I. R. and Rowe, R. K. (2004). Laboratory studies of clogging of landfill leachate collection and drainage systems. *Canadian Geotechnical Journal* **41:** 134-153.

Fleming, I. R., Rowe, R. K. and Cullimore, D. R. (1999). Field observations of clogging in a landfill leachate collection system. *Canadian Geotechnical Journal* **36:** 685-707.

Frascari, D., Bronzini, F., Giordano, G., et al. (2004). Long-term characterization, lagoon treatment and migration potential of landfill leachate: a case study in an active Italian landfill. *Chemosphere* **54:** 335-343.

Gálvez, A., A. Ramos, Rodríguez, M. L. and Zamorano, M. (2008). Characterization of the leachate produced in the closed cells of a landfill site at Alhendín (Granada, Spain). *Waste Management and the Environment IV* **109:** 163-172.

Gettinby, J. H., Sarsby, R. W. and Nedwell, J. C. (1996) The composition of leachate from landfilled refuse. Proceedings of the Institute of Civil Engineer, Municipal Engineer, AME 47-59.

Ham, R. K. and Bookter, T. J. (1982). Decomposition of solid waste in Test Lysimeters. *Journal of Environmental Engineering* **108:** 1147-1170.

Hudson, A. P., Beaven, R. P., Powrie, W., et al. (2008). Clogging potential of methanogenic leachate on tyre and aggregate drainage layers. Proceedings Waste 2008: Waste and Resource Management- a Shared Reponsibility. Stratford-upon-Avon, Warkwickshire, England,**:** pp. 16-17.

Hunter, K. S., Wang, Y. and Cappellen, P. V. (1998). Kinetic modeling of microbially-driven redox chemistry of subsurface environments: coupling transport, microbial metabolism and geochemistry. *Journal of Hydrology* **209:** 53-80.

Inanc, B., Calli, B. and Saatci, A. (2000). Characterization and anaerobic treatment of the sanitary landfill leachate in Istanbul. *Water Science and Technology* **41:** 223-230.

Kalcikova, G., Zagorc-Koncan, J., Zupancic, M. and Gotvajn, A. Z. (2012). Variation of landfill leachate phytotoxicity due to landfill ageing. *J Chem Technol Biotechnol* **2012:** 1349-1353.

Khattabi, H., Aleya, L. and Mania, J. (2002). Changes in the quality of landfill leachates from recent and aged municipal solid waste. *Waste Management & Research* **20:** 357-364.

Kim, Y. D. and Lee, D.-G. (2008). Comparative study on leachate in closed landfi ll sites: focusing on seasonal variations. *J Mater Cycles Waste Manag* **11:** 174-182.

Koerner, G. R. and Koerner, G. R. (2004). Leachate clogging assessment of geotextile and soil landfill filters. Cincinnati, Ohio, Geosynthetic Research Institute, Drexel University.

Konhauser, K. (2007). *Introduction to geomicrobiology*. Blackwell Publishing, Hoboken.

Kulikowska, D. and Klimiuk, E. (2008). The effect of landfill age on municipal leachate composition. *Bioresource Technology* **99:** 5981-5985.

McBean, E. A., Rovers, F. A. and Farquhar, G. J. (1995). *Solid waste landfill engineering and design*. Prentice Hall PTR, Upper Saddle River, Toronto.

McBean, E. A., Rovers, F. A. and Farquhar, G. J. (1995). *Solid waste landfill engineering and design* Prentice Hall PTR, Upper Saddle River, Toronto.

McBride, M. B. (1994). *Environmental chemistry of soils*. Oxford University Press, New York.

McIsaac, R. and Rowe, R. K. (2005). Change in leachate chemistry and porosity as leachate permeates through tire shreds and gravel. *Canadian Geotechnical Journal* **42:** 1173-1188.

Mor, S., Ravindra, K., Dahiya, R. P. and Chandra, A. (2006). Leachate characterisation and assessment of groundwater pollution near municipal waste landfill site. *Environmental Monitoring and Assessment* **118:** 435-456.

Poulsen, T. G., Moldrup, P., Sørensen, K. and Hansen, J. A. (2002). Linking landfill hydrology and leachate chemical composition at a controlled municipal landfill (Kåstrup, Denmark) using state-space analysis. *Waste Management & Research* **2002:** 445-456.

Qian, X., Gray, D. H. and Koerner, R. M. (2004). Estimation of Maximum Liquid Head over Landfill Barriers *Journal of Geotechnical and Geoenviornmental Engineering* **130:** 488-497.

Rowe, R. K. (2005). Long-term performance of contaminant barrier systems. *Geotechnique* **55:** 631-678.

VanGulck, J. F. and Rowe, R. K. (2004). Influence of landfill leachate suspended solids on clog (biorock) formation. *Waste Management* **24:** 723-738.

VanGulck, J. F., Rowe, R. K., Rittmann, B. E. and Cooke, A. J. (2003). Predicting biogeochemical calcium precipitation in landfill leachate collection systems. *Biodegradation* **14:** 331-346.

Warith, M. and Rao, S. M. (2004). Estimation of the maximum leachate head in tire shred drainage layer. Geo Jordan 2004. ASCE.

Yong, R. N. and Mulligan (2004). *Natural attenuation of contaminants in soil*. Lewis Publishers, Florida.

Ziyang, L., Bin, D., Xiaoli, C., et al. (2009). Characterization of refuse landfill leachates of three different stages in landfill stabilization process. *Journal of Environmental Sciences* **21:** 1309-1314.

3 Compressibility of tire-derived aggregates: effects on hydraulic performance and on long-term thickness of leachate collection and drainage systems

Materials in this chapter presented/ submitted as:

a) Marclus Mwai, Kristine Wichuk & Daryl McCartney. 2015. Effects of media compressibility on long-term performance of leachate collection and drainage systems (LCDS) (Accepted for publication).

b) Marclus Mwai, Daryl McCartney & Kristine Wichuk. 2012. The performance of tire-derived aggregates as media for leachate collection and drainage. In Proceedings of the 12th International Environmental Specialty Conference, Edmonton, Alberta, 6-9 June 2012.

c) Marclus Mwai, Kristine Wichuk & Daryl McCartney. 2010. Implications of using Tire-derived Aggregate for landfill leachate collection and drainage systems. In Proceedings of the Solid Waste Association of North America, Banff, Alberta, 18-21 April 2010.

3.1 Introduction

Adequate performance of leachate collection and drainage systems (LCDS) is a critical requirement for sustainable management of sanitary landfills. However, clogging can affect the performance of LCDS significantly (e.g. Fleming et al., 1999; Hudson et al., 2008; McIsaac and Rowe, 2005). Both gravel and tire derived aggregates (TDA) have been used as medium for LCDS. McIsaac and Rowe (2005) demonstrated that hydraulic conductivity of TDA can drop below 10^{-5} $m{\cdot}s^{-1}$ due to clogging. Hudson *et al*. (2008) did not observe significant clogging in LCDS, which they attributed to the applied low strength methanogenic leachates, compared to high strength acetogenic leachates used by McIsaac and Rowe (2005). The characteristics of the leachate notwithstanding, properties of TDA can influence performance of LCDS (Reddy and Saichek, 1998).

TDA are processed from end-of-life tires. Tires are made of natural rubber, synthetic rubber elastomers, polymers and additives such as clay, titanium dioxide, zinc oxide and sulfur (ASTM 2009; Reddy and Marella, 2001). The properties of TDA that influence performance of LCDS include particle size and shape, unit weight, compressibility, porosity, and hydraulic conductivity (Reddy and Marella, 2001). Table 3-1 gives an overview of properties that are reported in literature.

The particle sizes, unit weights, media compressibility and hydraulic conductivities of TDA vary greatly (Table 3-1), which may be attributed to different shredding processes, testing conditions, and procedures. There is limited information on the shredding unit processes used by different processors. However, Reddy and Marella (2001) have pointed out that different shred sizes are achieved by application of multiple shredders. Some processors also pass their material through screens. Consequently, different particle size distributions are possible, making it difficult to predict performance of TDA on the basis of particles size. Unit weights vary with compaction and the proportion of steel wire. In general, however, TDA are light-weight materials compared to gravel (Drescher et al., 1999). The porosity of loose TDA is about 0.60 but reduces to about 0.57, 0.46 and 0.1 under pressures of 10, 50 and 460 kPa, respectively (Drescher et al., 1999; McIsaac and Rowe, 2005). It would be expected that at low overburden pressures, TDA would be more permeable than gravel, which has porosity of 0.4.

Table 3-1. Overview of properties of TDA based on previous studies

Reference	Particle size, mm	Bulk unit weight $kN \cdot m^{-3}$ (load, kPa)	Specific gravity	Compression, % (load, kPa)	Porosity (load, kPa)	Hydraulic conductivity ($m \cdot s^{-1}$), (load, kPa)	Type of tire	Manufacturer/ Supplier
(Drescher et al., 1999)	30-90	3.5 - 4.3 (0) 4.2-5.1 (138)	1.11	-	0.64 0.57	-	Car tire	-
(Northstar, 1995)	25 (max)	4.1 (0)	1.112	46 (478)	-	0.005-0.007 (170)	Car tire	-
(Warith and Sudhakar, 2006)	25-75	5.0 - 5.3(0)	-	47 (330) 47 (330)	-	0.1 (75) 0.007 (330)	-	-
(Aydilek et al., 2006)	25-100	4.1-5.2 (0) 9.1-9.6 (220-240)	-	40-46 (230)	-	0.02-0.05 (220-240)	-	-
(McIssac, 2007)	12-40	4.6-4.7 (0) 9.0-9.9 (150)	1.18-1.35	44.5-46.9 (150)	0.266-275 (150)	0.02-0.03 (150)	-	Lafleche Environmental Inc, Ontario, Canada
(Hudson et al., 2007)	50 (average)	-		-	0.5 (50) 0.23 (600)	0.5 (50) 0.008 (600)		
	200 (average)	-		-	0.33 (150) 0.16 (600)	0.08 (150) 0.006 (600)		Credential Environmental Ltd
	330-580	-	1.29	-	0.4 (150) 0.23 (600)	0.06 (150) 0.003(600)		
(Meles et al., 2013)	12-100 (PLTT)	4.9 (0) 6.0 (180)	1.31	30 (50) 34 (180)	-	-	Car tire and light trucks	Rubber Tech International (Legal, AB)

Reference	Particle size, mm	Bulk unit weight $kN \cdot m^{-3}$ (load, kPa)	Specific gravity	Compression, % (load, kPa)	Porosity (load, kPa)	Hydraulic conductivity ($m \cdot s^{-1}$), (load, kPa)	Type of tire	Manufacturer/ Supplier
	12-100 (OTR)	4.8 (0) 6.5 (180)	1.27	27 (50) 23 (50)	-	-	Mining and construction equipment	CuttingEdge Tire RecyclingLP (Edmonton, AB)
(ASTM 2009)	25-64	4.6-6.0	-	-	-	0.1-0.24	-	-
	5-51	5.6-6.0	-	-	-	0.04-0.60	-	-
	10-51	6.3-8.2	-	-	0.33-0.48	0.02-0.08	-	-
	20-76	5-9-7.9	-	-	0.37-0.53	0.05-0.15	-	-
	10-38	6.1-7.9	-	-	0.29-0.45	0.01-0.07	-	-

Increase in overburden pressure reduces porosity and, hence hydraulic conductivity (Beaven et al., 2007; Powrie et al., 2005). However, TDA have been observed to maintain adequate hydraulic conductivity even at high overburden pressures (Aydilek et al., 2006; Hudson et al., 2007; Park et al., 2003; Powrie et al., 2005; Warith and Sudhakar, 2006).

TDA properties are influenced by the type of tire used. In Alberta, Canada, there are three main TDA products; namely, passenger car and light truck tires (PLTT), medium truck tires (MTT) and off-the-road (OTR) tires. PLTT and MTT are flat shaped while OTR are processed from tires used on construction and mining equipment and are block shaped (Meles et al., 2013). While MTT has limited applications in landfills, PLTT and OTR have been applied in LCDS of Alberta since 1995. OTR are made stronger than passenger car and light truck tires because of the expected heavy loads and rugged operating conditions (Goodyear, 2008). Therefore, OTR and a mixture of OTR and PLTT (OTR+PLTT) derived aggregates may perform differently from those made from PLTT when subjected to sanitary landfill conditions. Recently, Meles *et al.* (2013) investigated compression behaviour of PLTT and OTR. At a pressure of 54 kPa, PLTT exhibited strains of 17 to 23% while OTR strains ranged from 15 to 20%. The tests did not evaluate particle size distributions and specific gravities of MTT and OTR+PLTT. Limited data also exists on porosities and hydraulic conductivities of PLTT, OTR and OTR+PLTT despite their importance in evaluating performance of drainage media.

TDA may compress by 25 to 50% during the life of the landfill (Beaven et al., 2007; Warith and Sudhakar, 2006); Therefore, it is necessary to specify initial thickness of a drainage layer to ensure that it does not fall below the maximum leachate head of 300 mm

(Alberta Environment, 2010). Previous attempts by Warith and Sudhakar (2006) and Beaven *et al*. (2007) to specify the initial thickness of a drainage layer were based on uniform unit weights of landfilled waste mass. The approach presents uncertainties because unit weights of landfilled waste increase with overburden pressures (Zekkos et al., 2006).

The objective of this study were to evaluate particle size distribution, specific gravity, compressibility, porosity, and hydraulic conductivity of four types of TDA; namely, PLTT, MTT, OTR and OTR+PLTT. A further objective of the study was to develop a criterion for specifying initial thickness of TDA-based drainage layers.

3.2 Materials and methods

3.2.1 Materials

This study involved the main TDA products that are commercially available in Alberta; namely, PLTT, MTT and OTR (Figure 3-1). OTR and PLTT were mixed on 50:50 by weight basis to produce OTR+PLTT. Gravel was included as control, having traditionally been used as drainage media for LCDS. PLTT, MTT and OTR were supplied by Rubber Tech International (Legal, AB), Alberta Environmental Rubber Products (Edmonton, AB) and, CuttingEdge Tire Recycling LP (Edmonton, AB), respectively. Gravel was sourced from Lafarge Canada Inc.

3.2.2 Apparatus and test procedures

3.2.2.1 Particle size distribution tests

About 50 kg of TDA were sieved using a mechanical shaker (Sellbergs Engineering Testscreen, model LB/LO). The sieving was conducted in two stages. Stage 1 used sieves of diameters 305, 228, 152, 125, and 80 mm. Stage two sieved materials passing the 80 mm using sieves of diameters 50, 35, 20, 15, and 6 mm. The sieves were shaken for 2 minutes and the mass of the material remaining on each sieve weighed. The results were presented as particle size distribution curves. Uniformity coefficients were determined as the ratio of the sieve size that allowed passage of 60% of the particles to the sieve size that had 10% of the particles by weight passing (Qian et al., 2002).

Figure 3-1. Photographs of the test materials: a) PLTT-flat and elongated shape and clean cut edges, b) OTR-block shape and roughly cut edges, c) OTR+PLTT -a mixture of OTR and PLTT on 50:50 by weight basis, d) gravel (clean river bed gravel), e) MTT-flat and elongated shape and clean cut edges.

3.2.2.2 Specific gravity tests

TDA particles were saturated with water over a period of 24 hours. The particles were then surface dried until there was no visible water. A known mass of TDA ($m_{TDA,}$ kg) was placed in a bucket of water and the volume of water displaced (V_{water}, m^3) measured. The specific gravity, Gs, of the TDA was determined as:

$$Gs = \frac{m_{TDA}}{V_{water}} \cdot \frac{1}{\rho_{water}} \qquad [3\text{-}1]$$

where ρ_{water} is the density of water ($kg \cdot m^{-3}$)

3.2.2.3 Compression tests

The compression test apparatus Figure (3-2) consisted of four polyvinyl chloride (PVC) columns and a manual hydraulic system for uniaxial compression. The height and inner diameter of the columns were 112.0 and 57.3 cm, respectively (Figure 3-2). The PVC columns rested on a timber platform, about 1.0 m above the floor. The loading frame consisted of a steel framework, comprising of 100 x 100 mm vertical supports and a cross-beam spanning over the vertical supports. The cross beam supported a pneumatic cylinder of 100 mm diameter and four pressure gauges, one for each column.

The inner walls of the PVC columns were lined with 4 layers of 6 mil plastic sheet to reduce frictions between the sidewall and the TDA (Drescher et al., 1999). Test samples were obtained by quartering method and then placing into three to four 50 L bucket loads. Each bucket load was weighed and then placed loosely in the columns to a maximum height of 100 cm. The media were compressed at pressures of up to 330 kPa. Compression tests were conducted in triplicates, with new materials for each test.

Compression was calculated as the difference between the initial height and the height after compression. Applied pressures were read directly from the pressure gauges. The bulk densities were calculated from the mass of TDA placed in the columns and the compressed volume.

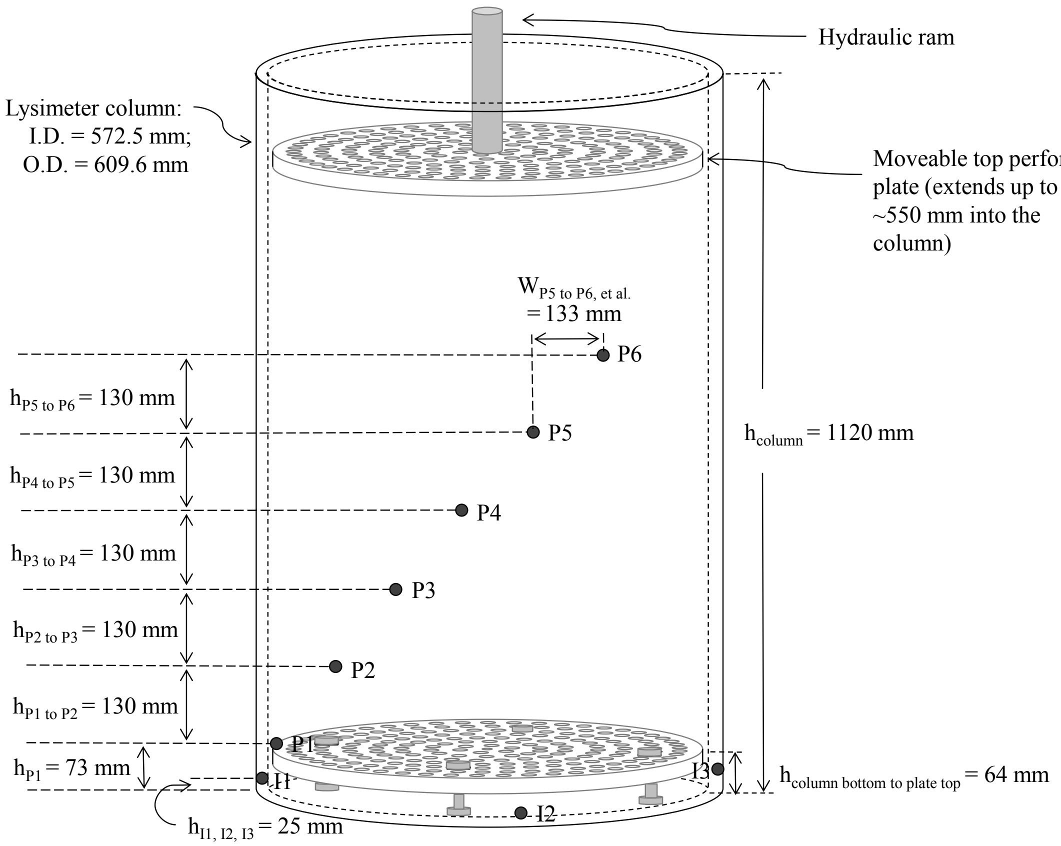


Figure 3-2. Assembly for compressibility tests column

3.2.2.4 Hydraulic conductivity and drainable porosity tests

Hydraulic conductivity tests used the compression test apparatus. Each column was fitted with six clear piezometers at 130 mm intervals (Figure 3-3). The TDA materials were prepared and placed in the columns using the procedure described for compression tests. Tap water was allowed to flow upwards using a wall faucet so as to achieve high velocities. At every level of compression, three to four permeability tests were conducted at increasing volumetric water flow rates.

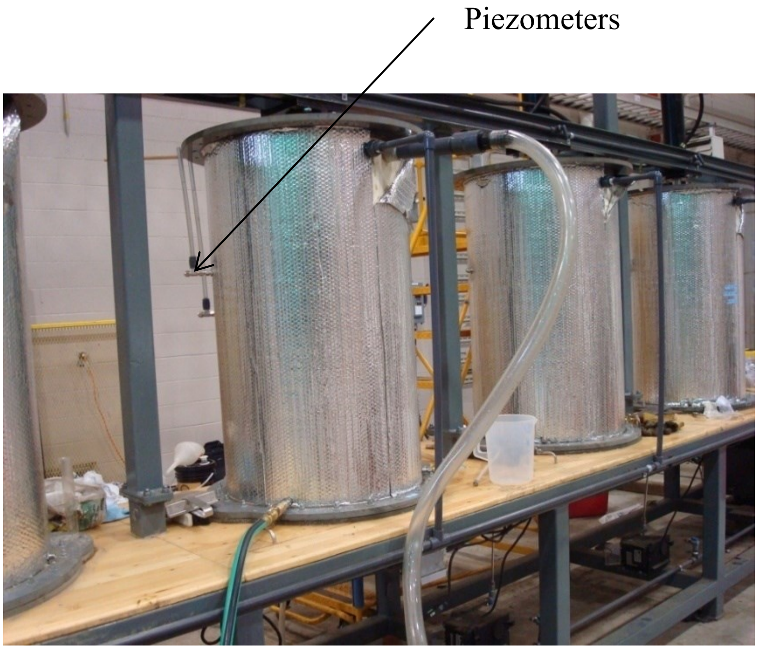


Figure 3-3. Set-up for hydraulic conductivity tests: inflow (bottom) and outflow (top) arrangements**.**

Hydraulic conductivity of the TDA was calculated using Darcy's equation (McIssac, 2007; Warith and Sudhakar, 2006):

$$v = -K_y \frac{\Delta h}{Ls} \qquad [3\text{-}2]$$

where, K_y is the vertical hydraulic conductivity in $m \cdot s^{-1}$; v is the specific discharge in $m \cdot s^{-1}$; Δh is the headloss in meters between two piezometers; and Ls is the length in meters of the sample between two piezometers.

Drainable porosity was determined by draining water and dividing the volume by the compressed bulk volume of the sample.

3.3 Results and Discussions

3.3.1 Particle size distributions

Figure 3-4 shows the particle distribution curves for the TDA and gravel samples. The curves for TDA are typical of well graded material with sizes ranging from 20 to125 mm. The uniformity coefficient (μ) of TDA ranged from 1.6 to 2.2 while that for 20 to 35 mm gravel was 1.4. In general, TDA samples had less-uniform particle size distributions, suggesting a higher potential to retain clog particles than for gravel.

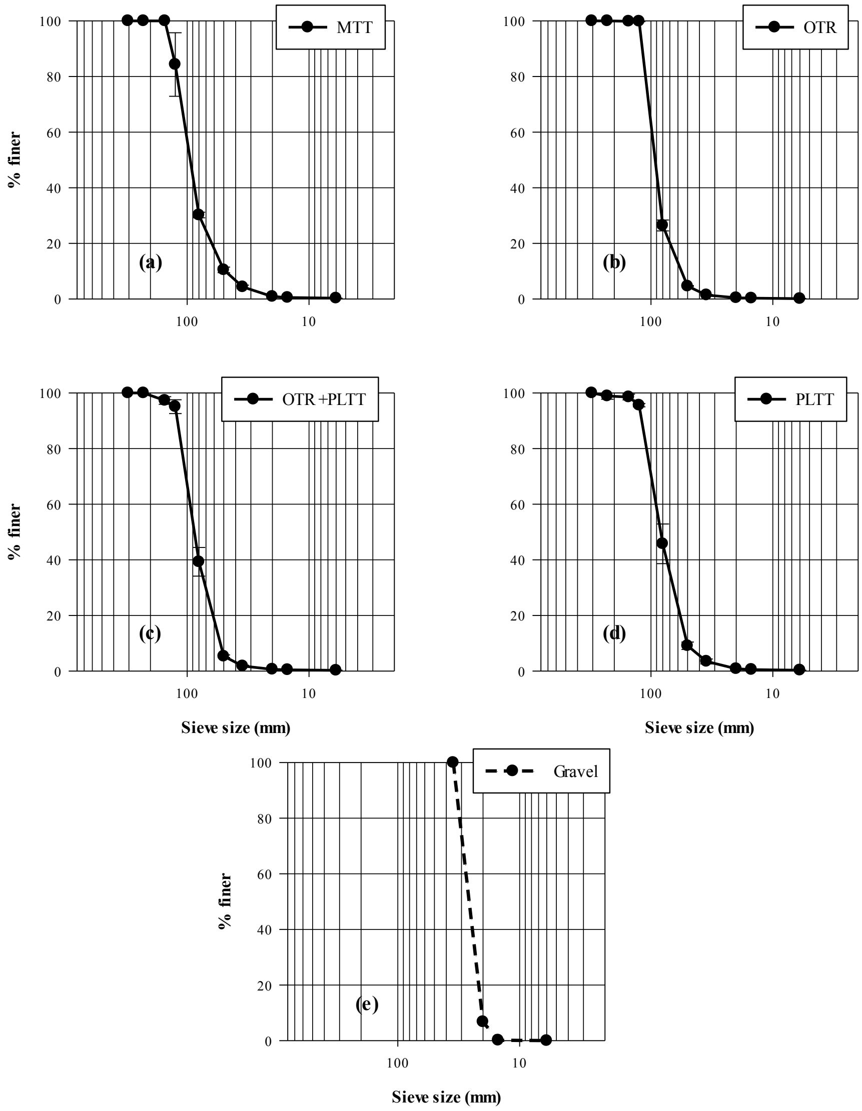


Figure 3-3. TDA distribution curves showing percentage of: (a) MTT, (b) OTR, (c) OTR+PLTT, (d) PLTT, and (e) gravel passing different sieve sizes.

3.3.2 Specific Gravities of TDA

Specific gravities of PLTT, MTT, OTR and OTR+PLTT ranged between 1.12 and 1.25 (Table 3-2). Wu *et al*. (1997) reported specific gravities range of 1.08 to 1.18 for size 38 mm tire shreds. Beaven *et al*. (2007) observed values ranging from 1.22 to 1.36 for tire shreds of size 50 to 200 mm. Specific gravity of gravel was 2.62 ± 0.13, therefore, the TDA samples depicted light-weight construction materials.

Table 3-2. Specific gravity of TDA products and gravel. Values are averages based on 3 samples

TDA type	Particle specific gravity
PLTT	1.19 ± 0.07
MTT	1.25 ± 0.06
OTR	1.12 ± 0.13
PLTT + OTR (50:50 mix)	1.16 ± 0.11
Gravel	2.62 ± 0.13

3.3.3 Uni-axial compression behavior of TDA

The variation of axial strains with vertical stresses for TDA samples is shown in Figure 3-5. PLTT, MTT, OTR and OTR+PLTT exhibited strains ranging between 38 and 52 % at 153 kPa. Strains varied from sample to sample, probably owing to differences in the placing unit weights (Table 3-3). In general, OTR exhibited lower compression compared with PLTT, MTT, and OTR+PLTT. While the smaller compression may result from the relatively high strength associated with OTR (Goodyear, 2008), analysis of variances (ANOVA) did not show statistically significant differences in axial strains of PLTT, OTR and OTR+PLTT at 153 kPa ($F(11, 95) = 1.90$, $p = 0.61$). It is to be noted that: i) F-value arises from F test while p refers to the probability value associated with the F-test results, and ii) if $p > 0.05$, then samples are considered not statistically different. Figure 3-6 shows the variation of unit weights with vertical stresses. A clear correspondence between strains achieved and the placing unit weights could also not be demonstrated (Figure 3-5 and 3-6). For example, the placing unit weights for samples 1, 2 and 3 of PLTT were 4.03, 3.88 and 3.96 kN.m^{-3} respectively, but sample 3 had largest strains of 0.52 at 153 kPa. This result contrasted with the findings of Meles et al. (2013) that the placing unit weight of the samples affected the media strains significantly. However, the samples tested by Meles et al. (2013) were placed in compacted layers, as opposed to loose samples used in the current study.

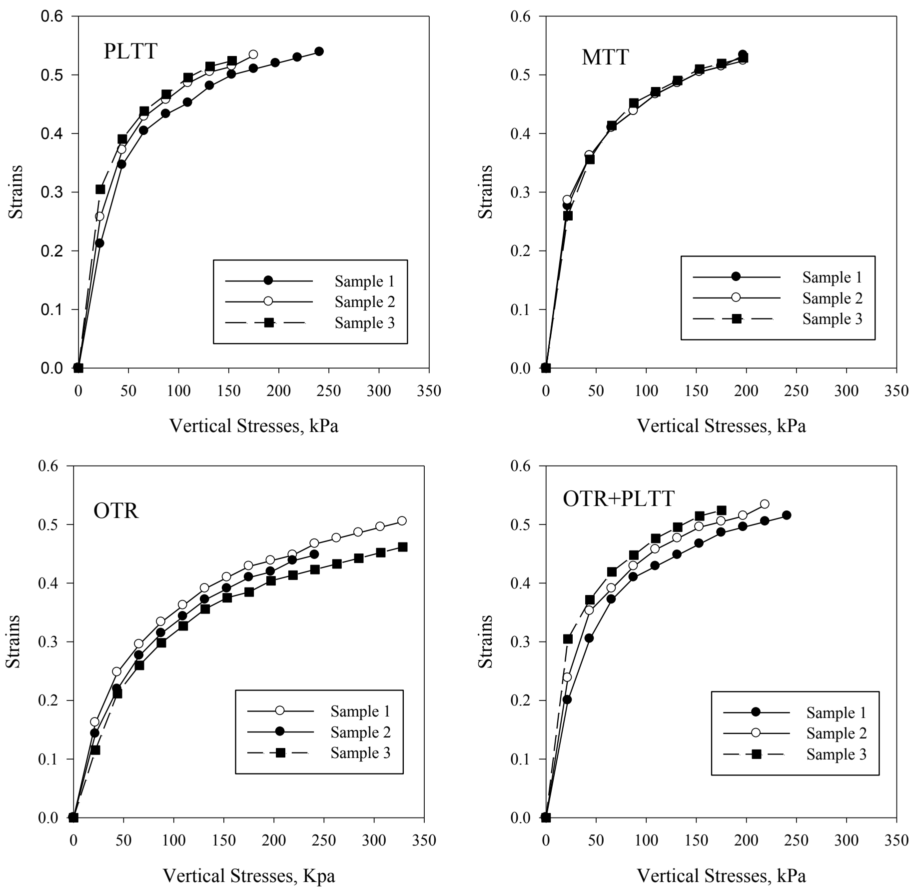


Figure 3-4. Showing strains against vertical stresses in case of PLTT, OTR, MTT and OTR+PLTT.

Table 3-3. Showing the strains achieved at compression pressures of 22 and 153 kPa for various samples of the TDA materials.

TDA type	Force applied (kPa)	Sample No	Loose unit weights (kN m^{-3})	Unit weight (kN m^{-3})	% Strains
PLTT	**22**	Sample 1	4.03	5.10	21.0
		Sample 2	3.88	5.23	25.7
		Sample 3	3.96	5.72	30.0
	153	Sample 1	4.03	8.14	50.0
		Sample 2	3.88	8.06	51.0
		Sample 3	3.96	8.32	52.0
OTR	22	Sample 1	4.57	5.45	16.2
		Sample 2	4.56	5.32	14.3
		Sample 3	4.10	4.56	11.5
	153	Sample 1	4.57	7.70	41.0
		Sample 2	4.56	7.50	39.0
		Sample 3	4.10	6.60	37.5
MTT	22	Sample 1	3.97	5.50	27.6
		Sample 2	3.88	5.40	28.6
		Sample 3	3.84	5.20	26.0
	153	Sample 1	3.97	8.00	50.4
		Sample 2	3.88	7.81	50.4
		Sample 3	3.84	7.93	51.0
OTR+PLTT	22	Sample 1	3.95	4.97	20.0
		Sample 2	3.85	5.04	23.8
		Sample 3	3.56	5.12	30.0
	153	Sample 1	3.95	7.58	46.7
		Sample 2	3.85	7.57	50.0
		Sample 3	3.56	7.31	51.4

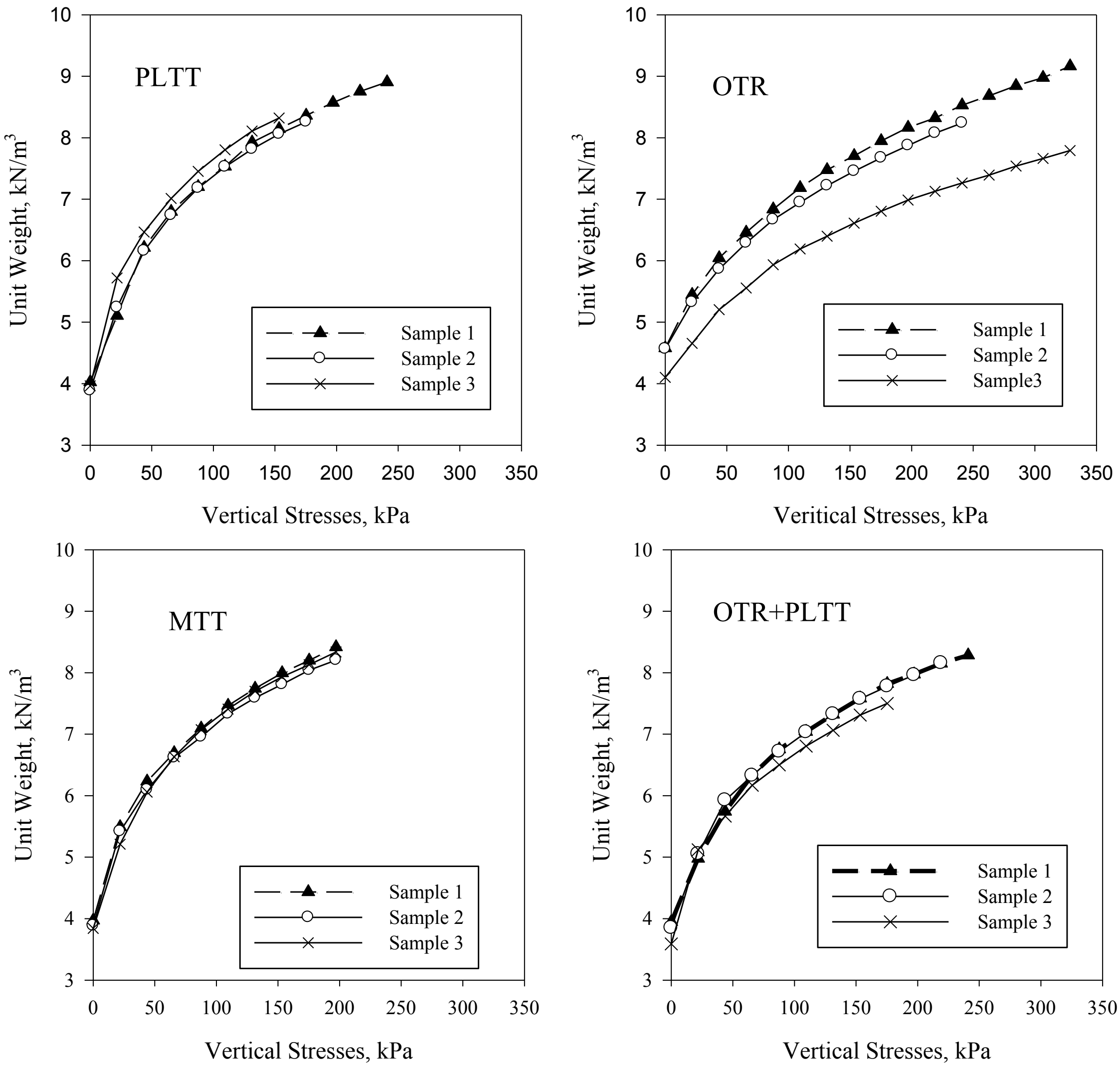


Figure 3-5. Showing unit weights against vertical stresses in case of PLTT, OTR, MTT and OTR+PLTT.

3.3.4 Changes in drainable porosity

The drainable porosity- pressure relationships for PLTT, MTT, OTR and OTR+PLTT (Figure 3-7) showed that the initial porosities of PLTT, MTT, OTR and OTR+PLTT ranged between 0.6 and 0.7. The porosities dropped to about 0.3 at overburden pressures 153 kPa, which is equivalent to a 11 m high landfill. However, a one-way ANOVA did not demonstrate significant differences on porosities for PLTT, MTT, OTR and OTR+PLTT ($F(3, 28) = 0.35$, $p = 0.78$).

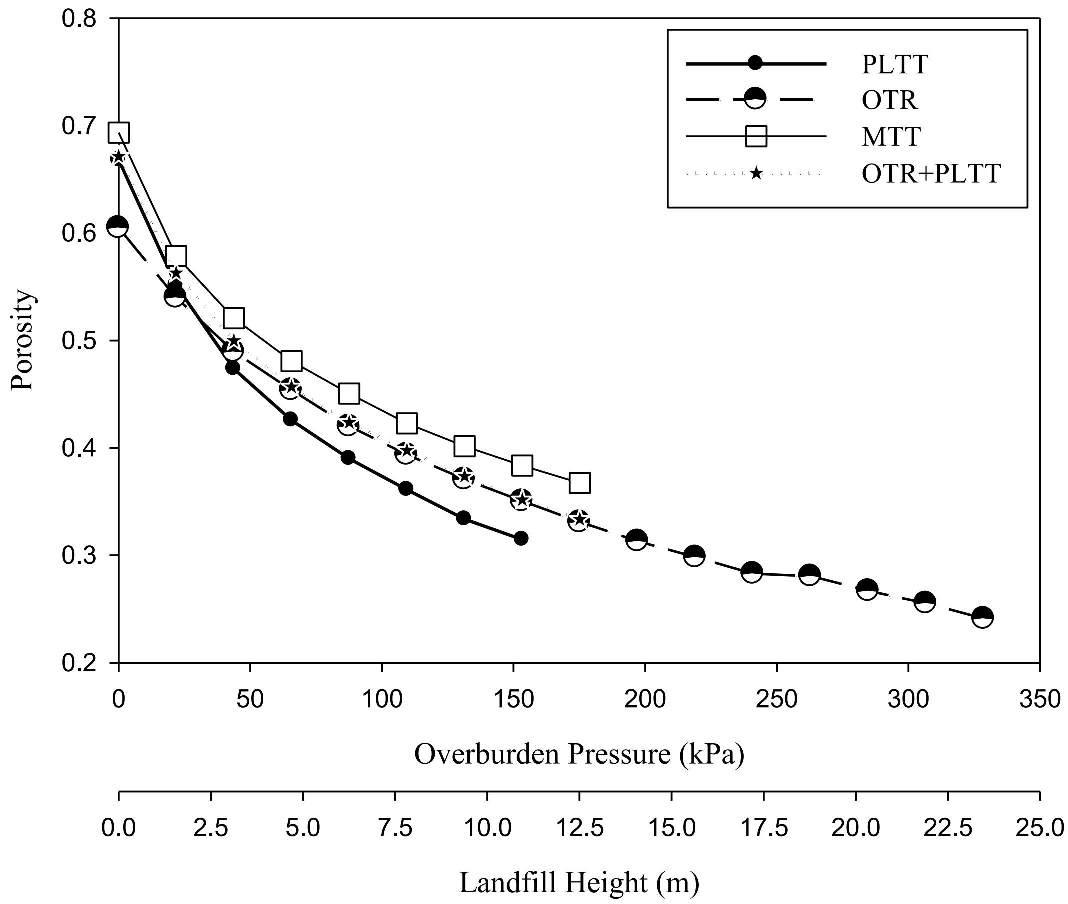


Figure 3-6. Lines of best fit showing variation of drainable porosities with overburden pressures. The corresponding landfill heights were based on the model recommended by Zekkos *et al.* (2006), assuming initial unit weight of waste as 10 $kN{\cdot}m^{-3}$.

3.3.5 Hydraulic conductivity of TDA

The initial hydraulic conductivity of the TDA samples ranged between 0.20 and 0.51 $m{\cdot}s^{-1}$ (Figure 3-7). It reduced to about 0.04, 0.08, and 0.03 $m{\cdot}s^{-1}$ for PLTT/MTT, OTR and OTR+PLTT, respectively, when porosities reduced to about 0.25.

The hydraulic conductivity of OTR was consistently higher than that of PLTT/MTT and OTR+PLTT at the overburden pressures applied (i.e. between 0 and 153 kPa). However, probably because of the high variability of the data, a one-way ANOVA did not show any significant difference between hydraulic conductivities of PLTT, MTT, OTR and OTR+PLTT [$F(3, 30) = 1.96$, $p = 0.13$]. Figure 3-8 shows the hydraulic conductivity curve for combined hydraulic conductivity data. As shown, the curve fitting regression value for the combined hydraulic conductivity data (Figure 3-8) was lower than that of individual curves (Figure 3-7).

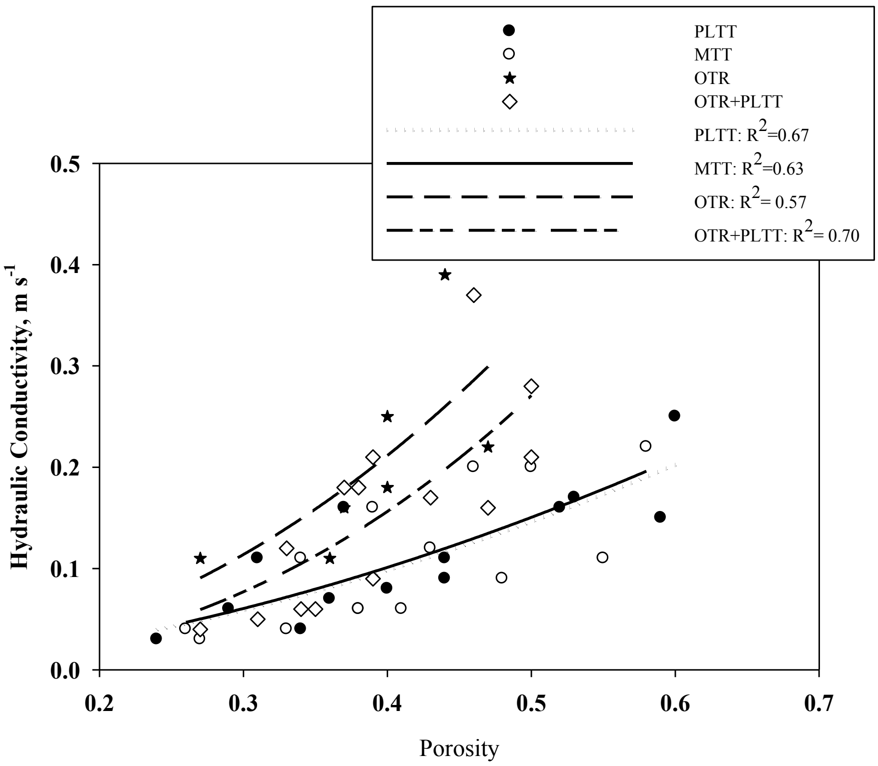


Figure 3-7. Lines of best fit showing variation of hydraulic conductivity with porosity of TDA

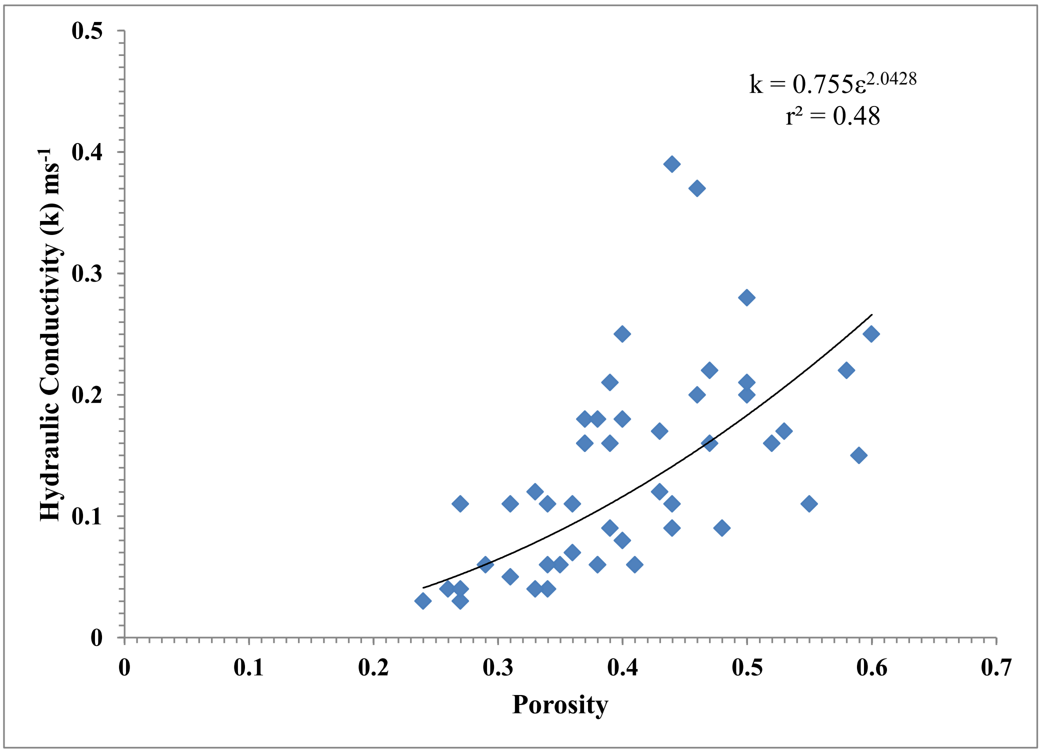


Figure 3-8. Variation of hydraulic conductivity data when combined for all TDA media types processed in Alberta.

Similar to previous studies (Table 3-1), the hydraulic conductivity of TDA reduced with media compression, but remained well above the threshold of 10^{-4} $m{\cdot}s^{-1}$ required for drainage media in LCDS (Alberta Environment, 2010; Hudson et al., 2007).

While the results represented in Figure 3-7 and Table 3-1 are for vertical hydraulic conductivity, TDA media tend to be anisotropic (Drescher et al., 1999; Hudson et al., 2007). The horizontal flow component may be lower than the vertical component, as demonstrated by Hudson *et al*. (2007) and hence critical for the performance of LCDS. Consequently, there is need to evaluate the horizontal conductivity of TDA as well.

3.4 A Criterion for determing as spread-thickness of a TDA-based drainage layer

Because of large strains exhibited by the TDA, it is important for landfill designers to have a clear method for predicting long-term thickness of a TDA layer. The goal would be to ensure that the as-spread layer thickness does not allow the long-term thickness fall below the allowable maximum leachate head of 300 mm.

Figure 3-10 shows the variation of media height with the overburden pressures, while Figure 3-11 shows the variation of void ratio with overburden pressures. The plots shown in Figures 3-10 and 3-11 depict straight lines for the overburden pressures of upto 150 kPa in case of PLTT, MTT and OTR+PLTT and 240 kPa in case of OTR. These plots were used to develop an empirical relationship between media compression and the overburden pressures.

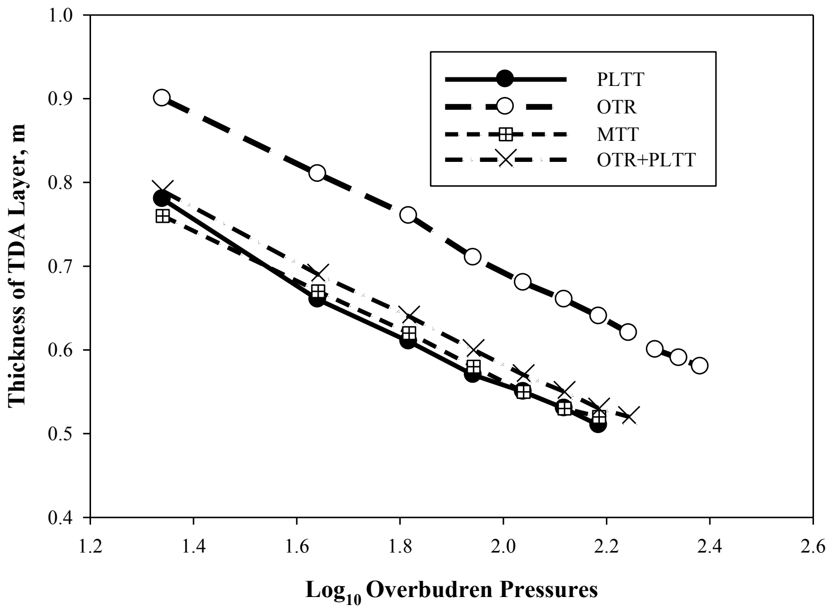


Figure 3-9. Relationship between thickness of TDA and $\log_{10}$ Pressure

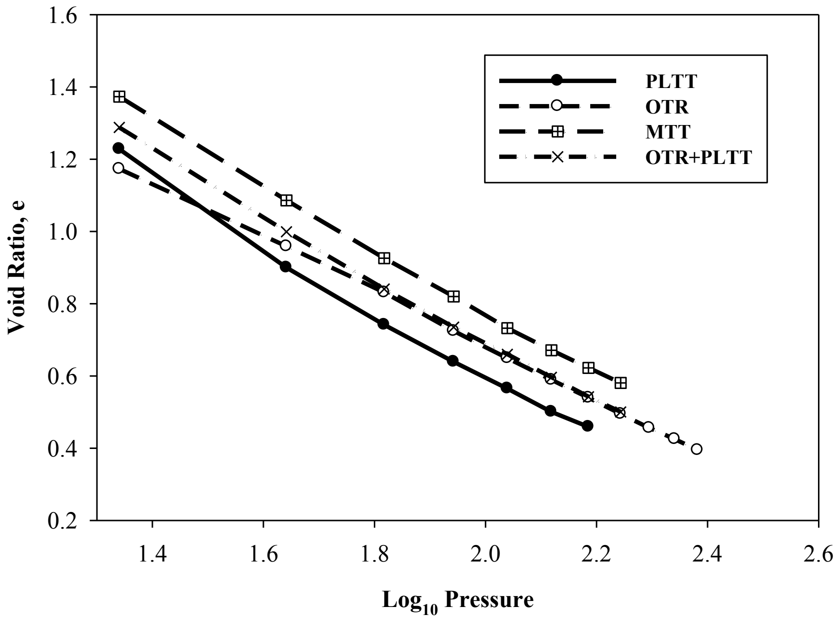


Figure 3-10. Relationship between void ratio of TDA and $\log_e$ Pressure

From Figure 3-10,

$$\Delta h = D_{initial} - D_{new} = CI * (\log_{10} P - \log_{10} P_o) \qquad [3\text{-}3]$$

where Δh is the change in media thickness, $D_{initial}$ is the as-spread media thickness; D_{new} is the prevailing media depth following compression; CI is the compression index, representing mathematical gradient of linearized media thickness - logarithm ($\log_{10}$) of overburden pressure plots (Figure 3-10); $\log_{10}$ P is the base 10 logarithm of overburden pressure and $\log_{10} P_o$ is the base 10 logarithm of the initial overburden pressures.

It is common practice to relate media compression to changes in void ratio (Geosyntec, 2008). From Figure 3-11, the relationship between void ratio and overburden pressures can be represented as:

$$e = e_o - Cc * \log_{10}\left(\frac{P_o + \Delta p}{P_0}\right) \qquad [3\text{-}4]$$

where e is the prevailing void ratio after media compression, e_o is the void ratio of the as-spread TDA media, Cc is the coefficient of compression and represents the mathematical gradient of e-$\log_{10}$ overburden pressure plots (Figure 3-11), Δp is the pressure increment while Po is the initial overburden pressure.

Since changes in media volume are associated with changes in void volume (Wartman et al., 2007), equations [3-3] and [3-4] may be combined to relate changes in media thickness with void ratio and overburden pressures (equation [3-5]).

$$\Delta h = \left[\frac{Cc * H_o}{1 + e_o} . \log_{10} \frac{p_o + \Delta p}{p_o} \right] \qquad [3\text{-}5]$$

Equation [3-5] accounts for short term-media compression. However, compression of TDA materials comprises of short- and long-term components. Wartman et al (2007) recommended a model for long-term compression of TDA (equation [3-6]).

$$\Delta h_L = C_{ae}\ H_o\ \log_{10} \frac{t_2}{t_1} \qquad [3\text{-}6]$$

where Δh_L is long-term compression of TDA; t_1 is the time at the start of long-term compression (days), t_2 is the time when long-term compression is to be determined (days) and H_o is the initial media thickness. It is assumed that H_o is measured just before the TDA layer is subjected to overburden pressures. It therefore represents the as-spread media thickness, which is equivalent to $D_{initial}$ defined above.

The most critical parameter (as it may be material specific) in the model (equation [3-6]) proposed by Wartman et al. (2007) is C_{ae}. It is defined as

$$C_{ae} = \frac{\Delta\varepsilon_{vol}}{\log_{10}\frac{t_2}{t_1}} \qquad [3\text{-}7]$$

where $\Delta\varepsilon_{vol}$ is change in time-dependent volumetric strains and t_2 and t_1 are as defined before.

Combining equation [3-5[and [3-6], the overall media compression becomes

$$\Delta H_{total} = \left[\frac{C_C}{1+e_o}.\log_{10}\frac{P_o+\Delta P}{P_o} + C_{ae}\log_{10}\frac{t_2}{t_1}\right]H_o \qquad [3\text{-}8]$$

where ΔH_{total} is the change in thickness of TDA (m). H_o is the as-spread media thickness (m) of TDA. Other terms are as defined before. Values of Cc and e_o are reproduced in Table 3-4 for ease of reference. A maximum value of 7300 days was adopted for t_2, which corresponded with a landfill active life of 20 years. In absence of experimental data, C_{ae} = 0.0074 as per the model recommended by Wartman et al. (2007).

Table 3-4. Values of coefficient of compression, Cc, and e_o values applicable for equation [3-8]. The Cc values are the gradients of the void ratio-$\log_e$ pressure plots.

TDA type	Cc	eo (at 21 kPa)
PLTT	0.905 ± 0.034	1.229 ± 0.026
MTT	0.892 ± 0.016	1.373 ± 0.008
OTR	0.735 ± 0.009	1.173 ± 0.022
PLTT+OTR(50:50 weight)	0.869 ± 0.016	1.288 ± 0.002

Equation [3-8] determines the change in media thickness given overburden pressure, time, and the as-spread media thickness, H_o. If H(t) is the specified long-term media thickness, equation [3-8] can also be used to determine the appropriate initial (i.e. as-spread) media thickness (H_o), by using the relation:

$$H_o = H(t) + \Delta H_{total}. \qquad [3\text{-}9]$$

A direct application of equation [3-8] is limited by the fact that landfills are frequently described by landfill heights rather than overburden pressures. To convert overburden pressures to landfill heights, knowledge of unit weight of landfilled mass is required. This requirement presents a challenge because unit weight of landfilled waste mass is not constant but varies with: (i) depth of the overlying waste mass, (ii) composition of the municipal solid waste including daily cover and moisture content, (iii) method and degree of compaction, and (iv) age of the waste (Qian et al., 2002). In previous studies, Warith and Sudhakar (2006) assumed bulk unit weights of 6 to 10 $kN \cdot m^{-3}$, while Hudson *et al.* (2007) assumed 10 $kN \cdot m^{-3}$. Zekkos et al. (2006) investigated models for estimating unit weight for landfilled municipal solid wastes and recommended a hyperbolic equation of the form:

$$\gamma_z = \gamma_i + \frac{z_w}{\alpha_w + \beta_w z_w} \qquad [3\text{-}10]$$

where γ_z is unit weight of the waste at depth z ($kN \cdot m^{-3}$); γ_i is the near-surface in-place unit weight of the waste ($kN \cdot m^{-3}$); z_w is the depth at which unit waste is to be estimated (m); α_w ($m^4 \cdot kN^{-1}$) and β_w ($m^3 \cdot kN^{-1}$) and are model parameters. Values for γ_i, α_w, and β_w (Table 3-5) depend on the compaction effort and amount of soil cover (Zekkos et al., 2006).

The model proposed by Zekkos *et al.* (2006) was adopted in the current study. The near-surface in-place unit weight, γ_i was assumed to take values of 5, 10, or 15.5 $kN \cdot m^{-3}$ to accommodate low, medium, and high compaction efforts as envisaged by Zekkos *et al.* (2006).

Table 3-5. Hyperbolic parameters for different compaction effort and amount of soil cover as recommended by Zekkos *et al.* (2006)

Compaction effort and soil amount	γ_i (kN m^{-3})	β_w m^3 kN^{-1}	α_w m^4 kN^{-1}
Low	5	0.1	2
Typical	10	0.2	3
High	15.5	0.9	6

By combining equations [3-8] and [3-10], it is possible to estimate H(t), given the landfill height. A plot based on these equations is shown in Figure 3-12 for PLTT and OTR. Media compression is given as the ratio of the prevailing media thickness, H(t), to the initial (i.e. as-spread) media thickness, Ho. Figure 3-12 also shows the variation of unit weight of waste with landfill height.

The application of the plots presented in Figure 3-12 can be demonstrated by considering a 20 m high landfill for which the TDA layer thickness should not fall below 300 mm. A PLTT layer under a 20 m landfill has H(t)/Ho ratios of 0.55, 0.52 and 0.50 assuming initial waste densities of 5, 10 or 15.5 kN m^{-3}, respectively. The corresponding initial (as-spread) thicknesses Ho, are 545, 580, and 600 mm. An OTR layer has H(t)/Ho ratios of 0.61, 0.60 or 0.58; giving Ho values of 495, 500 and 535 mm, respectively. For a 20 m high landfill, Warith and Sudhakar (2006) proposed a TDA layer of 405 mm based on a uniform waste density of 10 kNm^{-3}. The waste density in a landfill varies with depth

(Zekkos et al, 2006); their approach may underestimate the compression of a TDA-based drainage layer.

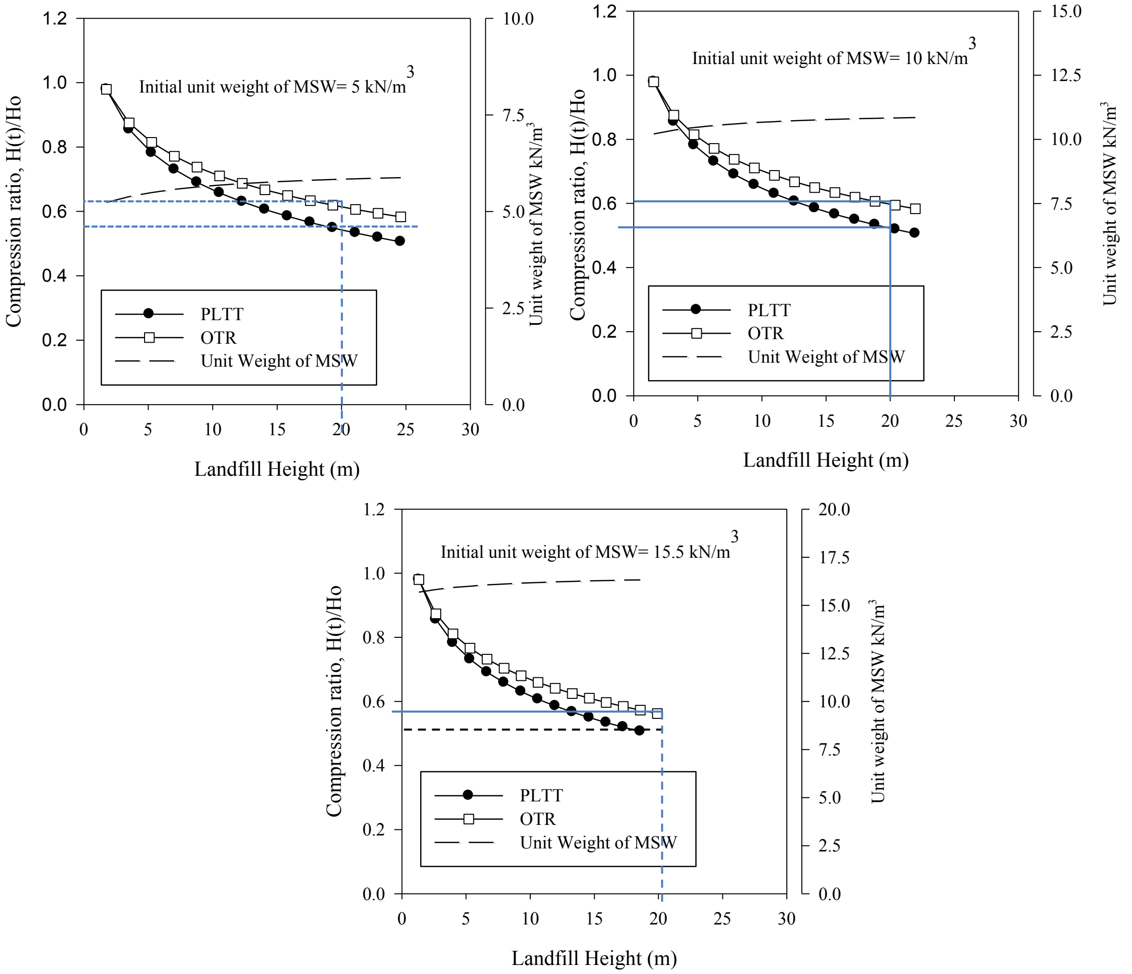


Figure 3-11. Relationship between thickness of PLTT and OTR layer and the landfill heights. The initial unit weight refers to the near surface weight density of MSW.

The data for relating media thickness to overburden pressures was based on average data as determined in the laboratory, and did not account for uncertainties associated with measurement errors. For the design of real LCDSs, Giroud et al. (2000) recommended application of safety factors to allow for uncertainties associated with measurement errors and field uncertainties. From the laboratory measurements, the initial void ratios for PLTT and OTR were 1.229 ± 0.026 and 1.173 ± 0.022, respectively (Table 3-4). The values of

Cc were 0.905 ± 0.034 and 0.735 ± 0.009 for PLTT and OTR, respectively (Table 3-4). From Equation 3.8, the change in media thickness, ΔH is maximum in case of upper bounds of Cc values and lower bounds of e_o. The factor of safety can therefore be determined as:

$$FS = \frac{\Delta H_{total}\,(upper\ values)}{\Delta H_{total}\,(average\ values)} \qquad [3\text{-}11]$$

Based on equation [3-11], the factors of safety for PLTT and OTR are 1.04 and 1.01 respectively. Therefore for a landfill of 20 m, the adjusted initial thickness Ho, for a PLTT layer becomes 570, 600, and 625 mm for initial waste densities of 5, 10 or 15.5 kN $m^{-3,}$ respectively.

The factors of safety determined above account for measurement errors associated with media compression. In case of media clogging, Giroud et al. (2000) proposes a safety factor of between 1.5 and 2.0. Applying these factors in case of allowable leachate mounding of 300 mm (Alberta Environment, 2010), the factored leachate mounding lies between 450 and 600 mm. Tables 3-6 and 3-7 show the factored values of initial media thickness, Ho for a 20 m landfill for PLTT and OTR media, respectively.

Based on a factor safety of 1.5, the as-spread thickness of PLTT based drainage layer should be lie between 820 and 900 mm, depending on the expected compaction effort. In the case of OTR-based drainage layer, the as-spread thickness should lie between 740 and 805 mm. For both PLTT and OTR, there is still a need to check if the proposed as-spread media thicknesses would suffice combined effects of clogging and errors associated media compression.

Table 3-6. Values of initial media thickness based on safety factors for media compression and clogging for a 20 m landfill with PLTT as media for drainage

Media type	Initial waste density kNm^{-3}	$H(t)/H_o$ ratio	Unfactored H_o (mm)	Factored H_o based on media compression (mm)	Factored H_o based on media clogging (mm)	
PLTT				FS = 1.04	FS = 1.5	FS =2.0
	5	0.55	545	570	820	1090
	10	0.52	580	605	870	1160
	15.5	0.50	600	625	900	1200

Table 3-7. Values of initial media thickness based on safety factors for media compression and clogging for 20 m landfill with OTR as media for drainage

Media type	Initial waste density kNm^{-3}	$H(t)/H_o$ ratio	Unfactored H_o (mm)	Factored H_o based on media compression (mm)	Factored H_o based on media clogging (mm)	
OTR				FS = 1.01	FS = 1.5	FS = 2.0
	5	0.61	495	500	740	985
	10	0.60	500	505	750	1000
	15.5	0.58	535	540	805	1075

References

Alberta Environment (2010). Standards for Landfills in Alberta. Government of Alberta. Alberta, Canada.

ASTM (2009). D6270-08: Standard Practice for use of scrap tires in civil engineering. ASTM International, West Conshohocken, PA, USA.

Aydilek, A. H., Madden, E. T. and Demirkan, M. M. (2006). Field evaluation of a leachate collection system constructed with scrap tires. *Journal of Geotechnical and Geoenvironmental Engineering* **132:** 990-1000.

Beaven, R. P., Powrie, W., Hudson, A. P. and Parkes, D. J. (2007). Compressibility of tyres for use in landfill drainage systems. *Waste and Resource Management* **159:** 173-180.

Drescher, A., Newcomb, D. and Heimdahl, T. (1999). Deformability of shredded tires, University of Minnesota, Department of Civil Engineering.

Fleming, I. R., Rowe, R. K. and Cullimore, D. R. (1999). Field observations of clogging in a landfill leachate collection system. *Canadian Geotechnical Journal* **36:** 685-707.

Geosyntec (2008). Guidance Manual for Engineering Uses of Scrap Tires, Maryland Department of the Environment. Baltmore, MD.

Giroud, J. P., Zornberg, J. G. and Zhao, A. (2000). Hydraulic Design of Geosynthetic and Granular Liquid Collection Layers. *Geosynthetics International* **7:** 4-6.

Goodyear (2008). Tire maintenance manual: Off-the-Road Tires. Akron, Ohio, USA. See http://www.goodyearotr.com/cfmx/web/otr/info/pdf/otr_MaintenanceManual.pdf (accessed 10/05/2015).

Hudson, A. P., Beaven, R. P., Powrie, W., et al. (2008) Clogging potential of methanogenic leachate on tyre and aggregate drainage layers. In Proceedings Waste 2008: Waste and Resource Management- a shared responsibility. Stratford-upon-Avon, Warwickshire, England, pp. 16-17.

Hudson, A. P., Beaven, R. P., Powrie, W. and Parkes, D. (2007). Hydraulic conductivity of tyres in landfill drainage syatems. *Waste and Resource Management* **160:** 63-70.

McIsaac, R. and Rowe, R. K. (2005). Change in leachate chemistry and porosity as leachate permeates through tire shreds and gravel. *Canadian Geotechnical Journal* **42:** 1173-1188.

McIssac, R. S. (2007). An Experimental Investigation of Clogging in Landfill Leachate Collection Systems. Department of Civil and Environmental Engineering The University of Western Ontario, Canada. **PhD**.

Meles, D., Bayat, A. and Soleymani, H. (2013). Compression Behaviour of Large-Sized Tire-Derived Aggregate for Embankment Application. *Journal of Materials in Civil Engineering* **25:** 1285-1290.

Northstar (1995). Assessment of tire chips for use as landfill leachate collection media. East Arkansas Regional Solid Waste Management District, Arkansas, USA.

Park, J. K., Edil, T. B., KIm, J. Y., et al. (2003). Suitability of shredded tyres as a substitute for a landfill leachate collection medium. *Waste Management & Research* **2003:** 278-289.

Powrie, W., Beaven, R. P. and Hudson, A. P. (2005). Factors affecting the hydraulic conductivity of waste. International Workshop: Hydro-Physico-Mechanics of Landfills. Lirigm, Grenoble 1 University, France.

Qian, X., Koerner, R. M. and Gray, D. H. (2002). *Geotechnical Aspects of Landfill Design and Construction*. Prentice Hall, Upper Saddle River, NJ.

Reddy, R. K. and Marella, A. (2001) The properties of different size scrap tire shreds: Implications on using as drainage material in landfill cover systems. In the proceedings of the Seventeenth International Conference on Solid Waste Technology and Management. Philadelphia, PA, USA, pp. 1-19.

Reddy, R. K. and Saichek, R. E. (1998) Characterization and performance assessment of shredded scrap tires as leachate drainage material in landfills. In Proceedings of the Fourteenth International Conference on Solid Waste Technology and Management. Philadelphia, PA, USA, pp. 1-10.

Warith, M. and Sudhakar, M. R. (2006). Predicting the compressibility behaviour of tire shred samples for landfill applications. *Waste Management* **26:** 268-276.

Wartman, J., Natale, M. F. and P. M. Strenk (2007). Immediate and Time-Dependent Compression of Tire Derived Aggregate. *Journal of Geotechnical and Geoenvironmental Engineering* **133:** 245-256.

Wu, W. Y., Benda, C. C. and Cauley, R. F. (1997). Triaxial determination of shear strength of tire chips. *J, Geotechnical and GeoEnvironmental Engineering* **123:** 479-482.

Zekkos, D., Bray, J. D., Kavazanjian Jr., E., et al. (2006). Unit Weight of Municipal Solid Waste. *Journal of Geotechnical and Geoenvironmental engineering* **132:** 1250-1261.

4 An Experimental Investigation of Clogging Behavior of TDA

Materials in this chapter presented:

a. Marclus Mwai, Kristine Wichuk & Daryl McCartney. 2012. Evaluating the performance of tire-derived aggregates when used as media for leachate collection and drainage systems. In Proceedings of the 27th International Conference on Solid Waste Technology and Management, Philadelphia, PA U.S.A, 11-14 March 2012.

4.1 Introduction

Clogging of leachate collection systems is of great concern in operations and management of sanitary landfills. Incidences of landfill clogging have been reported (e.g by Fleming and Rowe, 2004; Koerner and Koerner, 2004; Reinhart et al., 1998) in the past. Clogging is associated with loading of nutrients into the basal layers as leachates move through landfilled waste (Cooke et al., 2001; Fleming et al., 1999). The physical manifestation of the clogging process is accumulation of particulates, formation of biofilms, mineral species and biodegradation products within pores of a drainage media, thereby affecting its hydraulic conductivity (Fleming et al., 1999; McIsaac and Rowe, 2005). Potential risks associated with clogging include excessive leachate mounding, which may accelerate leachate leakage through the landfill containment system (Cooke and Rowe, 2008; Rowe, 2005).

Clogging in a drainage medium is linked to natural physical and bio-geochemical processes that may take place in a sanitary landfill (Table 2.2) (Brovelli et al., 2009; Cozzarelli et al., 2011; Fleming et al., 1999; Mostafa and Van Geel, 2007; Rowe, 2005). It was also discussed previously that clogging components can be split into three categories; namely, biological, chemical and physical. Biological clogging is associated with bacteria growth and attachment onto the solid matrix as biofilms (EWMCE, 2009). This component of clogging is closely associated with nutrient loading into the drainage media (Fleming et al., 1999; VanGulck et al., 2003). Chemical clogging involves precipitation reactions with main products being calcium based minerals (Cooke et al., 2001; Cooke et al., 2005; Cooke et al., 1999; EWMCE, 2009). The physical component is largely associated with deposition and trapping of suspended solids arising from biological and chemical components, daily cover and general deterioration products of the landfilled waste (Cooke et al., 2005). The net effect of these components is reduced media porosity and associated permeability (Fleming et al., 1999; McIsaac and Rowe, 2005; Mostafa and Van Geel, 2007).

To minimize problems associated with clogging, it is required sanitary landfills to have LCDS (Figure 4.1).

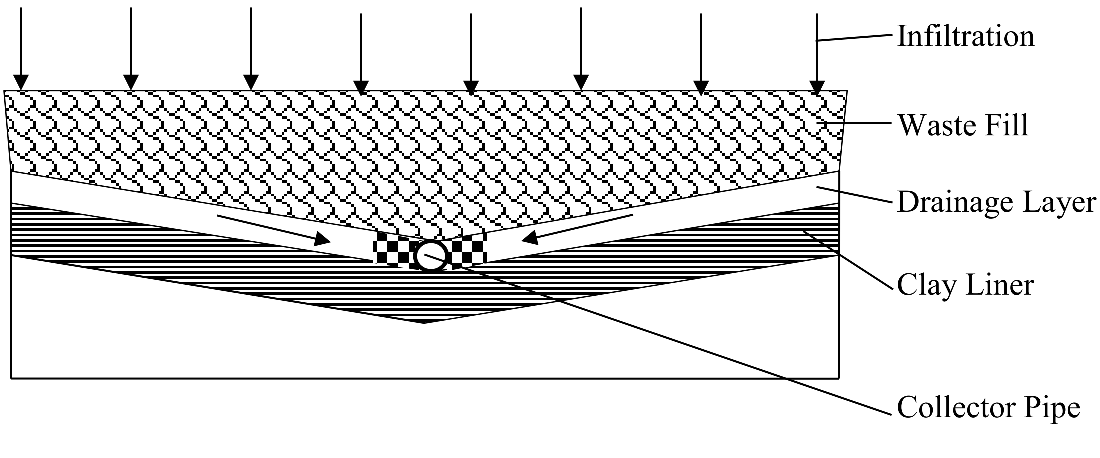


Figure 4-1. Typical cross-section for a LCDS

The primary function of a LCDS is to control the leachate head acting on the liner. The basic requirement is that the leachate mounding over the liner should not exceed 300 mm (Alberta Environment, 2010; Cooke and Rowe, 2008; Qian et al., 2004). The secondary function of LCDS is to facilitate removal of leachate for recirculation, treatment or disposal (Fleming et al., 1999; Rowe, 2005). The criterion for designing LCDS is based on hydraulic conductivity of the drainage media (Alberta Alberta Environment, 2010; Hudson et al., 2007; Warith et al., 2005). Typically, hydraulic conductivity should not fall below 1.0 x 10^{-4} ms^{-1}. Despite these requirements, clogging is a major problem facing sanitary landfills, as a technology for solid waste management (Hudson et al., 2008; Koerner and Koerner, 2004).

The clogging phenomenon of LCDS has been a subject of active research. Most studies have typically involved field, laboratory investigations and numerical analysis. Table 4.1 summarizes various studies involving clogging phenomenon and their key findings.

Table 4-1. Summary of the previous studies involving clogging phenomenon.

Study	Type of Study	Focus and key findings
Aydilek et al. (2006)	Field study	Evaluation of leachate collection systems constructed with tire shreds; adequate hydraulic conditions were comparable between cells using TDA and gravel.
Fleming et al. (1999)	Field study	Field observations of clogging phenomenon; clog material composed of mineral precipitates, fine granular particulate, and biofilm, growing under the ambient anaerobic conditions.
Reinhart et al. (1998)	Field Study	Assessment of leachate collection system clogging at Florida Municipal Solid Waste Landfills; permeability of the drainage media decreased by 33% following exposure to landfill leachates for a period of 7 years.
Fleming and Rowe (2004)	Laboratory Study	Clogging of landfill leachate collection and drainage systems; formation of clog particles closely associated with chemical oxygen demand (COD) stabilization and the depletion of calcium

Study	Type of Study	Focus and key findings
		in the leachate
Aydilek et al. (2006)	Laboratory study	hydraulic conductivity of TDA reduced by 43% (on average) when overburden pressure was increased from 0 to 244 kPa
Hudson et al. (2008)	Laboratory study	Clogging potential of methanogenic leachate on tyre and aggregate drainage layers; significant clogging may occur in both tire shred and gravel media when permeated with high strength leachates, and ii) little clogging would occur when tire shred or gravel medium is permeated with low strength leachates.
McIsaac and Rowe (2005)	Laboratory study	Changes in leachate chemistry and porosity as leachate permeates through tire shreds and gravel; tire shreds more susceptible to clogging than gravel; differences in pore structure between tire shreds and gravel may influence the clogging process.
VanGulck and Rowe (2004)	Laboratory study	Influence of landfill leachate suspended solids on clog formation; increase in volatile solids, which contributed to clog development, was primarily due to the retention of volatile suspended solids and growth of a biofilm capable of removing acetate, propionate, and butyrate from the leachate.
Cooke et al. (2001)	Laboratory study	Biofilm growth and mineral precipitation in synthetic leachate columns.
Cooke and Rowe (2008)	Theoretical modeling	2D modelling of clogging in landfill leachate collection systems; depending on the nature of the material used in the drainage layer, clogging can cause a decrease in hydraulic conductivity that can cause the leachate mound to exceed the design values in periods ranging from about 1 to 32 years for sand
Cooke et al. (2005)	Theoretical modeling	Modelling species fate and porous media effects for landfill leachate flow; A biofilm model controls growth of the substrate-degrading films, calcium carbonate precipitation is governed by carbonic acid production and calcium availability.
Cooke et al. (1999)	Theoretical modeling	Modeling bio-chemically driven mineral precipitation in anaerobic films; substrate utilization drives the clogging phenomenon, mineral precipitation most dominant process
VanGulck et al. (2003)	Theoretical modeling	Predicting biogeochemical calcium precipitation in landfill leachate collection systems; Thus, fermentation of acetate to form H_2CO_3 is what drives the calcium carbonate precipitation, provided a precipitating cation is available.

Field studies attempt to show the real time conditions within a LCDS. For example, the study by Fleming et al. (1999) showed that within a period of 1 - 4 years, the drainage layer of a sanitary landfill had accumulated large amounts of clog and slime materials that were composed of mineral precipitates, fine particulate matter, and biofilms growing under anaerobic conditions. The buildup of slimes was greatest near the perforated collection pipes, where the leachate flow within the drainage layer were the highest (Fleming et al., 1999). The solid particles forming the clog material were cemented by a mixture of minerals, consisting mainly of calcites. Fleming et al. (1999) contend that field investigations are rare, mainly because sampling leachates and clog materials in an operating landfill is difficult. There is also risk of damaging the geo-membrane layer, thereby undermining the landfill containment system.

Laboratory studies involve bench-scale experiments that aim at simulating LCDS (Fleming and Rowe, 2004) by permeating leachates through columns packed with drainage material (Fleming and Rowe, 2004; Fleming et al., 1999; Hudson et al., 2008; McIsaac and Rowe, 2005). These studies have facilitated controlled testing of hypotheses associated with clogging and, therefore, conceptualisation of clogging mechanisms. For example, Fleming and Rowe (2004) demonstrated that removal of COD correlated with decrease in drainable porosity. COD removal was also strongly associated with precipitation of calcite and, therefore, depletion of dissolved calcium in the leachate (Fleming and Rowe, 2004). Other studies have related clog development with retention of suspended solids, accumulation of mineral solids and growth of microorganisms (e.g VanGulck and Rowe 2004; VanGulck et al. 2003).

The properties of drainage materials play a role in the clogging phenomenon. McIsaac and Rowe (2005) observed changes in leachate chemistry and porosity as leachate permeated through drainage media consisting of tire shreds and gravel. They demonstrated that the type of drainage media influenced spatial and temporal variation of leachate characteristics and porosity changes within the drainage materials.

While laboratory studies have focussed primarily on tire shreds used on the passenger car and light trucks, jurisdictions with active construction and mining activities have also used tires from construction equipment to process TDA. For example, in Alberta, Canada, there are three main TDA products (PLTT, OTR, and MTT), as earlier mentioned. It is however expected that clogging phenomenon will affect PLTT and OTR differently because of their different shapes and particle sizes (Meles et al., 2013).

Adoption of different experimental procedures by researchers presents uncertainties in generalization of laboratory studies. For example, leachates applied by Hudson et al. (2008) were raw leachates while those used by McIsaac and Rowe (2005) were spiked with nutrients. Different experimental procedures notwithstanding, it is generally difficult to reproduce certain landfill aspects such as landfill geometry and rainfall conditions. The time scales also present a challenge; the lifespan of a sanitary landfill may exceed 100 years (Rowe, 2005), which is difficult to scale in a laboratory study. To accommodate these factors and, therefore, be able to predict long-term performance of LCDS, Cooke et al. (2001) and Rowe (2005) recommended application of numerical models. Cooke et al. (2001) studied prediction of changes in porosity in uniform porous media such as glass beads when permeated with synthetic leachates. The study by Cooke et al. (2001) evaluated the capacity of a theoretical model to explain the relationship between influent and effluent concentrations of COD and Ca^{2+} as observed under bench-scale experiments. Cooke et al. (2005) developed a 1-D, multiple species, reactive-transport model (BioClog) to predict changes in leachate chemistry and microbial community, along with loss of porosity in drainage medium. Cooke and Rowe (2008a) extended the 1-D BioClog model to a 2-D model with aim of predicting both clogging and leachate mounding in LCDS. The model used empirical relationships to establish porosity from the accumulated clog matter; and to derive hydraulic conductivity. Rowe and Babcock (2007) calibrated the BioClog model based on experimental data reported by McIsaac and Rowe (2005), to simulate clogging of tire shreds and gravel media.

McIsaac (2007) recommended further development of the BioClog model on the basis that the leachate samples were of lower strength than those actually entering the LCDS. Additionally, the BioClog, which was developed for granular drainage media such as sand and gravel does not have a routine for compression expected from TDA (Warith and Sudhakar, 2006; Wartman et al., 2007).

Laboratory studies my assist in development of numerical methods through (i) identification of key mechanisms associated with clogging, (ii) obtaining parameters for numerical analysis, and iii) verification of applicability of numerical models. To date, there is no published information on clogging behaviour of OTR and other types of TDA that are processed in Alberta. The objectives of this study were to investigate performance of the various types of TDA and gravel when permeated with raw leachates. The study also aimed at examining the characteristics of the clog materials formed within the porous media. This information may be useful in the development of numerical models for predicting long-term clogging behaviour of TDA-based LCDS.

4.2 Experimental Set-up, Material and Methods

4.2.1 The experimental set-up

The experimental set-up consisted of four polyvinyl chloride (PVC) columns, loading frame, manual hydraulic system for uniaxial compression, leachate storage tanks, chiller, inline heater, and four peristatic pumps (Figure 4-2). The PVC columns were the same ones used for the compression tests (Chapter 3). The columns simulated LCDS with respect to overburden pressures, drainage media, and flow of leachates. To facilitate sampling of leachates, six piezometers/sampling ports spaced at 0.125 m were provided in each column (Figure 4-2). Sampling ports C11, C21, C31 and C41 were at level 0, while ports C16, C26, C36 and C46 were at 0.625 m (Figure 4-2). The PVC columns rested on a timber platform, about 1.0 m above the floor. At the bottom of each column was fitted a perforated base plate, 10 mm thick. A similar plate was placed at the top and connected to the loading piston to keep the media compressed. To ensure that TDA did not lift the steel plate due to elasticity, a 50 x 50 mm steel angle bracket was used to restrain the upper steel plate in place. The arrangement ensured that the media height and, therefore, porosity remained constant even when the pressure dissipated. The loading frame consisted of a steel framework, comprising of 100 x 100 mm vertical supports and I cross-beam spanning over the vertical supports, that supported a pneumatic cylinder of 100 mm diameter and the pressure gauges. The hydraulic system consisted of a pneumatic cylinder and an oil tank. These columns were connected to a manual control valve that was used to apply pressure to the drainage media.

The leachate was stored in an insulated high density polyethylene (HDPE) holding tank with a capacity of 7,000 L. The inner wall of the tank was fitted with coolant pipes connected to a chiller that maintained temperatures at approximately 7 °C. The holding tank had an electric agitator to keep the tank contents in suspension, thereby minimizing settlement. Each column had a dedicated peristaltic pump for pumping the leachates to the columns. The pumps were connected serially along a 25 mm diameter PVC feed pipe (Figure 4.1), together with an inline heater placed 1.0 m from tank outlet and about 0.5 m to the first peristatic pump.

The leachates which entered the columns through an inlet port situated at level 0.75 m flowed downwards by gravity. The effluent leachate exited from the bottom of the columns to the ground drain channel. Leachates were sampled at levels corresponding with the piezometer ports (i.e. C11- C17; C21-C27; C31-C37 and C41-C47).

4.2.2 Materials

4.2.2.1 TDA materials and gravel

The TDA materials tested were passenger and light truck tires (PLTT), off-the-road tires (OTR), a mixture of OTR and PLTT (OTR+PLTT), and gravel. Table 4-2 shows the source of the test materials. PLTT and OTR were prioritised because they are TDA products commercially available in Alberta, Canada and have previously been used as media for drainage in Alberta landfills. OTR+PLTT were included in order to evaluate whether mixing the two types of TDA would improve drainage efficiency. Furthermore, during initial testing of short-term hydraulic conductivity, PLTT, OTR and PLTT+OTR showed distinct hydraulic characteristics (Chapter 3). Gravel, which has traditionally been used as drainage material in LCDS, was included as a control.

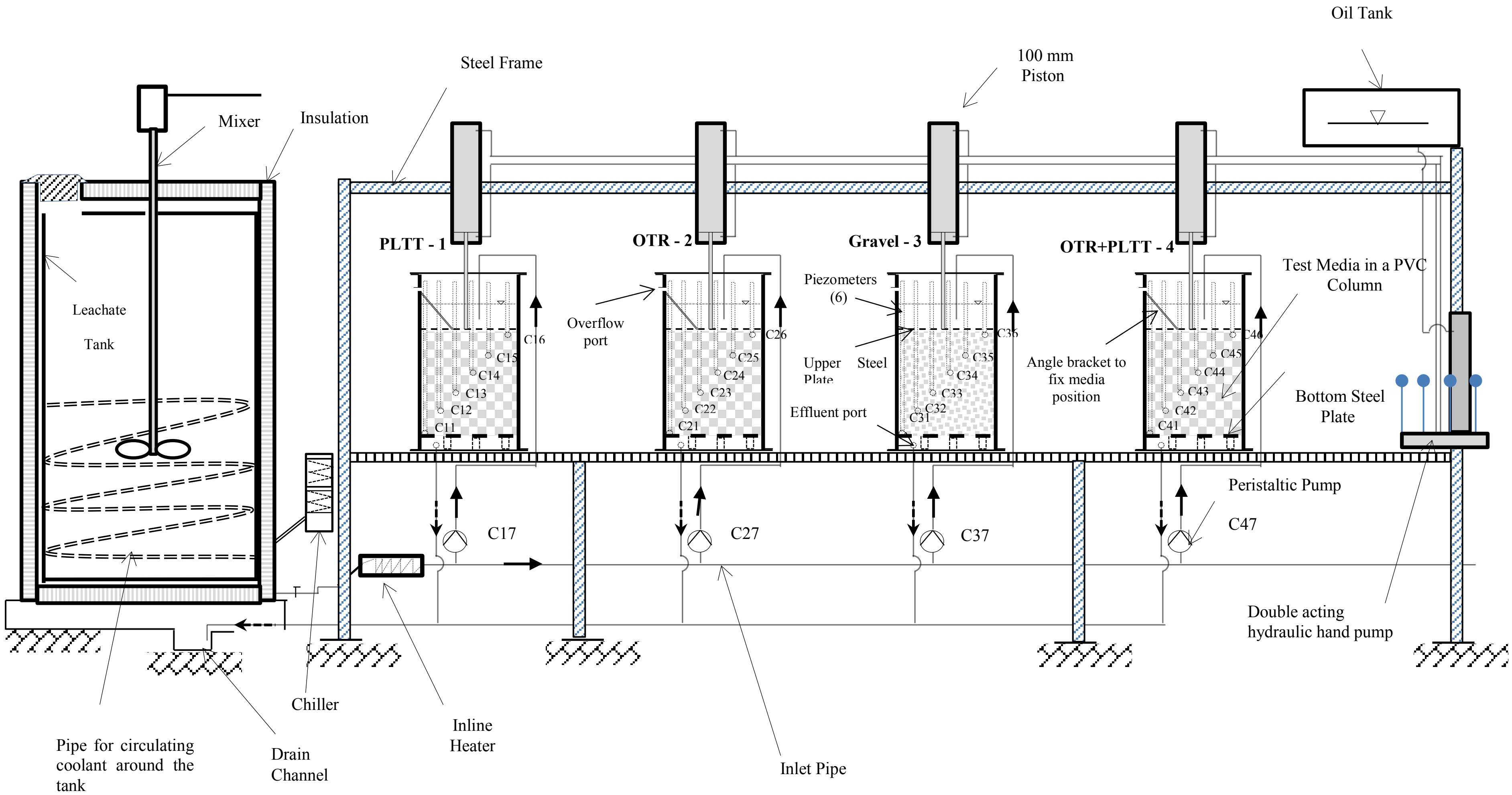


Figure 4-2. Schematic diagram showing apparatus set-up, sampling ports, leachate tank, inflow, and effluent flow directions.

Table 4-2. Sources of TDA and gravel test materials as applied in the study

TDA type	Source
PLTT	Rubber Tech International (Legal, AB)
OTR	Cutting Edge Tire Recycling LP (Edmonton, AB).
Gravel	Lafarge Canada Inc

Particle size distribution of the TDA was determined in accordance with D6270-08: Standard Practice for Use of Scrap Tires in Civil Engineering Applications (ASTM, 1998). The mass of the material remaining on each of the sieves was weighed and the results presented as TDA size distribution curves (Figure 3-4).

The TDA media were compressed uniaxially to attain an initial drainable porosity of approximately 0.4, which was similar to the initial drainable porosity of the 20 mm test gravel. Before compression, PLTT and OTR had an initial porosity of about 0.6 while OTR+PLTT had 0.56. The measured initial porosities for the four drainage materials were 0.447 for PLTT, 0.410 for OTR; 0.393 for gravel and 0.435 for OTR+PLTT. The applied loads for PLTT, OTR, OTR+PLTT were 60, 100 and 85 kPa, corresponding to 5, 7.5 and 6 m of waste overburden respectively. The corresponding final media depths were 0.65, 0.75 and 0.7 m for PLTT, OTR and OTR+PLTT, respectively. The depth for gravel remained constant at 0.75 m because it is incompressible.

In comparison to the current study, McIsaac and Rowe (2005) applied a constant load of 150 kPa. The initial porosities were 0.22 and 0.23 for tire shred types P and G, respectively and the 37 mm gravel had initial porosity 0.43. McIsaac and Rowe (2005) observed that tire shreds clogged much faster than gravel. However, the lower initial porosities may have contributed to rapid clogging in tire shreds.

4.2.2.2 Leachates

To facilitate selection of the leachates for the experiments, a characterization study of leachates from Alberta landfills was carried out during the first phase of the project. The study found that leachates in sanitary landfills exhibit both temporal and spatial variability, implying the need to focus on site-specific leachates. Table 4-3 shows typical values for pH and COD for sanitary landfills in Alberta. Also shown are pH and COD values for two Alberta landfills, referred to as A and B. The leachates used in this study were sourced from Landfill A, Clover Bar Landfill in Edmonton, Alberta. Weekly leachate analysis conducted in May 2009 showed that the COD concentration for Clover Bar was 6,940 $mg \cdot L^{-1}$. This value was only slightly higher than the average COD concentration of 5,958 $mg \cdot L^{-1}$ for Alberta. It was indicated in Chapter 2 that leachate characterized by slightly acidic and slightly alkaline conditions of $pH < 7.5$ indicate landfills that are in transition from acetogenic to methanogenic phases. Because the pH of Clover Bar landfill leachate was above 7.5, it follows that the leachates were already methanogenic.

Fresh leachates were received from the headworks of the leachate treatment plant at the Edmonton Waste Management Centre and stored in an insulated holding tank at the experiment site. A pump truck was used to move the leachates from the leachate tanks to the leachate holding tanks.

Table 4-3. Leachate characteristics based on an Alberta leachate characterization study (means ± standard error).

Statistic	pH			COD (mg O_2/L)		
	Landfills in Alberta	Landfill A (Year 2003 to 2009)	Landfill B (Year 1981 to 2009)	Landfills in Alberta	Landfill A (Year 2003 to 2009)	Landfill B (Year 1981 to 2009)
Mean	7.5 ± 0.1	7.9 ± 0.5	7.1 ± 0.1	5958 ± 471	3723 ± 905	3244 ± 640
Max	13	8	8	83000	5233	11100
Min	1.9	7.8	6.1	10	2106	240

4.2.3 Methods

4.2.3.1 Leachate Flow and Delivery System

Leachates were pumped from the leachate holding tank into the test columns using peristaltic pumps that were placed serially on the feed line (Figure 4-3). The leachates entered the columns through three ports at the base of the column. The ports were placed equidistant along the circumference of the columns to facilitate uniform flow into the columns (Figure 4.3). After passing through the drainage media, leachates were collected at the top of the columns, upon which it was delivered by gravity to the leachate waste tank.

The pump flow rates were based on the maximum volume of leachates that would flow through a LCDS during the active life of a landfill cell. A period of 30 years was selected as the active life, based on the fact the Clover Bar landfill was operated for a period of approximately 30 years from 1979 to 2007 before final closure. The average annual precipitation at the Edmonton International Airport (Environment Canada 2011), for 1975 to 2009 was 458 mm with a maximum annual precipitation of 650 mm (Figure 4-4).

Figure 4-3. Showing leachate inflow port at the base of the columns

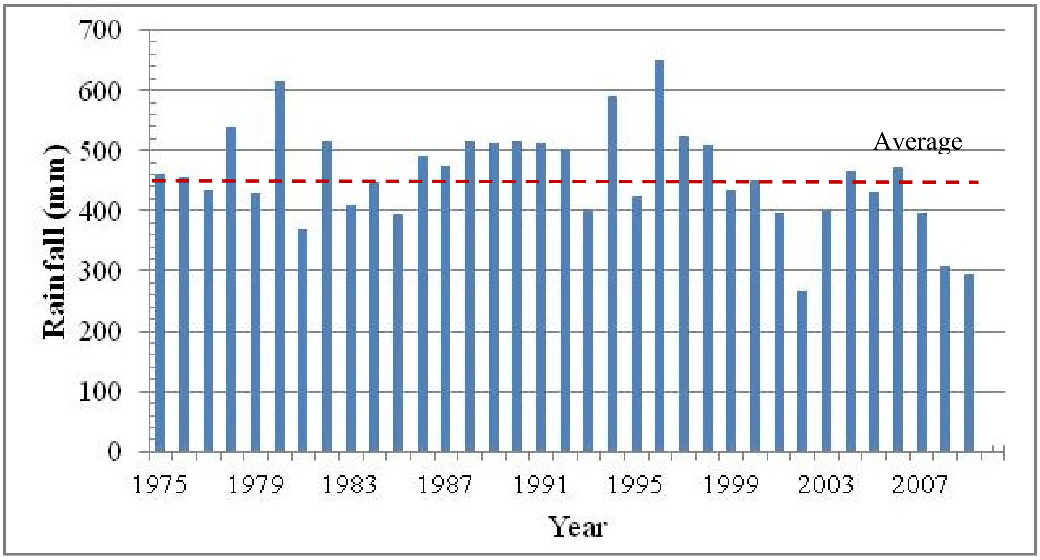


Figure 4-4. Annual rainfall data for the period between 1975 and 2009 as recorded at the Edmonton International Airport.

Due to time constraints, it was necessary to compress the time scale of the experiments. The conservative maximum annual rainfall value of 650 mm·yr^{-1} was adopted in determining the flow rate of leachates through the test columns. Originally, a testing period of 18 months was proposed. For the column had an area of 0.255 m^2, a flow rate of 0.4 $L \cdot h^{-1}$ (0.0376 $m^3 \cdot m^{-2} \cdot d^{-1}$) for 18 months was selected to simulate approximately 30 years of the maximum amount of rainfall that could be expected to reach the same surface area of drainage material in a landfill, compressed into a period of 18 months. The corresponding initial drainable porosities of various media types the hydraulic retention times (HRT) and other flow conditions are summarised in Table 4.4.

Table 4-4. Flow conditions adopted for the study

	PLTT	OTR	Gravel	OTR+PLTT
Drainable Porosity	0.45	0.41	0.39	0.44
Media Height (m)	0.65	0.70	0.75	0.68
Area (m^2)	0.26	0.26	0.26	0.26
Media volume (m^3)	0.07	0.07	0.08	0.08
Flow Rate (m^3 day^{-1})	0.0096	0.0096	0.0096	0.0096
HRT (days)	7.73	7.63	7.84	7.87

4.2.3.2 Leachate Monitoring

The leachate percolating through the media was monitored for temperature, pH, conductivity, COD, TSS, cations (Ca^{2+}, Mg^{2+}, Na^{+}), and anions (Cl^{-}, SO_4^{2-}). Leachate samples were collected from twenty-nine sampling points; seven for each of the four test columns through piezometer ports Cx1 to Cx7 (Figure 4-1, where x refers to the column numbers 1, 2, 3, and 4) and one sampling point at the effluent port, To, of the leachate holding tank. Samples for pH, COD, cations and anions were collected biweekly in 250 mL high density polyethylene (HDPE) bottles. The samples were analyzed immediately for pH and temperature and then transported to the laboratory for analysis of the other parameters. Whenever immediate analysis of the samples was not possible, samples were stored at 4 ^{o}C to reduce microbial activities. Only pH, COD, TSS, Ca^{2+}, and Mg^{2+} that are closely associated with clogging are discussed in this chapter; all collected data is presented in Appendix C.

The pH and electrical conductivity were both monitored in the collected leachate samples using an Accumet® XL20 pH/conductivity meter from Fisher Scientific. Anions and cations were analyzed by ion chromatography (IC) Dionex® IC2500 and Dionex® IC2000, respectively. Samples for ion chromatography were filtered through 0.22 µm filters, diluted using ultra-pure deionized water and then transferred into 10 ml IC vials. Calibration standards for the Dionex IC2500 were prepared from the Seven Anion Standard II (Dionex #057590) stock solution containing F, Cl, NO_2, Br, NO_3, PO_4, and SO_4 with 20, 100, 100, 100, 100, 200 and 100 mg·L^{-1} concentrations, respectively. Calibration standards for the Dionex IC2000 were prepared from the Six Cation Standard II (Dionex # 46070) stock solution containing Li, Na, NH_4, K, Mg and Ca with 50, 200, 250, 500, 250 and 5000 mg·L^{-1} concentration, respectively. Calibration standards were run at the beginning of each sequence, while water blanks were run after every 7 sample as a check against inter-column contamination.

The TSS and total COD tests were performed following Standard Methods for the Examination of Water and Wastewater (APHA, 2005). The TSS were analyzed by weighing a glass microfiber Whatman 934-AH™ filter in aluminum weighing dishes and on an analytical balance Denver Instruments® 210g with a readability of 0.1 mg. The leachate samples were filtered through weighed glass microfiber Whatman 934-AH™. The aluminum dish, the filter and the residue retained on the filter were dried at 103^{o}C (Oven Isotemp, Fisher Scientific®) for 1 hr, cooled to room temperature in a dessicator, and weighed. The TSS concentration was calculated as:

$$\text{TSS}\ \left(\frac{\text{mg}}{\text{L}}\right) = \frac{(\text{A} - \text{B})\ \text{x}\ 1000}{\text{sample volume, mL}} \qquad [4\text{-}1]$$

where

A = weight of the aluminum dish + filter + dried residue (mg)

B = weight of the aluminum dish + filter (mg)

COD was measured using the closed reflux, colorimetric method; 2.5 mL of non-filtered leachate samples were placed in 16 x 100 mm standard culture tubes and 1.5 mL of digestion solution and 3.5 mL sulfuric acid reagent added. The culture tubes were then placed in a preheated COD digester (150^{o}C, Hach®) and refluxed for 2 hours. A blank sample and 5 standards of COD equivalents were also placed in the COD digester. After cooling the digested samples, blank and the standards to room temperature, a COD photometer (Hach®, model: DRB 200) was used to determine light absorbance at 600 nm. A calibration curve, depicting absorbance measurements against COD equivalents, was prepared. The absorbance measurements from the digested leachate samples were related to calibration curve to determine the sample COD. The COD of the leachate samples was calculated as follows:

$$\text{COD}\ \left(\frac{\text{mg}\ \text{O}_2}{\text{L}}\right) = \frac{\text{mg}\ \text{O}_2\ \text{in sample x}\ 1000}{\text{sample volume, mL}} \qquad [4\text{-}2]$$

Volatile solids (VS) measurements are used to estimate the amount of organic matter in a sample. VS analysis in the leachate samples involved evaporating the liquid from the samples and then combusting at 550 °C following Standard Methods for the Examination of Water and Wastewater (APHA, 2005).

4.2.3.3 Determination of Hydraulic Conductivity

Hydraulic conductivity was determined at both the beginning of the study and immediately before column disassembly. The rationale was to check if the clog material in each of the columns had a major impact on the drainage properties of the respective media. Because of the constraints associated with passing leachates at high flow rates, which was required so as to observe head losses between piezometers, clean water direct from the tap was used for all the hydraulic tests. Based on findings of the initial hydraulic tests (Chapter 3) that downward flow conditions were affected by the narrow outlet ports at the base of the columns, constant head method and upward flow conditions were adopted. For each of the test columns, the water velocity was increased three to four times while recording the water levels in each of the six piezometers. Also measured were the outflow rates, the length of the flow section, the prevailing temperature and the drainable porosity. The hydraulic conductivity of each column was calculated following Darcy's Law:

$$\mathrm{Ky} = \frac{\mathrm{h\,Q}}{\mathrm{A_s\,L}} \qquad [4\text{-}3]$$

where

Ky = vertical hydraulic conductivity, $m \cdot s^{-1}$

h = head lost between the piezometers, m

Q = the volumetric flow rate (measured at the outlet of the column), $m^3 \cdot s^{-1}$

A_s = the cross-sectional area of the column, m^2

Ls = length of the drainage media, m

Because hydraulic conductivity varies with water temperature, a temperature correction was applied in order to adjust all measurements to standard values at 20°C, as follows.

$$K_{20} = K_{\theta}\frac{\eta_{\theta}}{\eta_{20}} \qquad [4\text{-}4]$$

where

K_{θ} is the coefficient of hydraulic conductivity calculated at a given temperature

η_{θ} is the dynamic viscosity of the water at the measured temperature, θ

η_{20} is the dynamic viscosity of the water at a standard temperature of 20 °C.

In addition to hydraulic conductivity tests, the power law relationships established for the clean tests were used to check whether the relationships between the hydraulic conductivity and the media also applied to media that was partially clogged. To check this, were applied. The power relationships were of the form:

$$Ky = A\varepsilon^{c} \qquad [4\text{-}5]$$

where

Ky = is the vertical hydraulic conductivity of the media in $m \cdot s^{-1}$

ε = media porosity

A and c are parameters established for each media during testing of the clean materials (values of A and c are reproduced in Table 4-5).

Table 4-5. Parameters for hydraulic conductivity as determined from clean media.

TDA Media type	A	c
PLTT	0.487	1.790
OTR	1.328	2.056
OTR+PLTT	1.559	3.159

4.2.3.4 Determination of Drainable Porosity

Drainable porosity is the volume of a fluid that can be drained from the pore spaces of a porous material by gravity, in relation to the total volume occupied by the media. It was determined by draining leachate from the columns and the volume of the leachate assumed to equal the volume of drainable pore space. The drainable porosity was determined as the ratio between the volume of drained leachate and the total volume of the drainage layer.

4.2.3.5 Column Disassembly and Characterization of the Clog Material

The disassembly of the test apparatus was conducted on day 480. The objective of the disassembly was to make a visual assessment of how the clog particles settled in different columns and also to determine the mineralogical composition of the clog materials. Because clean water was used to measure hydraulic conductivity of media types just before disassembly of the columns, it was likely that some of the clog material which was not firmly attached to the drainage media was flushed out of the column during this process. Therefore, only qualitative characterization of the clog material was carried out.

Column disassembly involved removal of the drainage media in three stages; the top, middle and bottom. For each stage, duplicate clog particles were carefully scraped off and placed in a plastic bag.

The collected samples were dried in an Oven Isotemp oven from Fisher Scientific®) at a constant temperature of 103°C until no further changes in weight were recorded. The dried samples were then ground to a fine powder for X-ray diffraction (XRD) tests. The results of XRD for the different levels of the columns and also within columns were compared for differences in mineralogy of the clog materials.

4.2.3.6 Process Controls

The flow of leachates through the columns was largely a process control exercise. The overall objective was to ensure that landfill conditions were simulated as closely as possible. It was initially proposed that the flow of the leachates would be in an upward direction, as per the study by McIsaac and Rowe (2005). However, after 4 weeks of operating in this configuration, it was noted that particles tended to settle more in the lower sections of the columns owing to gravitational and drag forces. The occurrence was considered unlikely in the downward flow conditions of a landfill; therefore, a decision was made to change the flow direction to downward (Figure 4-1).

The feedlines between the tank and the pumps tended to block with time. This problem was minimized by flushing the feed lines with clean water on a weekly basis. The outlet lines from the columns to the effluent storage tank also tended to block. Unlike in the feed lines, blockage in outlet lines was associated with air bubbles accumulating at high points and where the gradient of the effluent line changed (Figure 4-5). This problem was eliminated by installing pressure-break cups at the points where the gradient changed and at the same time adjusting the profile of the effluent lines so that the effluent flowed entirely by gravity. All data obtained prior to the installation of pressure-break cups was analyzed and reported separately from the data collected after installation of the pressure-break cups.

The leachate outflow rates were monitored regularly for each of the test columns to ensure that a flow rate of 0.4 $L \cdot h^{-1}$ was maintained throughout. Also monitored regularly was the temperature of the leachates in the holding tank to ensure it remained at $7^{o}C$ and that the chiller operated as required. Because landfills operate largely under anaerobic conditions (Fleming et al., 1999), the top of the columns and of the piezometers were sealed using a rubber gasket and a plastic tape, respectively.

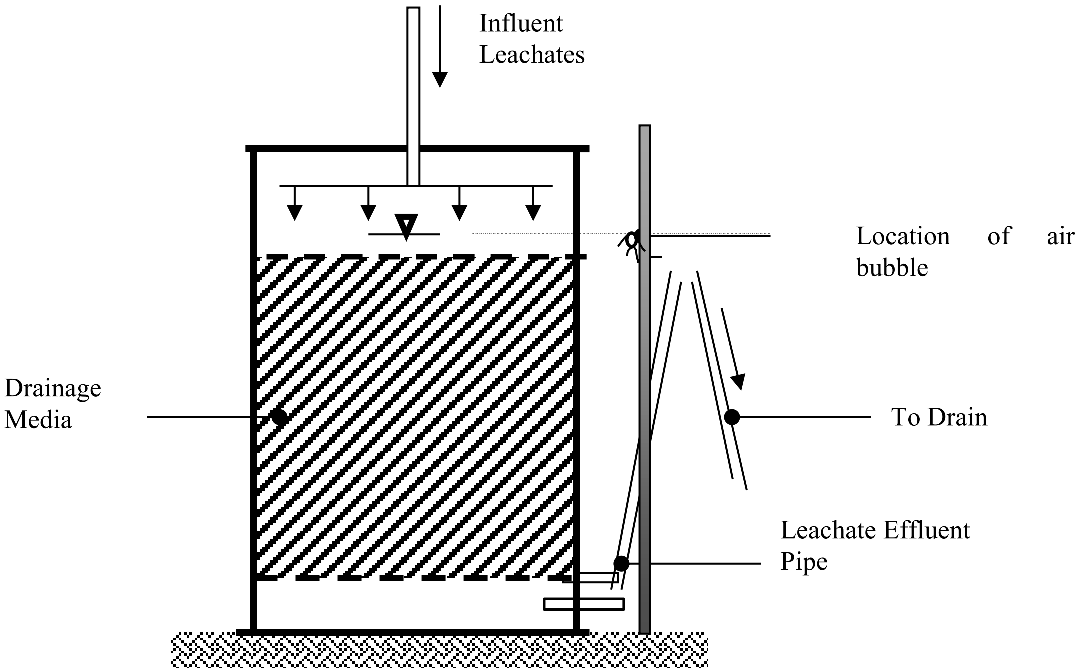


Figure 4-5. Leachate effluent arrangement showing position of air bubbles within the fluent lines.

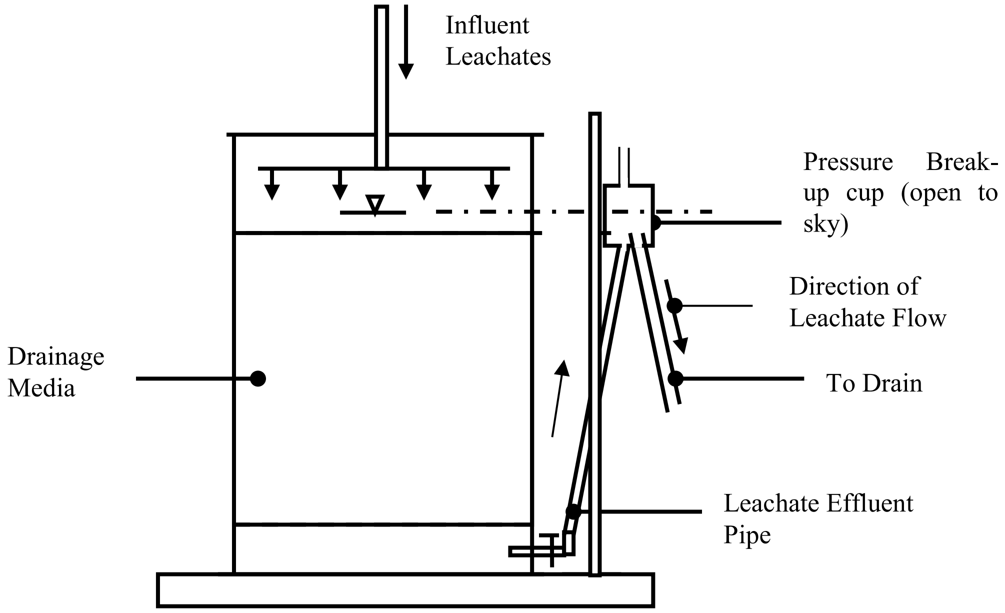


Figure 4-6. Leachate effluent arrangement consisting of effluent pipe, pressure break-up cups and drain pipe.

4.2.3.7 Statistical Analysis

Statistical analysis of the data was conducted with computation of averages, analysis of the variance (ANOVA) and multiple comparisons of data in cases where significant differences were detected. The ANOVA tests were conducted at a 95% confidence level. During leachate monitoring program, it was noticed that the influent concentrations varied from column to column. To reduce uncertainties associated with the variation and, therefore, facilitate comparison of different media types, data at sampling points 0, 125, 0.375 and 0.5 m were normalized against that obtained at level 0.625 m (Figure 4-2).

4.3 Results and Discussions

The key parameters monitored during long-term chemical tests were pH, TS, TSS, COD, cations and anions. The following sub-sections discuss the results, trends, and implications of the parameters to clogging of LCDS. Data for the period prior to installation of pressure-break cups (prior to Day 168) is presented separately from that obtained after the installation (Day 168 to 427). In some cases, the data for specific days is presented to illustrate the prevailing column conditions. Discussions on the implications of the study results to clogging were confined to the period between 168 and 427 days when the experimental conditions were considered more consistent. Complete test results are presented in Appendix C.

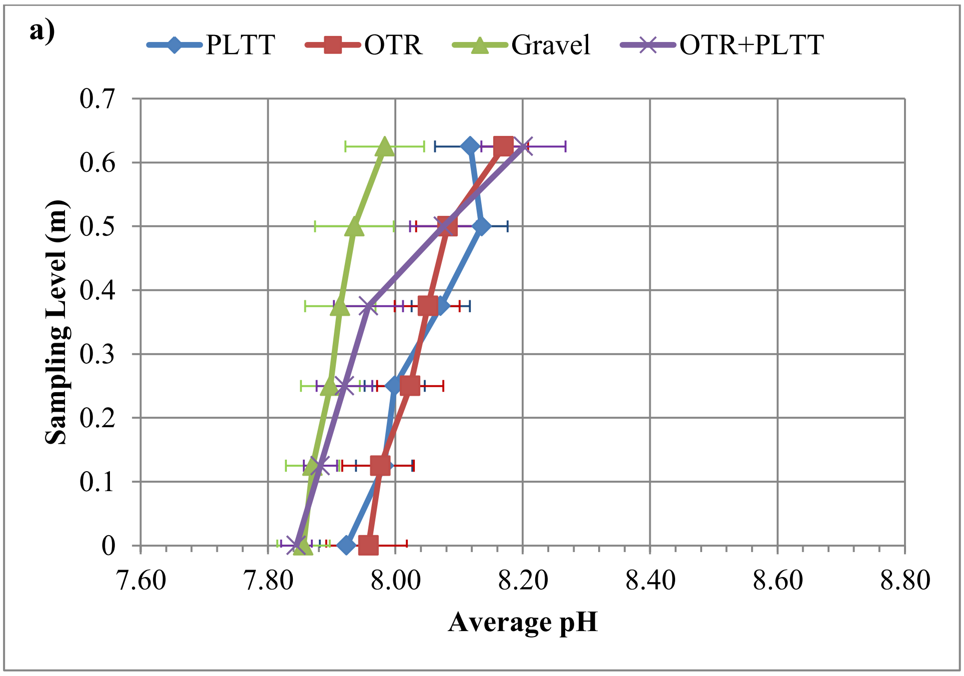
pH

4.3.1.1 pH – Day 0 to 168

The average pH data for the first 168 days of the experiment is presented in Figure 4-7. In general, pH decreased with depth in all the four test columns (Figure 4-7). A One-Way ANOVA did not show significant difference of pH values with $p > 0.05$ level ($F(3, 23) = 2.85$, $p = 0.063$). When the average pH data was normalized to the pH values at level 0.625 m, a one-way ANOVA showed that there were significant differences at the $p < 0.05$ level ($F(3, 23) = 3.25$, $p = 0.043$). Multiple analyses showed significant differences occurred between OTR+PLTT and all other media types, but no significant differences occurred between gravel and OTR, gravel and PLTT, or PLTT and OTR.

4.3.1.2 pH – Day 168 to 427

The average pH for PLTT column is shown in Figure 4-8. Similar to the first 168 days, there was a general decrease in pH as the leachate flowed downward, which was confirmed by one-way ANOVA $p < 0.05$ values ($F(3, 23) = 3.11$, $p = 0.049$). There were significance differences between media types OTR and OTR+PLTT, but not between the others. For the normalised data, the one-way ANOVA did not show any significant difference ($F(3, 23) = 1{,}2$, $p = 0.329$), which implied that observed variability in pH may have been due to differences in influent concentrations rather than the biogeochemical conditions within the drainage media. Figure 4-9 shows that the influent pH values, differed from sample to sample. Differences in influent concentrations may have been caused by biogeochemical reactions taking place within the serially connected feed pipes.



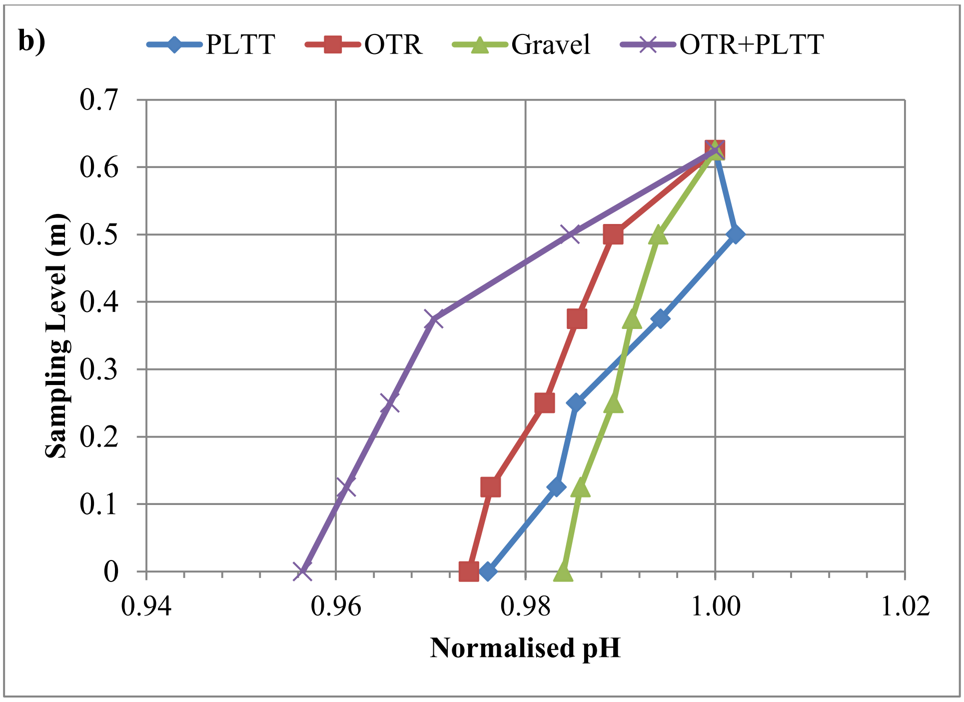
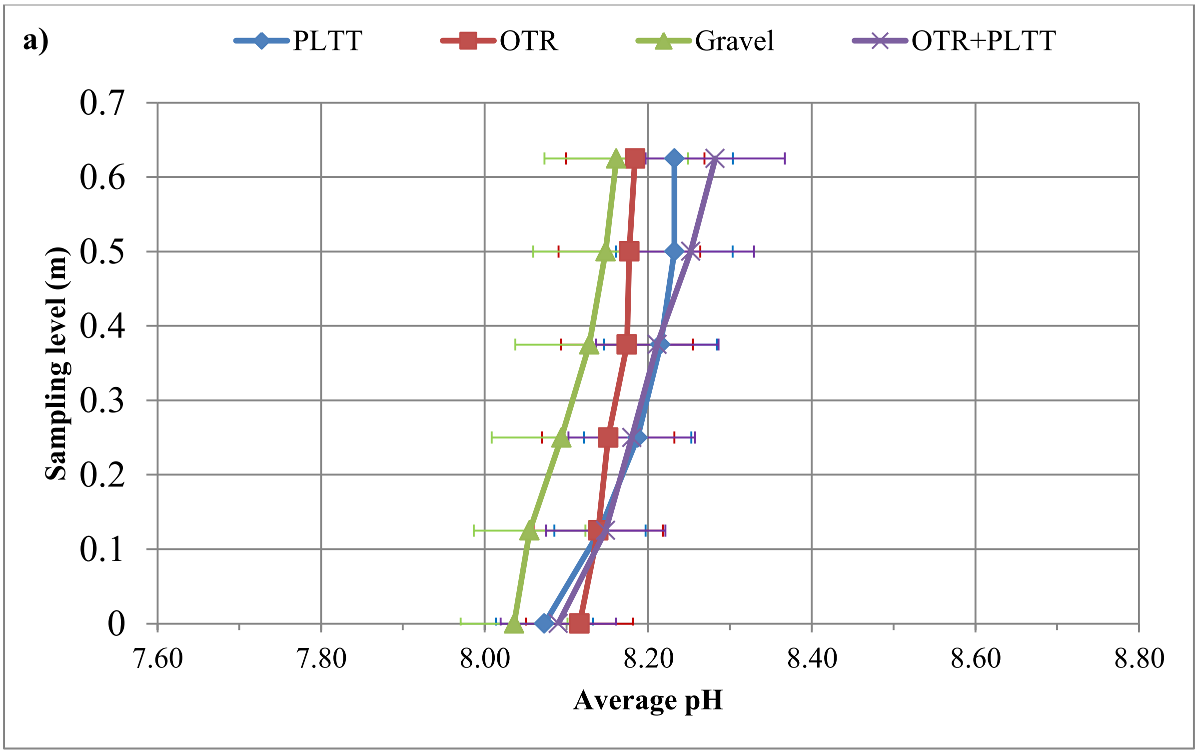


Figure 4-7. (a) Average and (b) normalized average pH values as leachate permeated through TDA and gravel media for the period between day 0 and 168.



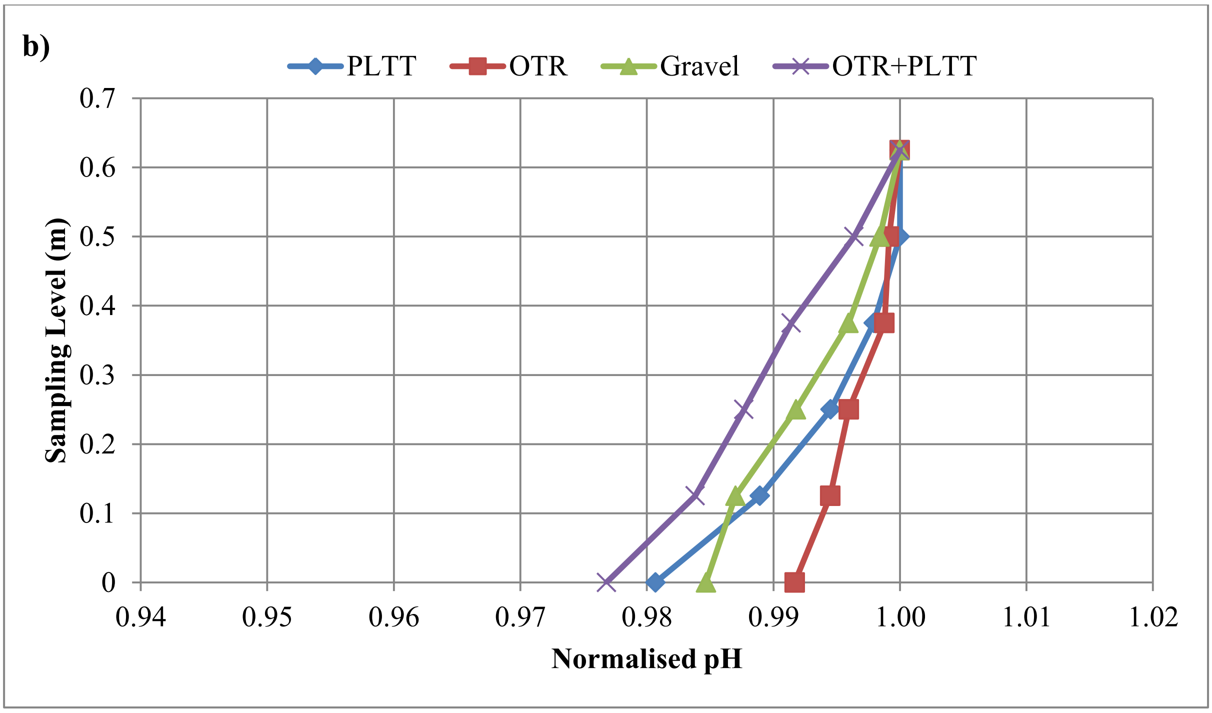


Figure 4-8. (a) Average and (b) normalized average pH for the period from day 168 to 427 as leachate permeated through TDA and gravel media.

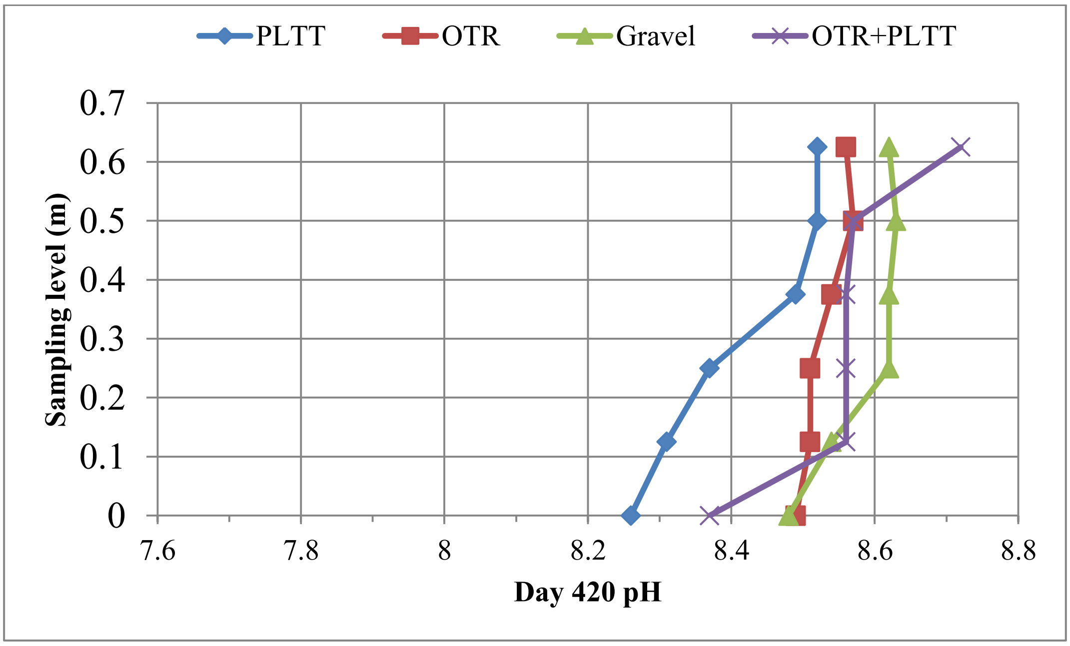


Figure 4-9. Variation of pH on day 420 as leachate permeated through TDA and gravel media.

The decrease in pH from the top to the bottom of the columns may be attributed to biological reactions taking place within the columns, specifically the oxidation of COD to generate CO_2, which dissolves to form carbonic acid (H_2CO_3) and lowers pH (Fleming and Rowe, 2004; VanGulck and Rowe, 2004). In addition, a higher redox potential at the top of the columns, indicated by higher COD values suggests consumption of H^+ resulting in higher pH values. In contrast to the current study, McIsaac and Rowe (2005) found a net increase in pH from 7.0 to 7.5. The authors hypothesized that the increase in pH was caused by consumption of COD (Rowe and McIsaac 2005), which increased the concentration of carbonates in the leachates, and caused chemical precipitation of $CaCO_3$. The differences could be associated with the lower influent pH of about 7.0 in the study by McIsaac and Rowe (2005) compared to the pH ranges of 7.86 to 9.91 in this study. Generally, pH tends to stabilize around 7.5 (Rowe, 2005); that above 7.5 pH decreases because of production of carbonic acid (H_2CO_3) while that below 7.5 increases because of production of CO_3^{2-} (Chu et al., 1994).

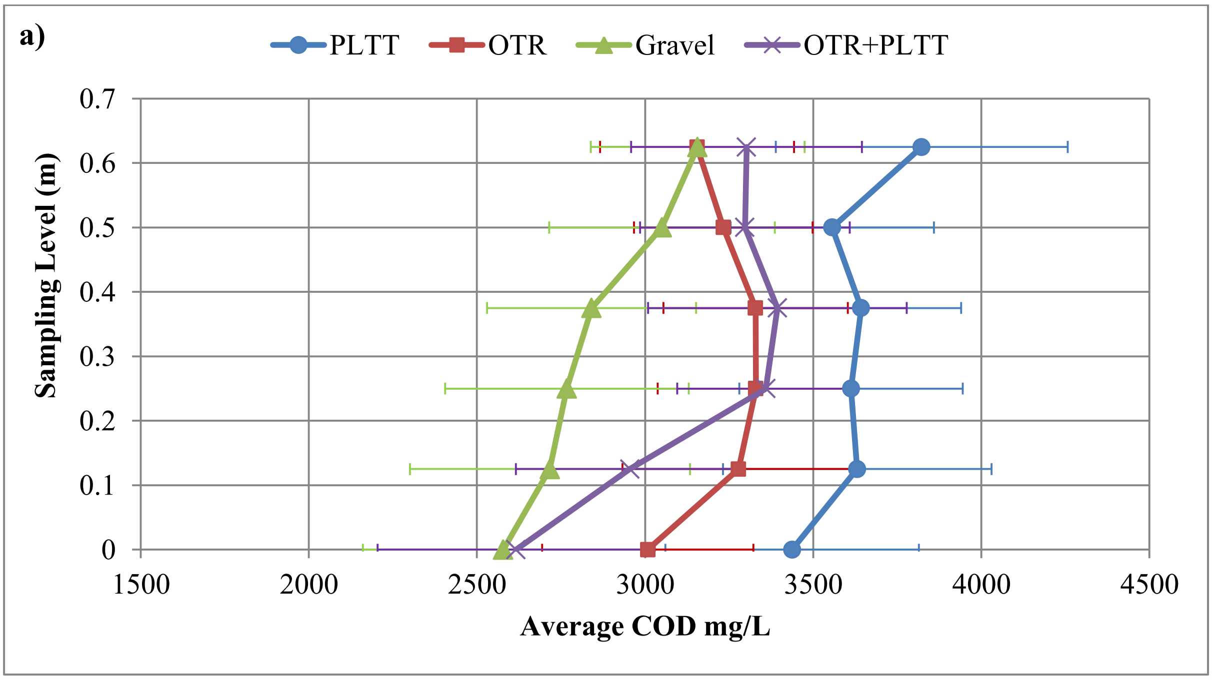
4.3.1.3 Media Performance Based on pH Results

As observed previously, the normalized data for day 168 to 427 did not show significant differences in pH between gravel and any of the TDA media types. The result implies that the physical and chemical (polymeric) characteristics of TDA did not influence the pH and that TDA materials did not leach out acidic or alkaline compounds. Therefore, the TDA tested was inert with respect to composition and strengths of leachates applied. A similar observation was made by Aydilek et al. (2006) when comparing two LCDS field test cells, one with tire chips and the other with gravel.

4.3.2 COD

4.3.2.1 COD – Day 0 to 168

The average COD values for the first 168 days are presented in Figure 4-10. In general, the COD near the top of columns was higher than at the bottom. However, the COD tended to increase towards the middle of OTR and OTR+PLTT columns. The reduction in COD between the top and bottom of the columns was highest in the gravel and OTR+PLTT columns, at 18% and 20%, respectively. The average COD level in the PLTT column was 10% lower at the bottom. OTR had the lowest COD reduction in COD, at 4.6%. A one-way ANOVA data showed that there was a significant difference between the top and the bottom with $p < 0.05$ level [F (3, 23) = 13.87, $p < 0.0001$]. Similar results were obtained for the normalized average data with $p < 0.05$ level [F (3, 23) = 3.57, $p = 0.032$]. Based on multiple comparisons, the differences were between OTR and gravel media. These differences may be attributed to differences in influent concentrations, as evidenced by COD profiles for day 27 to 168 (Figure 4-11), which may have resulted from chemical reactions occurring within the feed line.



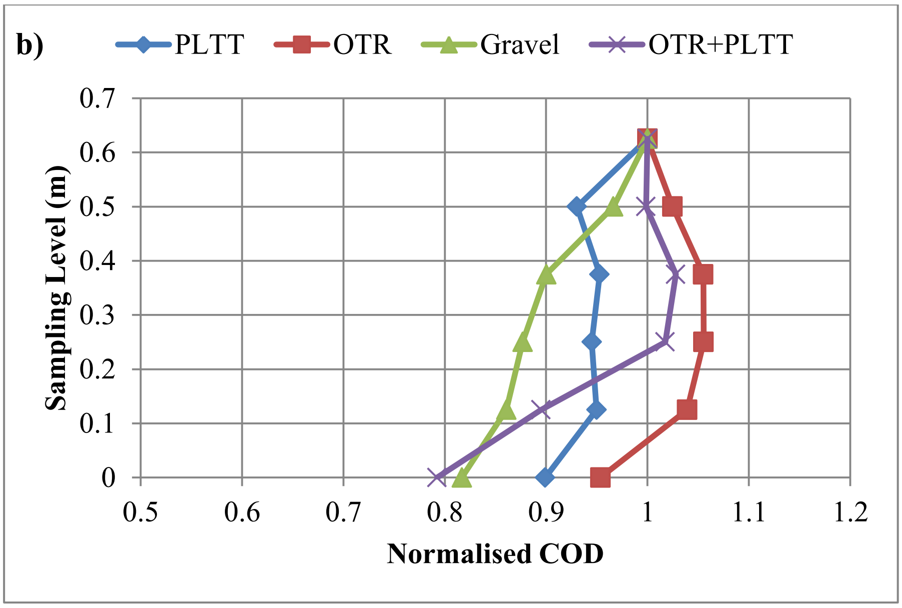


Figure 4-10. (a) Average and (b) normalized average COD levels as leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, for the period between days 0 and 168.

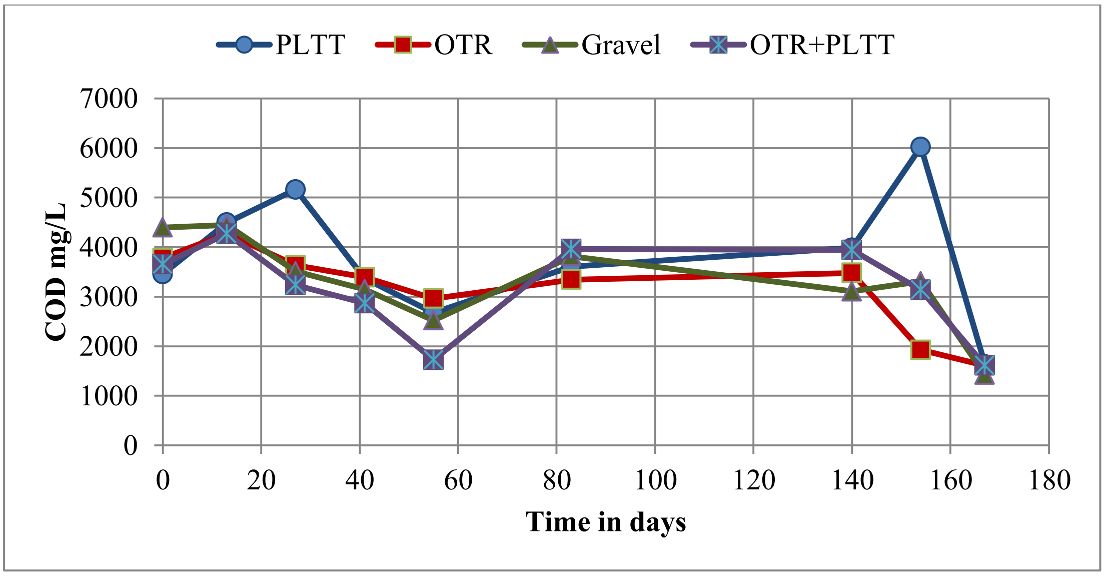


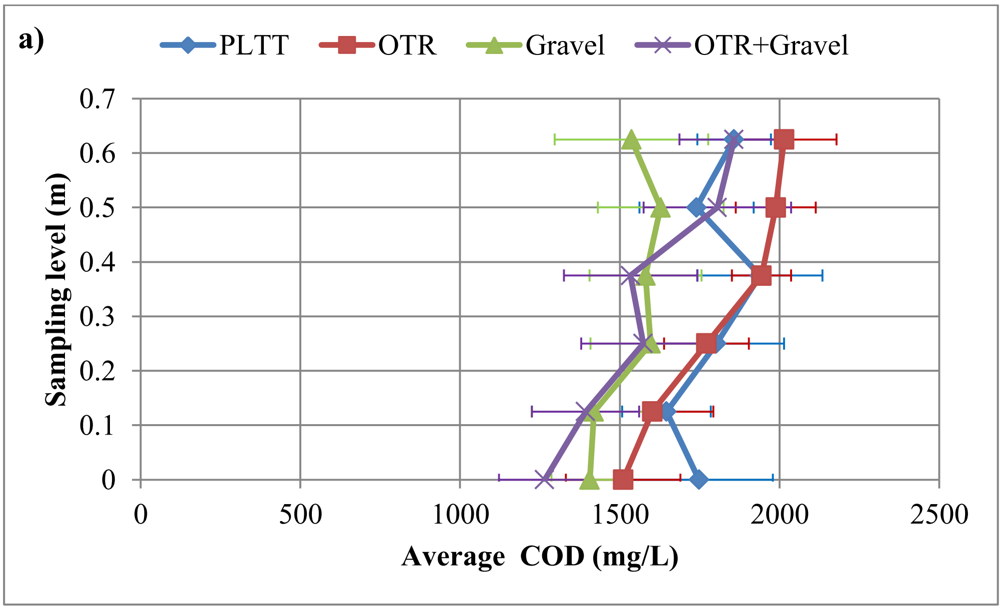
Figure 4-11. Temporal variation of COD as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, based on the COD influent concentrations at sampling level 0.625 m.

4.3.2.2 COD – Day 168 to 427

The average concentrations of COD for the period between day 168 and 427 are presented in Figure 4-12. The COD values were 39 to 52% lower than the COD levels during the first 168 days, possibly because of changes in the quality leachate from the landfill in combination with microbial consumption of COD within the storage tank.

Similar to the first 168 days of the experiment, the COD at the effluent ends of the TDA and gravel medium was lower than the COD at the influent ends. The average leachate COD decreased by 6, 25, 8 and 32% between the top and bottom of the PLTT, OTR, gravel and OTR+PLTT columns, respectively, for day 168 to 427.

A one-way ANOVA was conducted to compare the normalized COD data averaged over day 168 to 427. A significant difference was detected at the $p < 0.05$ level among the four media types [$F(3, 215) = 8.557$, $p < 0.001$]. A multiple comparison of the normalized COD averages showed that the difference was between gravel and each of the TDA (PLTT, OTR, and OTR+PLTT) columns.



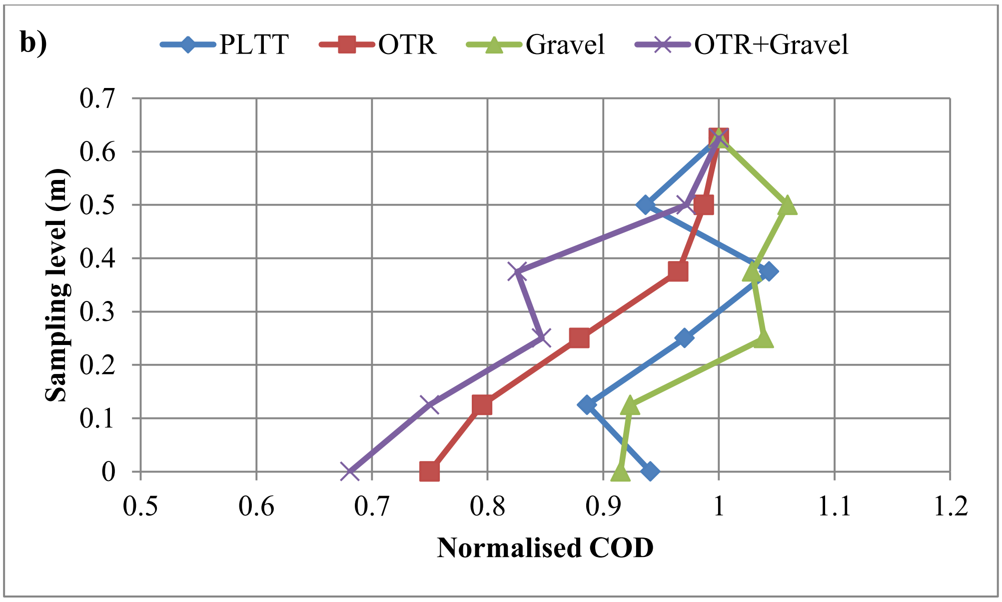


Figure 4-12. (a) Average and (b) normalized average COD concentrations for the period from day 168 to day 427 as leachate permeated through TDA and gravel media.

Figure 4-13 shows the temporal variability of COD based on days 234, 301, 364 and 407. There was no clear trend in COD levels over time. For example, COD levels for day 234 were higher than for other days. These differences may be attributed to differences in influent COD concentrations (Appendix C2, Table C2-5). It was also noted that the COD concentration levels with point 0.75 m were generally higher that with point 0.625 m. For example, in the case of PLTT, day 364, the COD concentration was 3,469 and 1,777 mg L^{-1} at levels 0.75 and 0.625 m respectively. It would appear that there was a sink for COD at the upper part of the columns, probably due to biofilms attached around the top 10 mm steel plate (Figure 4-2). It was also observed that gravel tended to have more uniform COD concentration levels down the column, compared to the TDA columns. A similar observation was made by McIsaac and Rowe (2005), which they attributed to a uniform development of biofilms within the gravel column compared to tire shred columns.

4.3.2.3 Media Performance based on COD Results

The general decrease in leachate COD concentrations with media depth is associated with microbial digestion of organic matter, a hypothesis also advanced by other researchers (e.g. Manning, 2000; McIsaac and Rowe, 2005; Rowe et al., 2000; VanGulck and Rowe, 2004). In reference to clogging, consumption of organic substrates implies an environment conducive for biofilm growth within the pores of a drainage medium. The consumption of COD in the gravel column is much lower and more uniform compared to the TDA, implying an environment less favorable for microbial growth, and therefore less susceptible to clogging. McIsaac and Rowe (2005) reached a similar conclusion although the average normalized effluent COD values were 0.43, 0.44, and 0.52 for the two types of tires shreds and 0.75 for the gravel columns compared to 0.93, 0.75, 1.05 and 0.71 for the current study columns, respectively. The higher COD removals in McIsaac and Rowe's (2005) study may have been caused by higher COD loading, following spiking of raw leachates with a mixture of acetic, butyric and propionic acids.

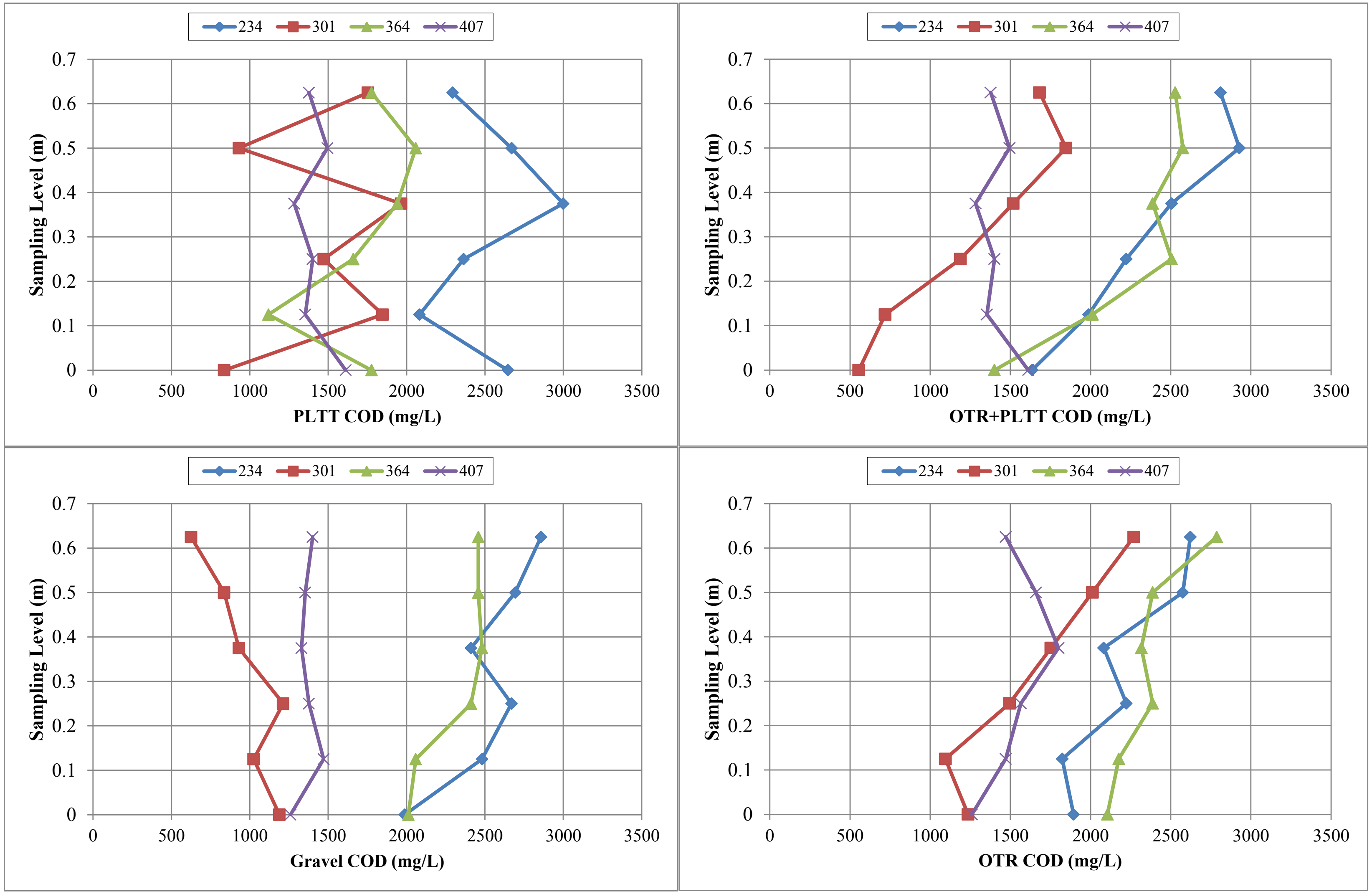


Figure 4-13.Temporal variations in normalized COD for TDA and gravel media columns. Data shown is for days 234, 301, 364, and 407

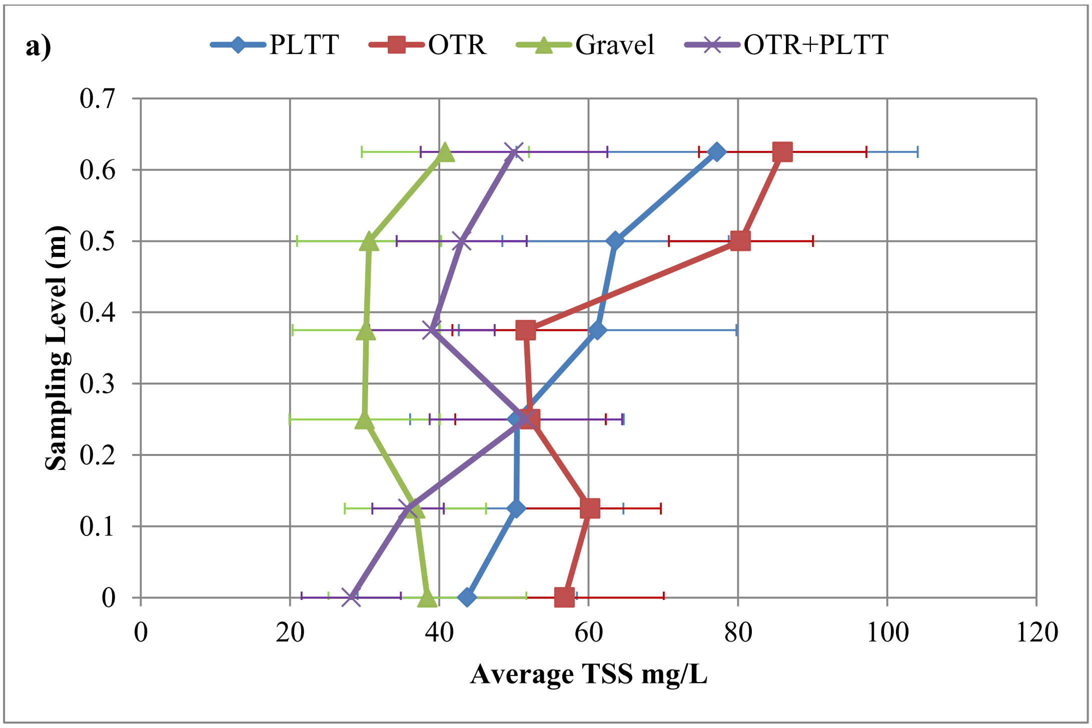
4.3.3 TSS

4.3.3.1 TSS – Days 0 to 168

The TSS profiles based are shown in Figure 4-14. In general, the TDA media reduced TSS concentration by 43, 34 and 44% for PLTT, OTR, OTR+PLTT, respectively. TSS reduction in gravel was lower at 7%. McIsaac and Rowe (2005) observed a 37% decrease in TSS in tire shreds and 64% in gravel columns between the influent and effluent ends of their test columns. However, in the McIsaac and Rowe (2005) study, leachate flow was upwards as opposed to downwards in the current study. Therefore, the gravitational forces retarding the upward movement of particles may have contributed to the observed higher removals by gravel.

A one-way ANOVA showed there was significant differences ($p < 0.05$ level) among the four media types [$F (3, 23) = 10.02$, $p < 0.001$]. A multiple comparison of the means showed the differences were between the PLTT and gravel columns and among OTR, gravel, OTR+PLTT columns. No significant differences were noted between PLTT and OTR columns. For the normalized average TSS data, a one-way ANOVA did not show significant difference among the media types [$F (3, 23) = 0.6$, $p = 0.61$].

The result imply that variations observed with average TSS concentrations (Figure 4-14) may have been associated with variations in influent concentrations rather than media type. Figure 4-15 shows the temporal variation of TSS concentration on days 27, 83, 140 and 168. The TSS concentration at level 0.75 m was much higher than at level 0.625 m. For example, in the case of PLTT, the average TSS concentration at level 0.75 m was 5,118 ± 2,493 mg L^{-1}, compared to 77 ± 27 mg L^{-1} (Appendix C, Table C1-3). Between sampling points 0.75 m and 0.625 m, there was a 10 mm steel plate, which appears to have intercepted suspended solids before they reached the drainage media, thus causing low TSS concentrations at level 0.625 m. A similar observation was made for COD, as discussed before.



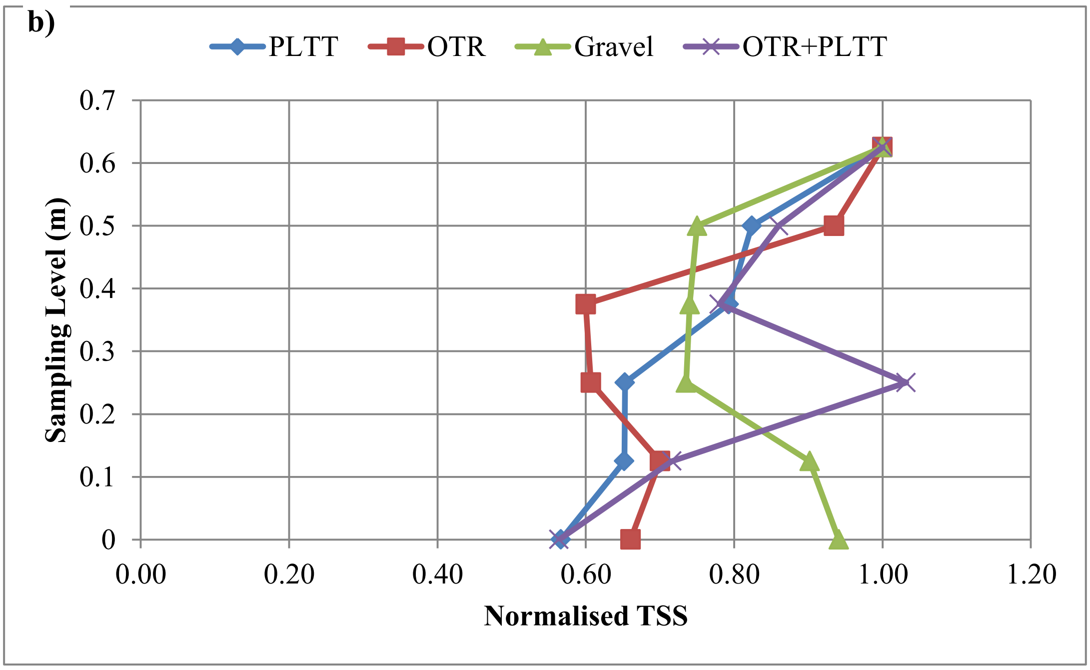


Figure 4-14. (a) Average and (b) normalized average TSS concentrations for the period between days 0 and 168 as leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns.

Figure 4-15 shows variability of TSS with media depth for days 27, 83, 140 and 167. There was no consistent tread. A decrease in TSS would probably indicate a phase transfer of suspended solids from liquid to solid phase. An increase would imply that some previously trapped materials were re-suspended probably due to attachment-detachment processes. McIsaac and Rowe (2005) observed a similar attachment-detachment phenomenon.

4.3.3.2 TSS – Days 168 to 427

The TSS levels in the columns after the pressure-release cups were installed (after day 168) are presented in Figure 4-16. The concentration of TSS varied from 87.5 to 55.8 $mg \cdot L^{-1}$ for PLTT, 75.5 to 37.5 $mg \cdot L^{-1}$ for OTR, 93.1 to 45.5 $mg \cdot L^{-1}$for gravel and from 81.7 to 50.2 $mg \cdot L^{-1}$ for OTR+PLTT. A one-way ANOVA showed no significant difference at the $p < 0.05$ level among the four media types [$F (3, 23) = 3.11$, $p = 0.05$]. A one-way ANOVA on normalized average TSS values among the four media types showed significant differences at the $p < 0.05$ level [$F (3, 216) = 7.046$, $p < 0.001$]. A multiple comparison showed that the differences were between gravel and PLTT, gravel and OTR+PLTT, PLTT and OTR, and OTR and OTR+PLTT. No differences were detected between PLTT and OTR+PLTT or between gravel and OTR.

In general, TSS were lower at the bottom of the drainage media than at the top (Figure 4-16), which is similar to the first 168 days. This result indicates that a portion of the influent TSS was captured within the drainage media. The overall decrease in TSS between the influent and effluent ends of the columns was largest in gravel at 66% and smallest in PLTT and OTR+PLTT at 40%. Similar decreases in TSS were observed by McIsaac and Rowe (2005), who found that TSS levels decreased by 64% for gravel and 37% for tire shreds.

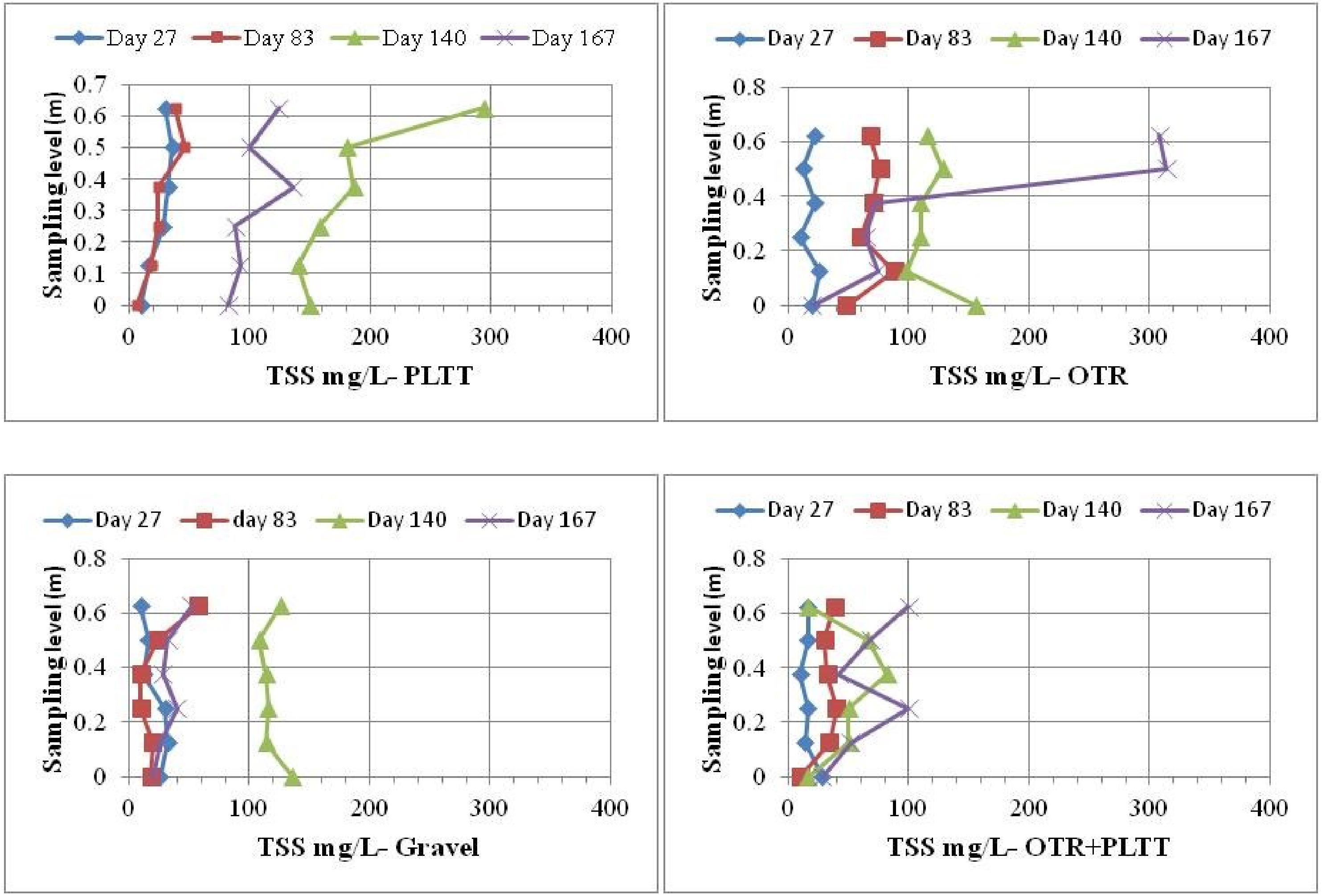
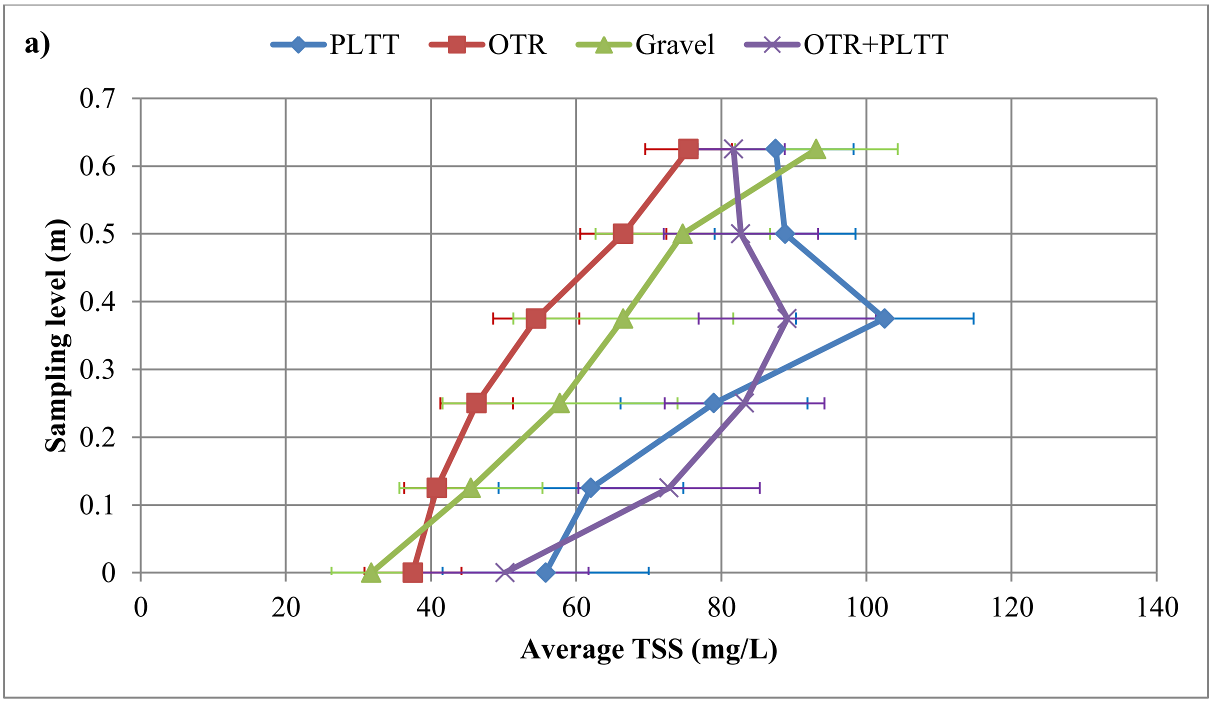


Figure 4-15. Temporal variations in TSS in PLTT, OTR, gravel and OTR+PLTT columns, for day 27, 83, 140 and 168.

Inspection of the TSS trends over time (Figure 4-17) revealed that TSS decreased steadily down the column on some dates, while on other dates there was an increase in TSS somewhere in the middle of the drainage media. These changes were probably due to variability in net entrapment versus net re-suspension of particles throughout the columns. In all TDA media, however, TSS tended to increase relative to the influent concentration at or below level 0.5 m (Day 414, Figure 4-17). This effect was not observed in gravel. As pointed out previously, there was a perforated 10 mm steel plate at the top of the drainage media, which may have facilitated retention of suspended solids as leachates passed through. Because TDA was under compression, it is possible that pieces of TDA blocked perforations on the steel plate, thereby preventing more solids from reaching the TDA media as compared to gravel. The retained solids may have acted as sources resulting in a build-up of TSS with time (Figure 4-16).

4.3.3.3 Media Performance based on TSS Results

There was a general decrease in TSS between the top and bottom of the TDA and gravel columns. A comparison between the average normalized TSS concentrations for days 168 to 427 (Figure 4-16) showed that there were significant differences between media containing PLTT and media without PLTT, while at the same time the performance of the two PLTT-containing media was similar to that of OTR and gravel. It is hypothesized that the flat shaped PLTT particles had a significant effect on settling of solids and movement through the columns. The similarities between PLTT and OTR+PLTT imply that mixing PLTT and OTR on 50:50 basis is of no advantage to movement of solids within LCDS.



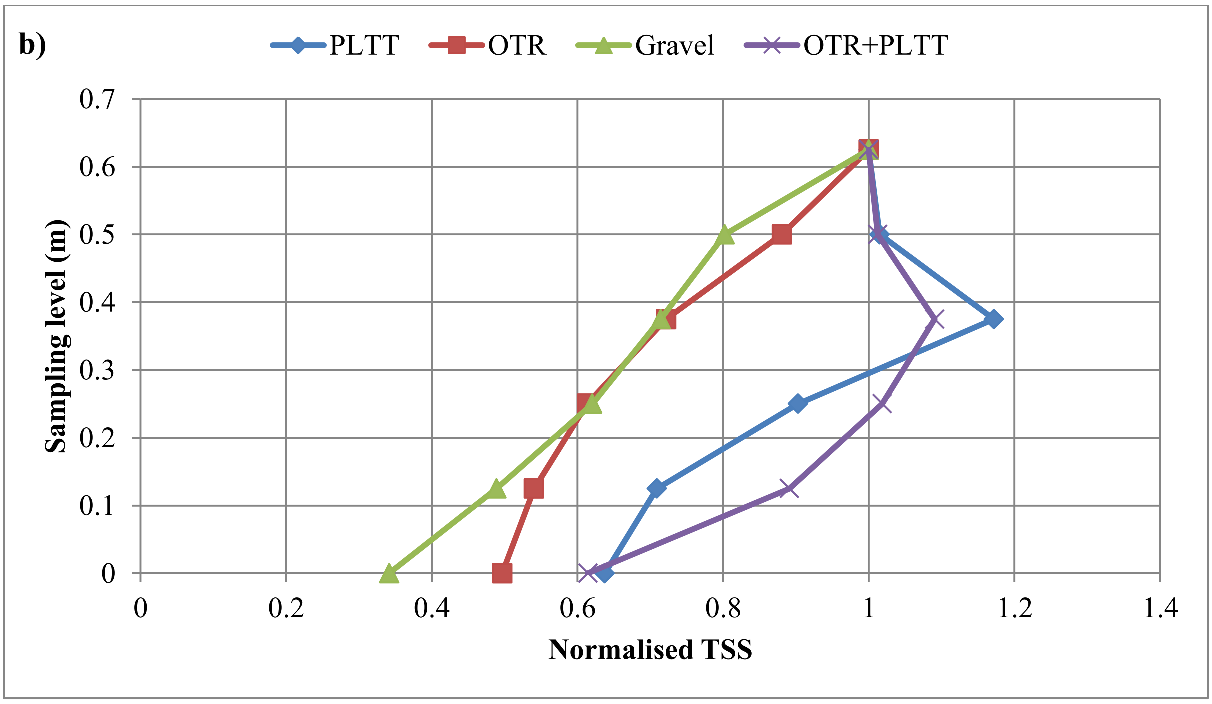


Figure 4-16. (a) Average and (b) normalized average TSS concentrations for the period from day 168 to day 427 as leachate permeated through TDA and gravel media.

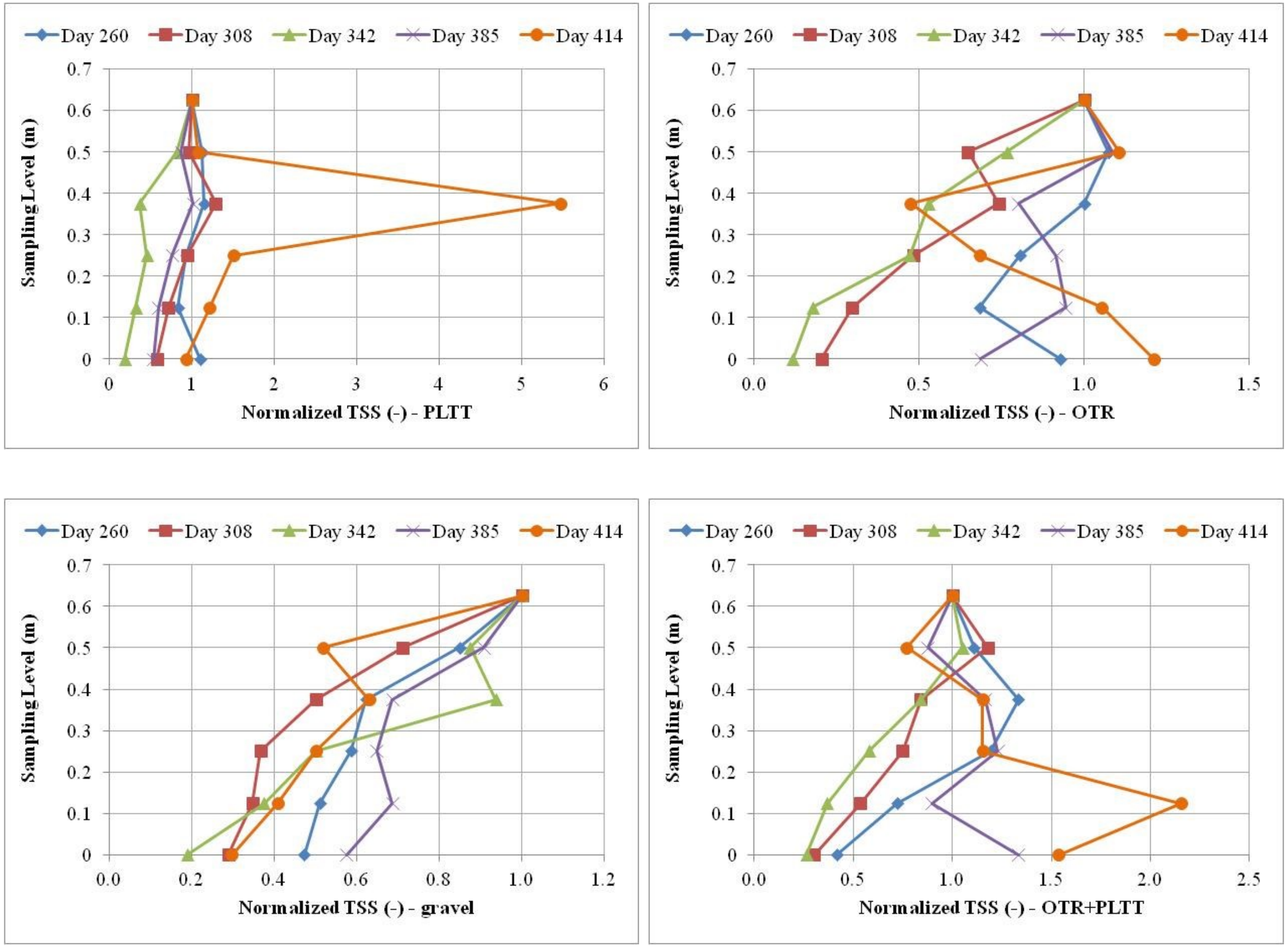


Figure 4-17. Temporal variations in TSS (normalized to column influent concentration) as leachate flowed through PLTT, OTR, gravel and OTR+PLTT columns. Data is shown for days 260, 308, 342, 385 and 414.

Decrease in TSS was greater in gravel columns than in tire shred columns. This observation may imply that: 1) there was enhanced retention of the suspended solids and, therefore, a higher potential for gravel to clog than PLTT and OTR+PLTT; or 2) gravel and OTR are more efficient in passing particles out of the system so that retained TSS is not only low, but the media also remains relatively clean. The second hypothesis seems more likely, because both gravel media and OTR were observed to have less clog matter following column disassembly. The PLTT and OTR+PLTT sections with high average TSS concentrations had higher reduction of drainable porosity, indicating that clogging was more pronounced. Considering a mass balance from top to bottom, PLTT column retained 33.7% of the total TSS flux, compared to 50.3, 55.5 and 52.2% retained in the cases of OTR, gravel and OTR+PLTT. Because PLTT is characterized by tortuous flow conditions (McIsaac and Rowe, 2005), the low TSS retention may indicate the significance of the resultant higher velocity (Appendix C, Tables C3-9 to C3-12). In addition to filtration, straining and internal generation of TSS from precipitation and biomass, there are other processes such as attachment and detachment that may control overall mass balance of TSS (McIsaac and Rowe, 2005). However, typical column experiments for investigating clogging phenomenon cannot isolate each of these processes sufficiently to allow determination of their relative importance.

The average influent TSS levels of 81.7 to 93.1 $mg \cdot L^{-1}$ at level 0.625 m, were much less than the mean value of 1,743 $mg \cdot L^{-1}$ established for municipal sanitary landfills in Alberta (Chapter 2) and tended towards the lower end of the general range of 3 to 21,940 $mg \cdot L^{-1}$. This observation is attributed to the settling out of particulate matter in the feed lines, as may be deduced from Tables C1-5 and C2-4 in Appendix C. The TSS concentrations at the tank outlet ranged from 140 to 11,005 $mg \cdot L^{-1}$ (average 3,498 ± 819 $mg \cdot L^{-1}$) over the course of the experiment. In addition, influent TSS in this study were less than those for McIsacc and

Rowe's study of 287 $mg \cdot L^{-1}$ for tire shred and 584 $mg \cdot L^{-1}$ for the gravel potentially contributing to the observed lower level of clogging. TSS levels were also lower than would be expected in an actual sanitary landfill; therefore, the clogging levels observed most probably underestimated field conditions. For future studies, there may be a need to improve the arrangement for feed lines so as to reduce settling of the suspended particles.

4.3.4 Calcium

4.3.4.1 Calcium – Day 0 to 168

The average calcium data for day 0 to 168 are shown in Figure 4-18(a). The calcium concentration varied from 31.4 to 27.7 $mg \cdot L^{-1}$ for PLTT, 27.6 to 26.2 $mg \cdot L^{-1}$ for OTR, 33.4 to 30.7 $mg \cdot L^{-1}$for gravel and from 29.0 to 28.2 $mg \cdot L^{-1}$ for OTR. A one-way ANOVA showed a significant differences at the $p < 0.05$ level [F (3, 23) = 13.77, $p < 0.0001$]. A multiple comparison of the averages showed that the differences were associated with OTR, on one hand and PLTT, gravel and OTR+PLTT on the other. Figure 4.18(b) shows the normalised average TSS data. A one-way ANOVA showed significant differences at the $p < 0.05$ level [F (3, 140) = 4.609, $p = 0.004$]. A multiple comparison showed that the differences were associated with OTR+PLTT on one hand and PLTT, OTR, and gravel on the other. There were no differences detected between PLTT and gravel, OTR and gravel, or OTR and PLTT. It would appear that media surface characteristics of either gravel or TDA did not affect the concentration of Ca^{2+}.

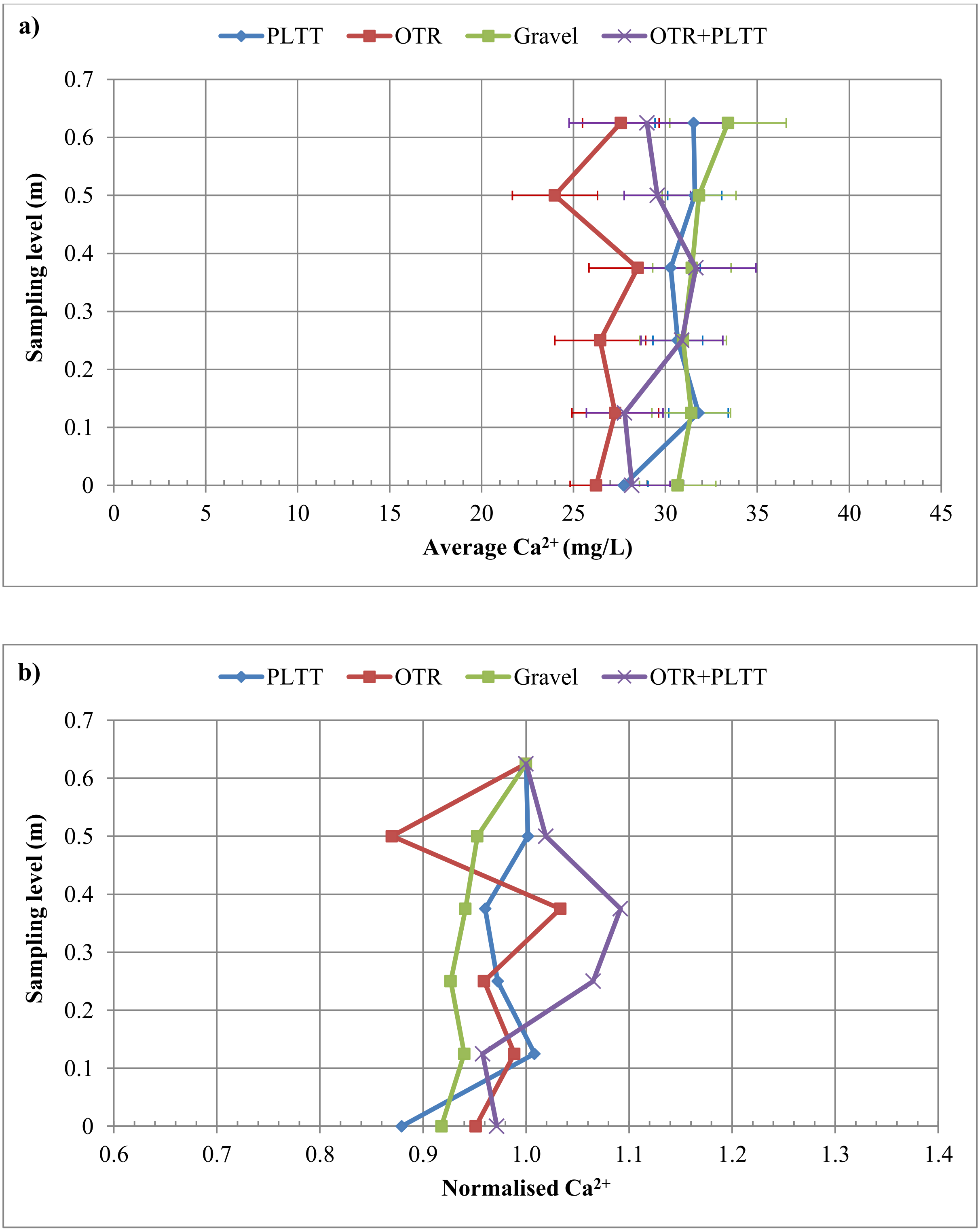


Figure 4-18. (a) Average and (b) normalized average calcium concentrations in PLTT, OTR, gravel and OTR+PLTT columns for the period between days 0 and 168.

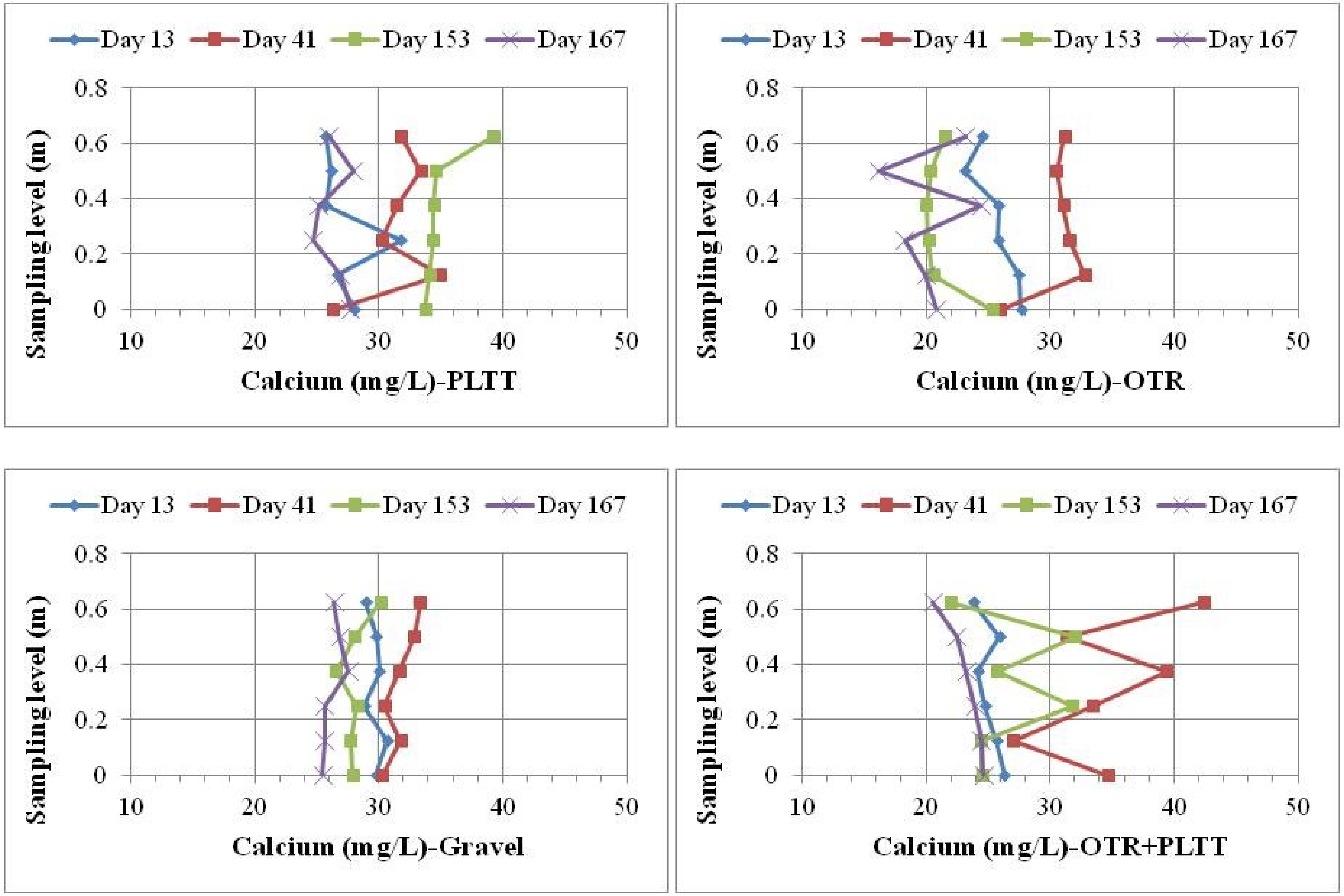


Figure 4-19. Temporal variation of calcium as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, based on the calcium concentrations on days 13, 41, 153 and 167.

4.3.4.2 Calcium – Days 168 to 427

The average calcium concentrations for day 168 to 427 are presented in Figure 4-20(a). The calcium concentration in the PLTT column varied from 11.88 to 11.51 $mg\cdot L^{-1}$ for PLTT, 12.99 to 12.61 $mg\cdot L^{-1}$ for OTR, 10.30 to 13.11 $mg\cdot L^{-1}$for gravel and from 9.05 to 8.37 $mg\cdot L^{-1}$ for OTR+PLTT. A one-way ANOVA did not show a significant difference, with $p = 0.05$, for average calcium concentrations ([F (3, 23) =3.02, $p = 0.053$]).

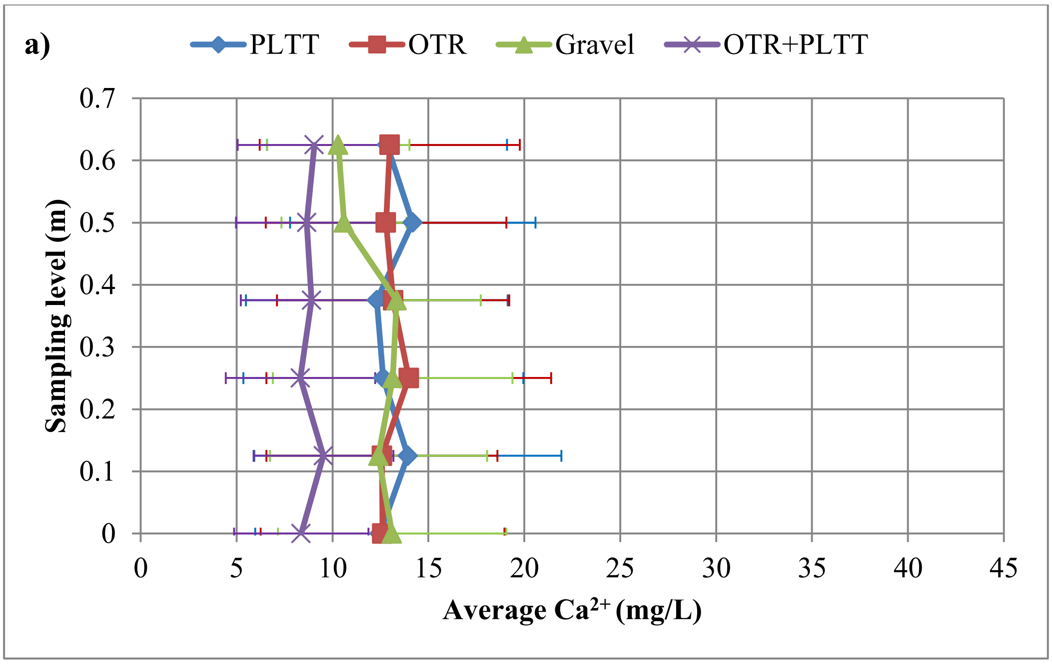
As in the first 168 days, calcium concentrations in the PLTT, OTR and OTR+PLTT media had near vertical profiles, implying there were no major reactions or processes that affected Ca^{2+} concentrations (Figure 4-20). When normalized, a one-way ANOVA showed significant difference with $p < 0.05$ ([F (3, 23) = 12.17, $p < 0.001$]). Multiple comparisons showed the differences were between gravel and PLTT. This difference may have been influenced by sampling point 0.375 m on day 343 in which calcium concentration increased by 30% near the middle (level 0.375 m) and by 27% near the bottom (Figure 4-20a); with other days showing fairly consistent calcium levels throughout the gravel column (Figure 4-21). It was not established why there was an increase in Ca^{2+} with point 0.375 m on day 343. Compared to the period between day 0 and 168, calcium concentrations were lower in all tests (Figures 4-18 and 4-20). This observation was attributed to the lower calcium concentrations in the storage tank after day 168, which averaged 22.19 ± 15 $mg\cdot L^{-1}$ for the period between day 168 and 427 compared to 40.7 ± 12.98 $mg\cdot L^{-1}$ for the period between 0 and 168 days. The lower concentrations in the tank may be attributed to the low levels in the leachate obtained from the treatment plant (Tables C1-7 and C2-9 in Appendix C). These values were also much lower than the average of 522 $mg\cdot L^{-1}$ reported for Alberta landfills (Chapter 2).

McIsaac and Rowe (2005) reported larger decreases in calcium levels than were observed in the current study. McIsaac and Rowe (2005) observed between 69 and 55% in tire shred columns and 35% in gravel column. The higher levels of Ca^{2+} reduction observed by McIsaac and Rowe (2005) may be attributed to higher concentrations of calcium at 100 to 1,665 mg·L^{-1} compared to 2 to 48 mg·L^{-1} for the current study and thus likely to precipitate more $CaCO_3$. In previous columns studies (VanGulck and Rowe 2004; Rowe 2005; McIsaac and Rowe 2005), a strong relationship between precipitation of $CaCO_3$ and clog development in LCDS was observed.

4.3.4.3 Media Performance based on Calcium Results

As discussed above, there were no statistically significant differences among the media types, based on normalized calcium levels between days 168 to 427. From mass balance calculations (Appendix C3; Tables C3-5 to C3-9), about 13.3% of the influent Ca^{2+} was retained within the PLTT column. In the case of OTR, gravel and OTR+PLTT only 2%, 4.22% and 2.3% of Ca^{2+} was retained, respectively. The low values of Ca^{2+} retention in the gravel, OTR and OTR+PLTT columns imply that conversion of Ca^{2+}, for example, to $CaCO_3$ was minimal. The higher retention of Ca^{2+} in the PLTT column may be associated with COD oxidation (Cooke et al., 2001), which was higher in PLTT compared to OTR, gravel and OTR+PLTT (Figure 4.10(a)). As observed previously, calcium carbonate precipitation is closely linked to COD oxidation, which produces CO_2 and, ultimately, carbonates; the precursors for calcium carbonate precipitation (David 2000; VanGulck et al. 2003).

The observation that PLTT retained more calcium carbonate precipitates than the other media is corroborated by findings of McIsaac and Rowe (2005). It was observed that effluent Ca^{2+} concentrations were 0.31, 0.32, and 0.45 mg.L^{-1} for the two types of tire shreds and 0.65 for gravel columns (McIsaac and Rowe, 2005), implying that more calcium may have been deposited probably as calcium carbonate in the tire shred media as compared to gravel.



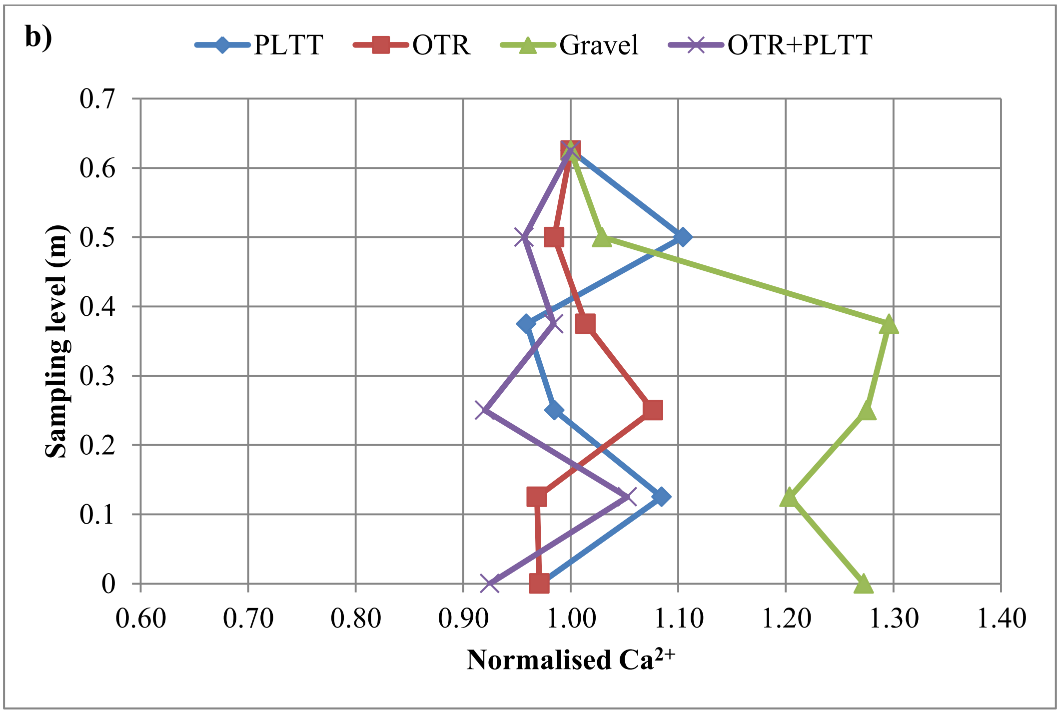


Figure 4-20. (a) Average and (b) normalized average calcium concentrations for the period between day 168 and day 427 as leachate permeated through TDA and gravel media.

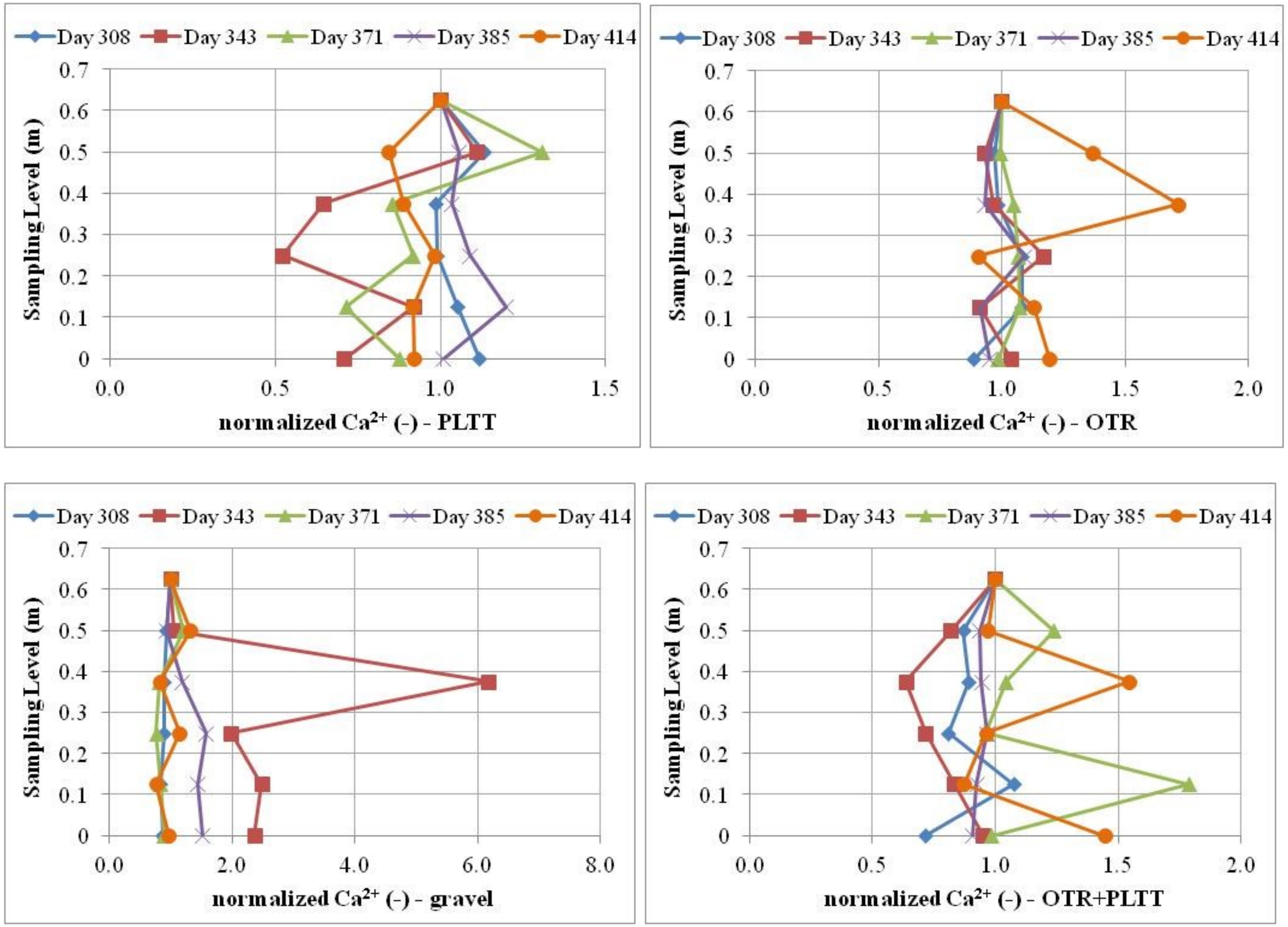


Figure 4-21. Temporal variations in normalized calcium concentrations as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns on days 308, 343, 371, 385, and 414.

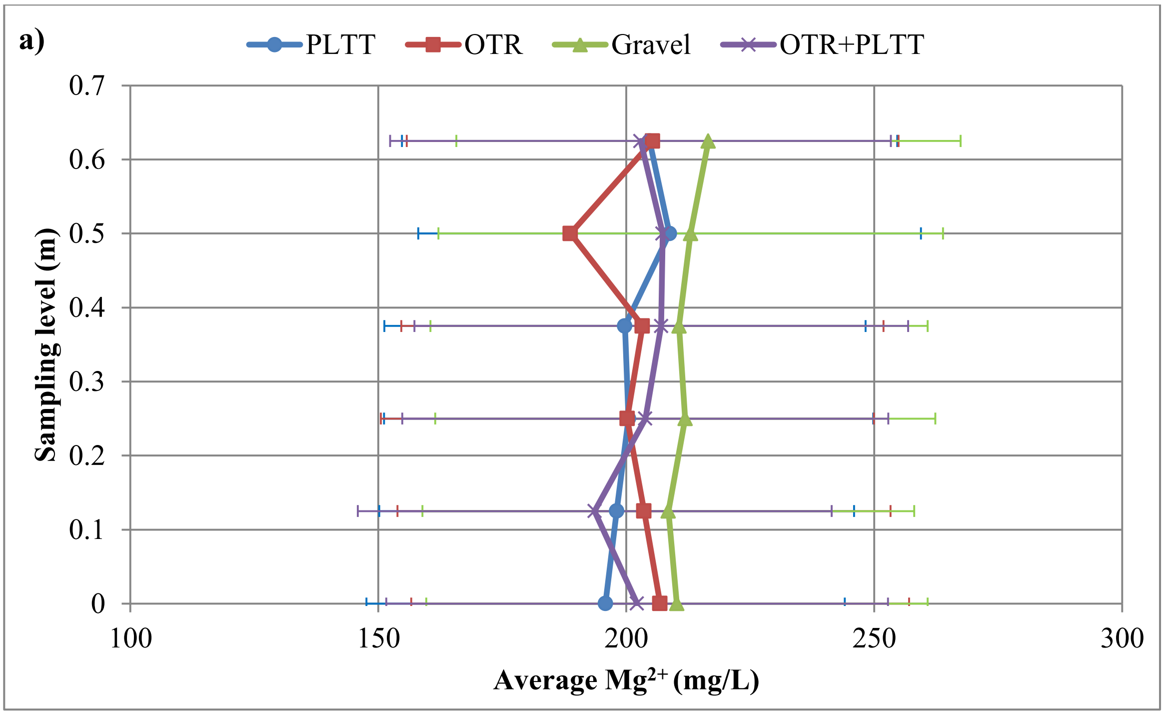
4.3.5 Magnesium

4.3.5.1 Magnesium – Day 0 to 168

Figure 4-22 shows the profiles for magnesium for day 0 to 168. The average magnesium concentration varied from 204.731 to 195.83 mg·L^{-1} for PLTT, 205.34 to 206.82 mg·L^{-1} for OTR, 216.59 to 210.22 mg·L^{-1} for gravel and from 202.89 to 202.18 mg·L^{-1} for OTR+PLTT. A one-way ANOVA showed significant differences with $p < 0.05$ level [F (3, 23) = 6.28, $p < 0.004$]. A multiple comparison of the averages showed that the differences were associated with OTR, on one hand and PLTT, gravel and OTR+PLTT on the other. However, a one-way ANOVA comparing the normalized average magnesium concentrations for day 0 to 168 showed no significant differences with $p < 0.05$ level [F (3, 116) = 0.292, $p = 0.831$]. This observation implied differences associated with average data were not related to type of media, but probably to differences in influent concentrations. A measurement error was also likely considering that average concentration of Mg^{2+} in gravel column seems to have been influenced by day 167, at sampling point 0.5 m (Figure 4-23).

4.3.5.2 Magnesium – Day 168 to 427

The average magnesium concentrations between days 168 and 427 are shown in Figure 4-24. The concentration of magnesium varied from 156.9 to 164.8 mg·L^{-1} for PLTT, 244.8 to 174.5 mg·L^{-1} for OTR, 248.4 to 265.4 mg·L^{-1}for gravel and from 236.9 to 252.5 mg·L^{-1} for OTR+PLTT. In general, the concentration of magnesium in PLTT, gravel and OTR+PLTT did not vary appreciably between top and bottom, compared to OTR, which exhibited a steady decrease below level 0.25 m. The difference of magnesium in gravel may have been influenced by very low concentrations recorded on day 407 at sampling points 0.375, 0.125 and 0.0 m (Appendix C2, Table C2-10).


a)
PLTT
OTR
Gravel
OTR+PLTT
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Sampling level (m)
100
150
200
250
300
Average Mg²⁺ (mg/L)

b)

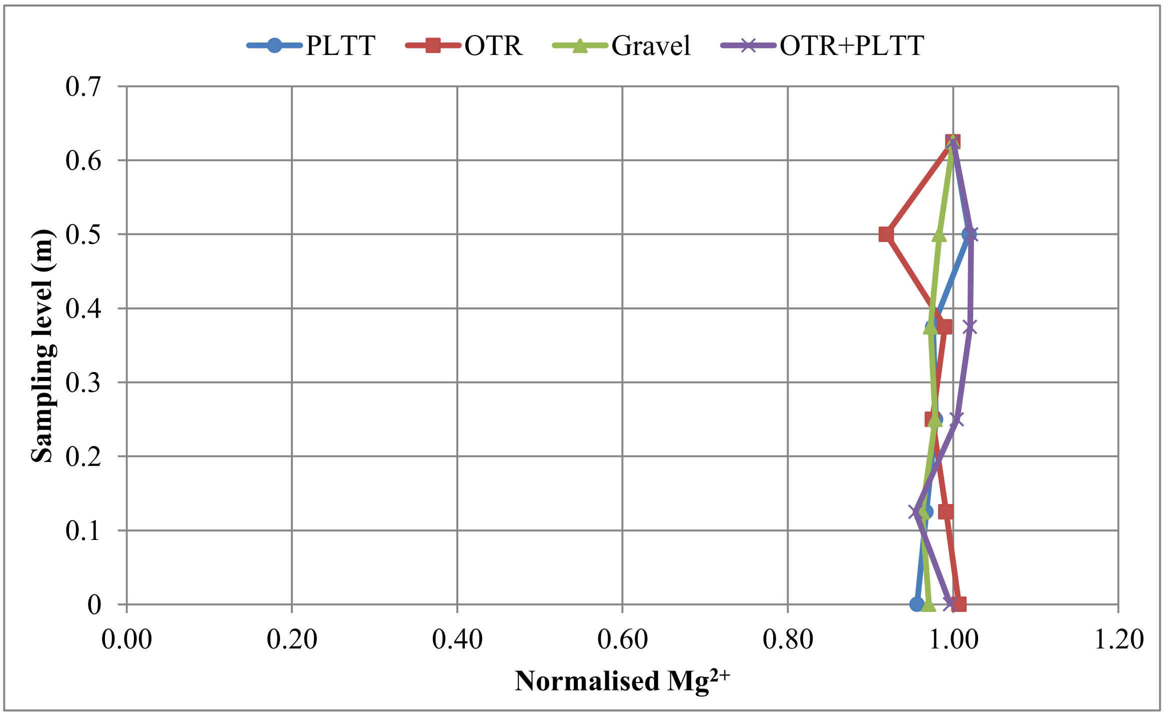

PLTT
OTR
Gravel
OTR+PLTT
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Sampling level (m)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Normalised Mg²⁺

Figure 4-22. (a) Average and (b) normalized average magnesium concentrations as leachate permeated through the gravel and TDA columns, for the period between days 0 and 168**.**

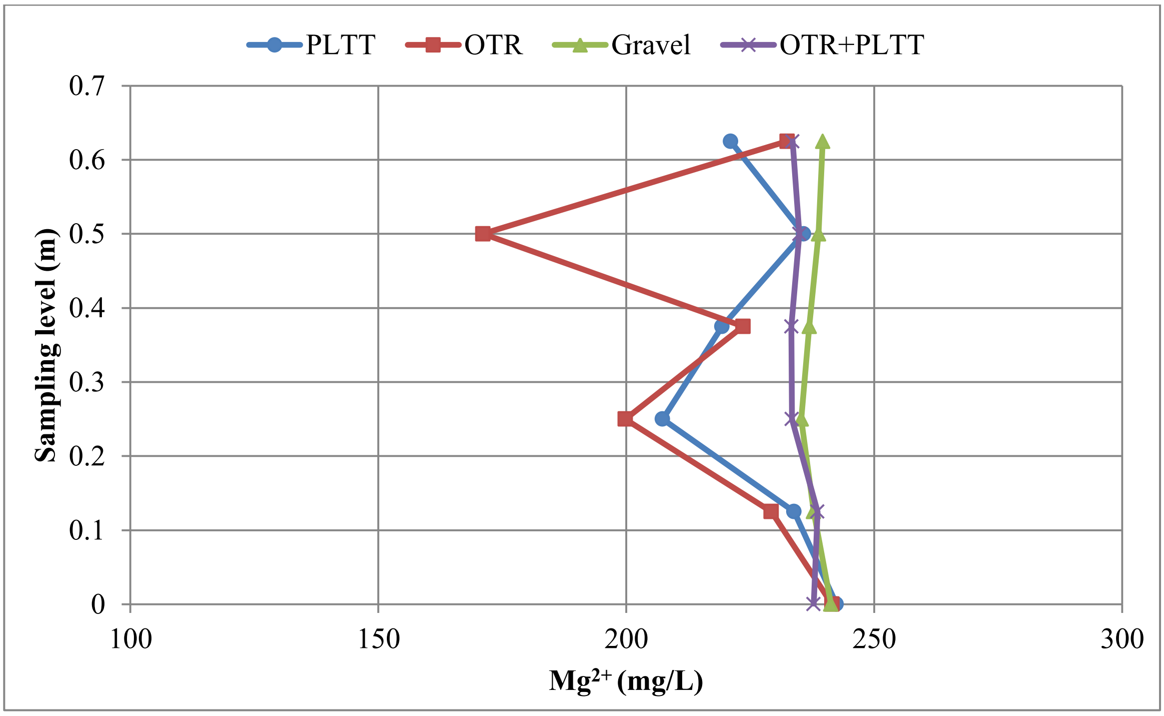
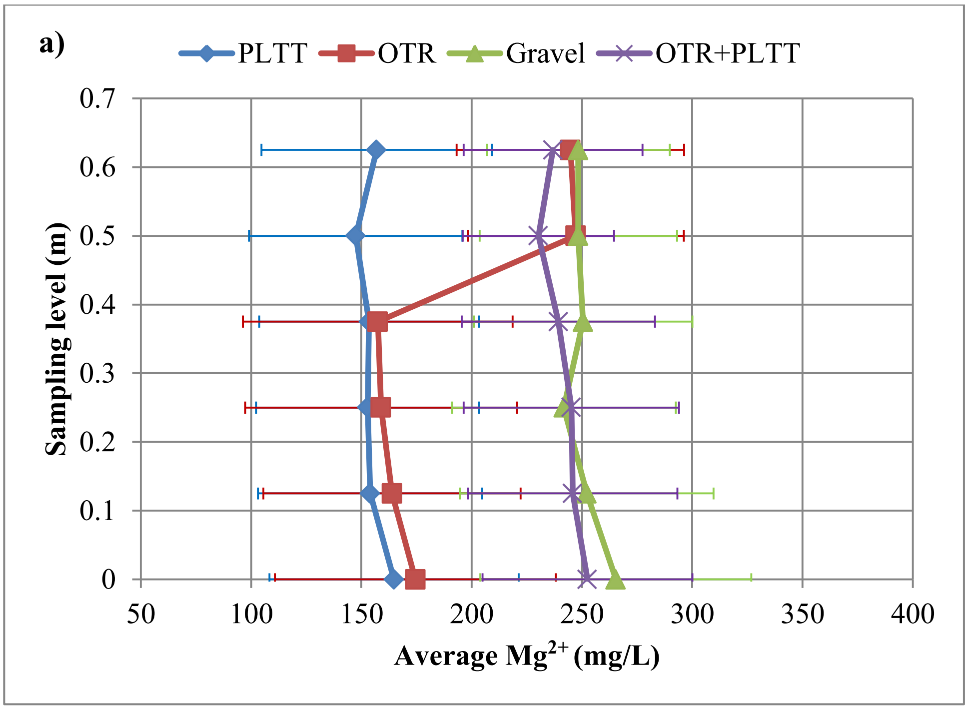


Figure 4-23. Variation of magnesium with depth for PLTT, OTR, Gravel and OTR+PLTT columns, based on the magnesium concentrations on day 167.

The cause of the low magnesium concentration values was not established, but an experimental error may have influenced results considering that other cations did not exhibit a similar behaviour. Furthermore, a one-way ANOVA of the normalized magnesium data presented in Figure 4-24 showed no significant differences among the four media types [F (3, 90) = 0.783, p = 0.507]. The near-vertical profiles for PLTT, gravel, and OTR+PLTT media suggest relatively low participation of magnesium in biogeochemical processes. This hypothesis is supported by a compositional analysis of inorganic constituents in field clog matter, which were reported by Fleming et al. (1999) to be about 20% calcium, 30% carbonates, 21% silicon, 5% magnesium and 2% iron.



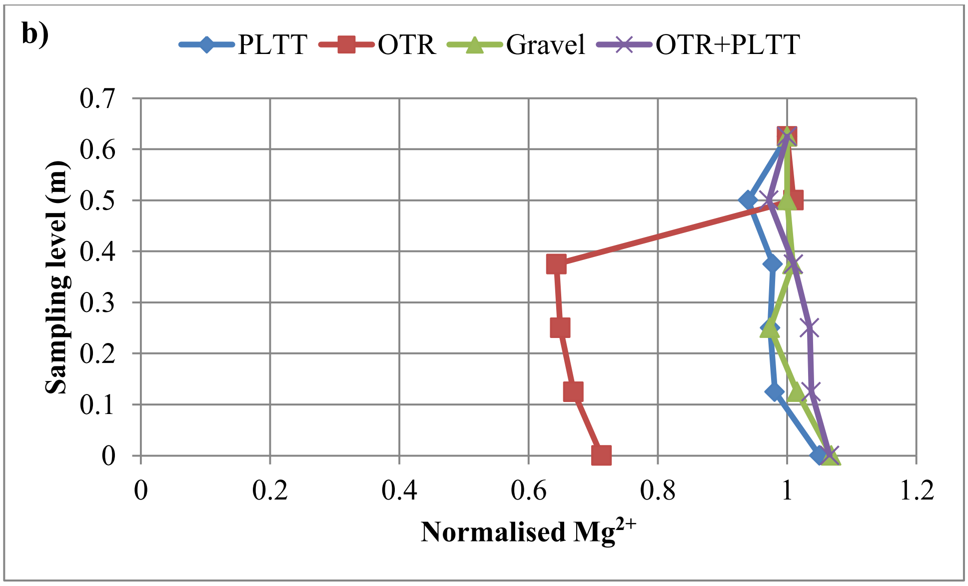


Figure 4-24. (a) Average and (b) normalized average magnesium concentrations for the period from days 168 to 427 as leachate permeated through TDA and gravel drainage media.

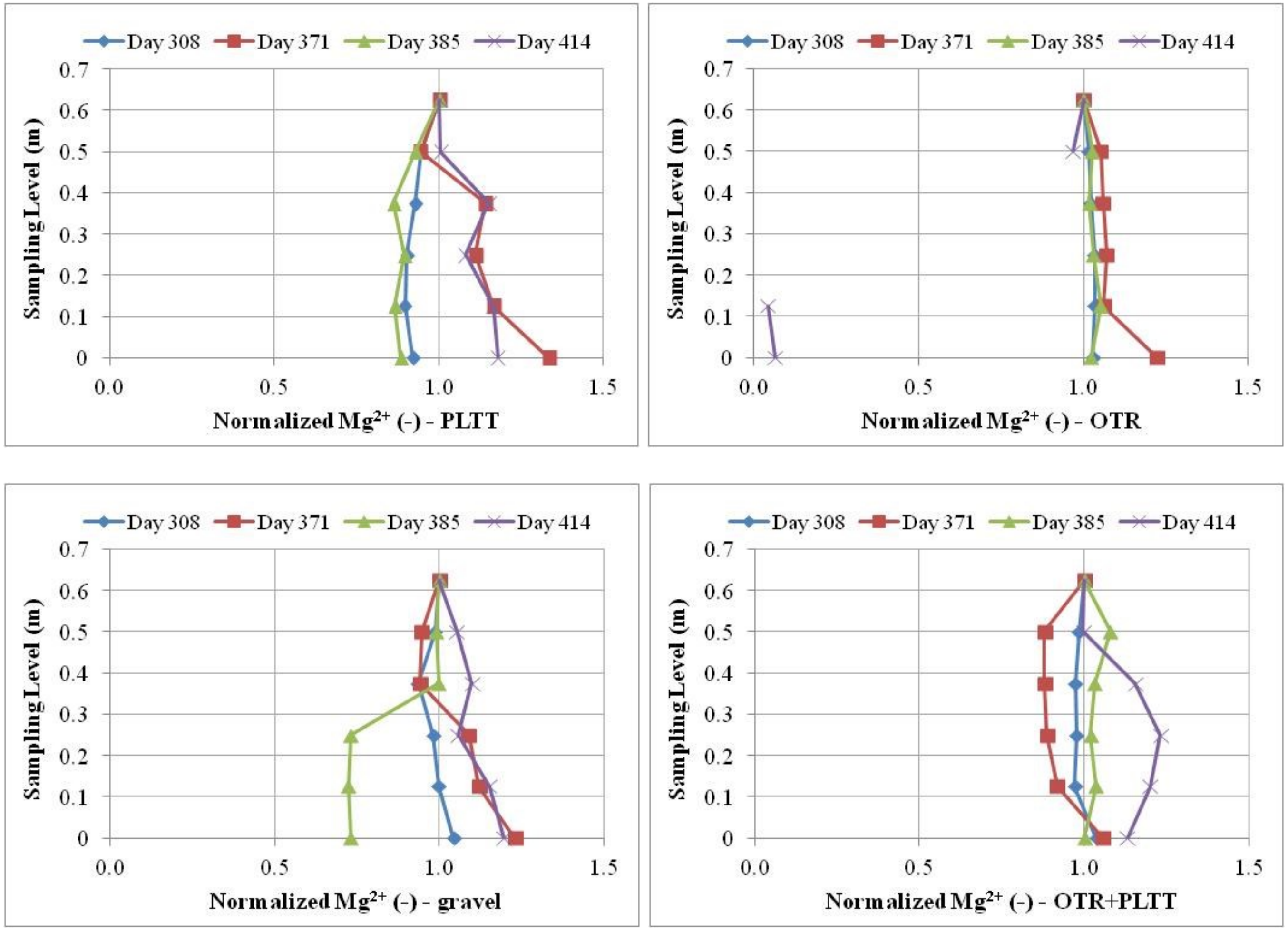


Figure 4-25. Temporal variations in normalized magnesium concentrations as the leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns on days 308, 371, 385 and 414.

4.3.5.3 Media Performance Based on Magnesium Results

There were no significant differences among the various media types. In addition, the near-vertical profiles shown in Figure 4-25, together with the observed low composition of magnesium in field clog materials as reported by Fleming et al. (1999), seem to show that magnesium would not pose a problem to the long-term performance of either TDA- or gravel-based LCDS.

4.3.6 Drainable Porosity

Drainable porosity is a measure of available pore space. The accumulation of biological materials and inorganic solids within the pore space of a drainage medium leads to clogging, which reduces both porosity and the interconnectivity of pore spaces (Fleming and Rowe 2004). Therefore, the decrease in drainable porosity indicated the extent of clogging within the drainage media.

4.3.6.1 Drainable Porosity – Day 168

The loss in drainable porosity by day 168 is shown in Figure 4-26, as a percentage of the initial porosity of approximately 0.4. For the TDA products, losses were greatest near the middle of the column. Gravel showed a more uniform loss in drainable porosity of between 4 and 6% at all sampling points. This uniformity may be associated with the uniform size and shape of the gravel used.

A one-way ANOVA showed there was a significant difference in drainable porosity among the columns with $p < 0.05$ level [$F(3, 15) = 5.253$, $p = 0.011$]. A multiple comparison of the means showed that the significant difference was associated with the OTR+PLTT and gravel columns. The drainable porosity test at the end of the tests, day

427, provided more information on long-term porosity loss as discussed in the following section.

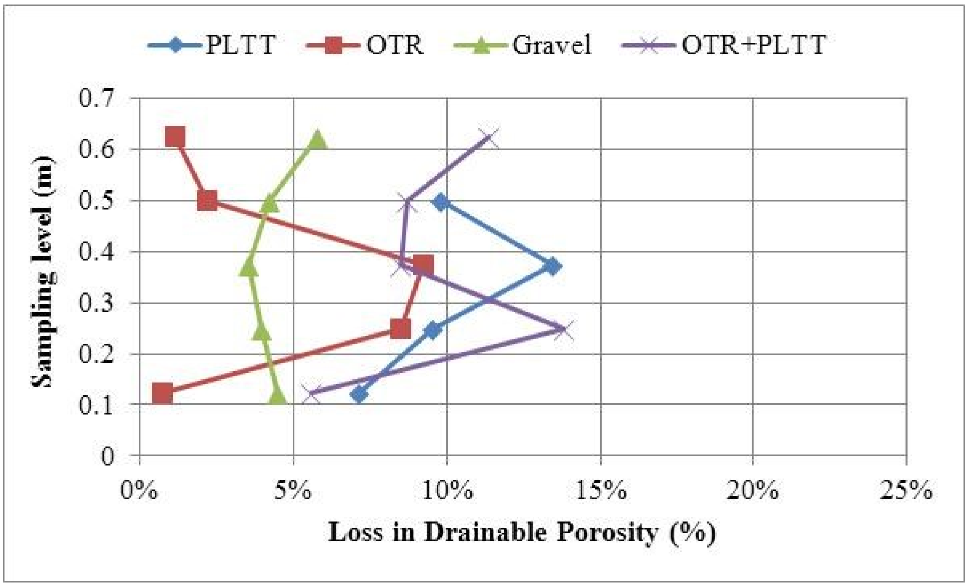


Figure 4-26. Loss in drainable porosity as determined in each of the media columns on day 168. The percentage loss in porosity was determined by dividing the drainable porosity in each segment of the column on day 168 by the initial drainable porosity (≈ 0.4) in each of the columns and subtracting from 100%.

4.3.6.2 Drainable Porosity – Day 427

Drainable porosity measurements were carried out on day 427 to determine the decrease in void volume at the end of the tests. Loss in drainable porosity relative to initial porosity is shown in Figure 4-27. Detailed data are shown in Appendix C4, Table C4-1. All media types exhibited decreasing drainable porosity (Table 4-6), a phenomenon associated with build-up of clog materials with time. In general, the porosity loss was lower at the bottom of the three TDA columns than at the top and/or in the middle. The location of greatest porosity loss varied among medium types (Figure 4-27).

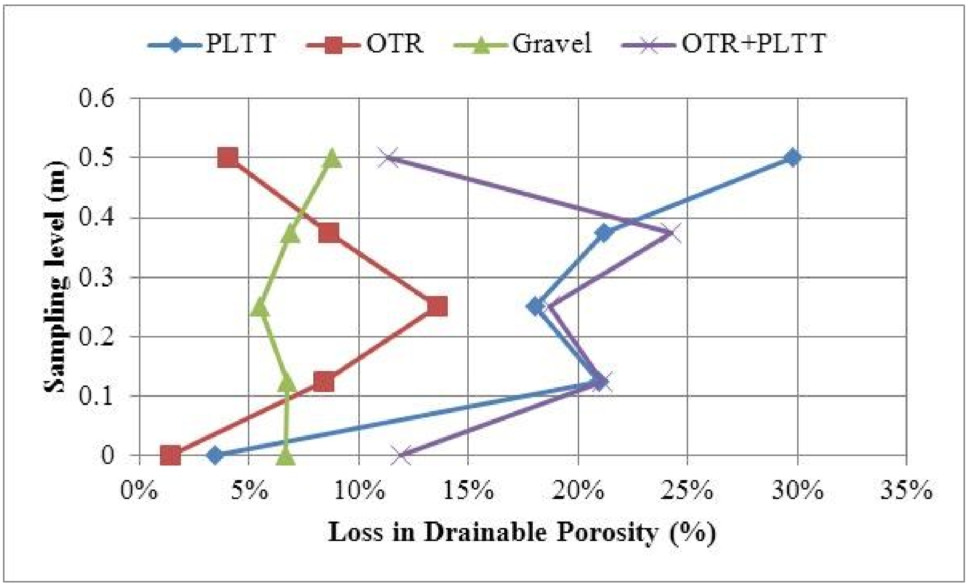


Figure 4-27. Drainable porosity losses in PLTT, OTR, gravel and OTR+PLTT columns by day 427, as a percentage of the initial drainable porosity of about 0.4.

The gravel column showed a relatively uniform loss of porosity with depth, compared to TDA (Figure 4-27). The result may be explained by the observation made by Rowe and Babcock (2007) that tire shreds are characterized by more variable void structure than gravel and therefore tend to have higher dispersivity; a value of 45 mm was reported for clean tire shreds compared to 4 mm for clean gravel, these values increase as clogging progresses. Dispersion affects clogging, as it influences the distribution of clog particles within the drainage media; high dispersivity at the top of the drainage layer could result in more clog particles being dispersed to the lower layers.

Table 4-6. Average loss in drainable porosity in different media columns, compared to initial porosities, after leachate was run through the columns between 168 and 427 days.

Drainage media	Loss in drainable porosity (%)	
	Day 168	Day 427
PLTT	10.0	18.7
OTR	4.4	7.2
Gravel	4.8	6.9
OTR+PLTT	9.6	17.5

An ANOVA showed that there was a significant difference among the four media types [F (3, 16) = 5.510, p = 0.009]. A multiple comparison revealed that the differences were between gravel and PLTT, gravel and OTR+PLTT, PLTT and OTR, and OTR+PLTT and OTR. Significant differences could not be detected between: 1) gravel and OTR; or 2) PLTT and OTR+PLTT.

4.3.6.3 Drainable Porosity after Column Flushing

Drainable porosities (Table 4-7) were measured after flushing of the columns (Appendix C4, Table C4-2). The higher velocities used during hydraulic conductivity tests may have caused some clog material get flushed out of the columns.

A comparison between drainable porosity at the end of clogging tests and drainable porosity after flushing of the columns showed that porosity increased slightly in all columns. Because the differences in all columns were small, it is possible that: i) the clog particles tended to attach strongly to the media; ii) the particles were physically trapped in the media; and/or iii) the particles had a high density so that they could not suspend readily for wash-out.

Table 4-7. Comparison between drainable porosity at the end of clogging tests and drainable porosity after column flushing. Values presented are averages for the whole column.

Drainage Media	Initial drainable porosity (-)	Drainable porosity at end of clogging tests (-)	Drainable porosity after media flushing (-)	Difference in porosity before and after flushing (%)	Porosity loss from initial after flushing (%)
PLTT	0.447	0.363	0.386	6.3	13.6
OTR	0.410	0.380	0.387	1.8	5.6
Gravel	0.393	0.366	0.367	0.3	6.6
OTR+PLTT	0.435	0.359	0.370	3.1	14.9

4.3.6.4 Media Performance Based on Drainable Porosity Results

OTR and gravel had similar drainable porosity as PLTT and OTR+PLTT (Figure 4-26 and 4-27). PLTT and OTR+PLTT contained flat-shaped particles; OTR was block shaped while gravel comprised of rounded particles. Therefore OTR and gravel would have more uniformly-shaped and sized void spaces, which may allow clog particles pass out of the media easily, thereby clogging less compared to PLTT and OTR+PLTT. Rowe and Babcock (2007) made similar observations for tire shreds and gravel, and concluded that uniform void spaces result in less tortuous flow paths, fewer small-sized voids, and reduced constrictions between pores. The result is more uniform clogging profiles. Conversely, the combined effect of flat and non-uniform shape and size of PLTT particles may result in more pronounced tortuous flow paths that enhance clogging. These observations are consistent with the findings of McIsaac and Rowe (2005) that tire shreds columns experienced greater porosity losses than gravel columns. McIsaac and Rowe (2005) also argued that gravel is likely to have a longer service life than tire shreds, and therefore a more effective drainage system.

Even after the end of experiments, it was still not possible to achieve appreciable head differences from piezometric measurements. This is in contrast with findings of McIsaac and Rowe (2005) that all columns clogged to levels that allowed piezometric measurements. Possible reasons for the differences between the two studies were: 1) higher loading rates of Ca^{2+} and COD in the McIsaac and Rowe (2005) study due to spiking of raw leachates with nutrients; 2) higher leachate flow rates in the McIsaac and Rowe (2005) study (0.4 $m^3 \cdot m^{-2} \cdot d^{-1}$ vs. 0.038 $m^3 \cdot m^{-2} \cdot d^{-1}$); and 3) lower initial porosities in the tire shred media (0.22 to 0.25) in McIsaac and Rowe's (2005) study than in their gravel (0.45) or in the current study (close to 0.4). Loss in drainable porosity in TDA may arise from media compression (Beaven et al., 2006; Wartman et al., 2007). Therefore, a combined effect of media compression and clog development, especially if the clog material is compacted in the process, could be the most limiting operating condition for the hydraulic performance of TDA-based LCDS.

4.3.7 Hydraulic Conductivity

4.3.7.1 Hydraulic Conductivity of the Clogged Media – Day 427

The hydraulic conductivities were determined just before disassembly of the apparatus. To observe piezometric head losses, the velocity of the water was increased from the 7.4×10^{-5} $m \cdot s^{-1}$ used for the leachate parameters tests to 0.09 - 0.016, 0.013 - 0.015, 0.015 - 0.018 and 0.003 - 0.006 $m \cdot s^{-1}$ for PLTT, OTR, gravel, and OTR+PLTT, respectively. The measured hydraulic conductivities (K) are shown in Table 4-8. Also shown are the values of the predicted hydraulic conductivity.

Table 4-8. Measured and predicted hydraulic conductivity (K) values for TDA and gravel drainage media at the end of the clogging experiment.

Media	Measured K ($m\cdot s^{-1}$)	Porosity after flushing, ε	A	c	Initial K ($m\cdot s^{-1}$)	Predicted K ($m\cdot s^{-1}$) ($K_p = A\varepsilon^c$)
PLTT	0.06	0.386	0.487	1.79	0.07	0.09
OTR	0.20	0.387	1.328	2.056	0.22	0.19
Gravel	0.07	0.365	-	-	0.09	-
OTR+PLTT	0.11	0.370	1.559	3.159	0.17	0.07

The measured hydraulic conductivity after flushing was lowest for PLTT and gravel, and highest for OTR. A one-way ANOVA did not show a significant difference between initial and measured hydraulic conductivities with $p < 0.05$ [$F(1,6) = 0.33$, $p = 0.58$].

Drainable porosity values after flushing (Table 4-7) were used to predict the hydraulic conductivity (K_p) of the clogged media ($m\cdot s^{-1}$), assuming power law relationships established during initial hydraulic conductivity tests (Chapter 3). The rationale was to check if the power relationships were valid, even where the media contained clog particles as opposed to clean media used during the initial hydraulic conductivity tests. In the case of TDA, the power relationships were of the form:

$$K_y = A\varepsilon^c$$

[4-5] where A and c were constants established for each media, and ε is the drainable porosity. For ease of reference, the values of A and c are reproduced in Table 4-8. As shown in the table, the measured and the predicted K values in the three TDA columns were close. Also, a one-way ANOVA did not also show a significant difference between initial, measured and predicted hydraulic conductivities with $p > 0.05$ [$F(2, 8) = 0.23$, $p = 0.80$]. The small differences noted may be due to the low levels of clogging

observed in the columns and also due to the variability generally associated with hydraulic conductivity measurements.

High hydraulic conductivities are desirable for LCDS operation. All of the values measured in this study were at least three orders of magnitude greater than the level of 10^{-5} $m \cdot s^{-1}$ proposed by McIsaac (2007) as the beginning of significant clogging. If flow had continued, the degree of clogging would have increased. Nevertheless, the leachates applied in this study had already passed through a LCDS and may not be representative of what actually enters the drainage layer in a landfill, (Fleming et al., 1999). Further complications may have been caused by reactions and settling of the particles in the storage tank and within the feed lines. In general, much strong leachates could have been used in the current experiments, but as noted by Hudson et al. (2009), higher strength leachates, combined with long durations for leachate flow, would accelerate the rate of clogging and probably give false alarm on susceptibility of a medium to clog. Therefore, there may be need to establish appropriate spiking levels for leachates to be consistent with field characteristics.

4.3.8 Clog Material

4.3.8.1 Observations of the Clog Mud

A visual examination of the quality and amount of clog mud was made after disassembly of the test columns. Photographs showing disassembly of the PLTT column are shown in Figure 4-28 and in Appendix C7. More clog material was observed in PLTT and OTR+PLTT as compared to OTR and gravel. There appeared to be more buildup at the influent than at the effluent ends. This result was consistent with the findings of VanGulck and Rowe (2004). However, for this study, columns were flushed with water under very high pressure prior to column disassembly. This may have caused the movement of the particles to the upper part of the columns.

Figure 4-28. Visual examination of clogging in the PLTT column: a) top of the media, b) middle of the media and c) bottom of the media.

A blackish slime was observed at the bottom compartment of each column indicating microbial growth (e.g. Fleming et al. (1999). Strong odours were not noticed during leachate sampling sessions or during column disassembly, as may be expected with high strength wastewaters. The result reinforces the notion that the leachates applied in this study were generally stable against microbial degradation and, therefore, at methanogenic stage.

4.3.8.2 Mineral Phases in the Clog Mud

Mineral phases forming the clog mud were determined by X-ray diffraction (XRD) analysis. (Appendix C6, Table 4-9). The quantities of various mineral phases were not differentiated in the current experiments and, therefore, the relative performance of media for the different mineral phases could not be quantified. However, the influent and middle sections of the columns tended to contain more mineral species than the effluent sections. Similar to having more clog material at the influent ends, presence of more mineral species is consistent with filtration and/or physical straining of particles in a porous media (Rowe and Babcock, 2007).

The most common mineral phases in all of the TDA and gravel columns were magnesium-based calcite ($Mg_{0.1}Ca_{0.9}$) (CO_3), and quartz (SiO_2); these minerals were observed at the top, the middle and bottom of all four columns. Calcite ($CaCO_3$) and quartz were also observed in the suspended solids removed during hydraulic conductivity tests prior to disassembly of the columns. The occurrence of quartz could be explained by the fact that it is a common constituent of most soils and rocks and that it is highly resistant to weathering (Konhauser 2007). Its presence is attributed to dirt or cover soils usually applied in sanitary landfills.

In addition to calcite, aragonite ($CaCO_3$) was observed in the upper to middle zones of PLTT and OTR+PLTT columns. It had similar properties to its polymorph calcite (Tucker and Wright 1990).

Table 4-9. Mineral phases forming the clog cake and suspended solids (removed during column flushing), as determined by XRD analysis.

Media	Location	Mineral Phases	
PLTT	Influent	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$; Quartz - SiO_2; Goethite - FeO(OH); Aroganite - $CaCO_3$;	Lepidocrocite - FeO_3H_2O; Bassanite - $CaSO_40.67H_2O$; Siderite - $FeCO_3$; Muscovite - $KMgAl(Si_4O_{10}(OH)_2$
	Middle	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$; Quartz - SiO_2; Goethite - FeO(OH); Aroganite - $CaCO_3$;	Lepidocrocite - FeO_3H_2O; Bassanite - $CaSO_40.67H_2O$; Illite-2M2 - $KAl_2(Si_3Al)O_{10}(OH)_2$
	Effluent	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Quartz - SiO_2
	Flushed solids	Quartz - SiO_2;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$
OTR	Influent	Quartz - SiO_2; Calcite, magnesian - $(Ca,Mg)CO_3$; Goethite - FeO(OH); Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$;	Aroganite - $CaCO_3$; Bassanite - $CaSO_40.67H_2O$; Lepidocrocite- FeO_3H_2O
	Middle	Quartz, - SiO_2; Calcite, magnesian - $(Ca,Mg)CO_3$; Quartz - SiO_2; Goethite - FeO(OH);	Lepidocrocite - FeO_3H_2O; Siderite - $FeCO_3$; Arrojadite - $Na_3Ba(CaSr)(Fe,Mg)_{14}Al(PO_4)_{12}(OH)_2$
	Effluent	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$; Quartz - SiO_2;	Arrojadite - $Na_3Ba(CaSr)(Fe,Mg)_{14}Al(PO_4)_{12}(OH)_2$
	Flushed solids	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Quartz - SiO_2
Gravel	Influent	Quartz - SiO_2; Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$; Bassanite - $CaSO_40.67H_2O$
	Middle	Quartz - SiO_2; Calcite, magnesian - $(Ca,Mg)CO_3$;	Arrojadite - $Na_3Ba(CaSr)(Fe,Mg)_{14}Al(PO_4)_{12}(OH)_2$
	Effluent	Quartz - SiO_2; Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$
	Flushed solids	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$; Silicon Oxide-Alpha - SiO_2;	Magnesium Oxide - $Mg_3O(CO_3)_2$
OTR+ PLTT	Influent	Quartz - SiO_2; Calcite, magnesian - $(Ca,Mg)CO_3$;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$; Aroganite - $CaCO_3$
	Middle	Quartz - SiO_2; Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$; Aroganite - $CaCO_3$
	Effluent	Quartz - SiO_2; Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Ferrihydrite - $Fe_{9.56}O_{14}(OH)_2$
	Flushed solids	Calcite, magnesian - $Mg_{0.1}Ca_{0.9}CO_3$;	Quartz - SiO_2

The formation of calcite and aragonite indicated either: i) propensity of calcium carbonate to precipitate when TDA and gravel media is permeated with landfill leachates; or ii) interception and build-up of carbonate-based precipitates previously suspended in the landfill leachates into clog mud. Various researchers (e.g. Konhauser 2007; Cardoso et al. 2006; McIsaac and Rowe 2005) have found that carbonate-based precipitates are the main contributors to clogging in LCDS.

The other mineral phases identified in the clog material were largely iron-based. In the PLTT and OTR columns, the influent ends contained goethite ($FeO(OH)$), lepidocrocite (FeO_3H_2O) and ferrihydrite ($Fe_{9.56}O_{14}(OH)_2$), which are all largely associated with iron oxidation (Konhauser 2007). While the presence of these mineral phases could be attributed to exposed steel wires in TDA, the fact that they were oxidized suggests they are less likely to pose a major problem because LCDS are largely characterised by anaerobic conditions.

The presence of arrojadite ($Na_3Ba(CaSr)(Fe,Mg)_{14}Al(PO_4)_{12}(OH)_2$) can be explained by the relative abundance of Na^+ observed in the leachates (see Appendix C2). However, despite the abundance of sodium, arrojadite was only detected in the middle of the OTR and gravel columns. The absence of this compound at the majority of sampling points could be explained by the fact that Na^+ precipitates are only expected after Ca^{2+}, Fe^{2+} and Mg^{2+} are depleted (Tucker and Wright 1990). This could also explain the presence of non-Na-based clays, such as illite and muscovite, detected in the PLTT column. These clays are non-swelling and, therefore, do not affect the hydraulic conductivity of the clog material as would Na-based clays (McBride 1994).

4.3.9 Chemical Stability of TDA Materials

The XRD profiles showed little evidence of mineralization of the TDA, as zinc, a key ingredient of rubber tire (1-2% by weight), was not detected in the clog muds. Aluminum was detected in some locations of the PLTT and OTR columns, but not in the OTR+PLTT column. It was not determined if this aluminum came from the TDA or was in the influent leachate, as leachate aluminum levels were not tested. Iron was detected in clog mud from all of the columns, including gravel, in the form of lepidocrocite, goethite, siderite, ferrihydrite, and/or arrojadite. Unfortunately, the XRD analysis alone does not allow a comparison of the relative quantities of mineral species in different columns. However, the fact that iron was detected in the gravel columns indicates that at least some of the iron came from the leachate itself, rather than solely from the steel wires in the TDA. Based on this observation and the absence of zinc (Table 4-9), the degradation or decomposition of the TDA was not detected under the current experimental conditions. However further tests are required to investigate chemical and structural integrity of TDA materials at low and high pH values.

4.4 Practical Implications of the Clogging Study on the Long-Term Performance of TDA as Media for LCDS

The overall objective of the current study was to evaluate the performance of TDA processed in Alberta, Canada as media for leachate collection and drainage. The design of the columns and the overall experimental set-up were such as to mimic a saturated section within LCDS. The analytical procedures adopted aimed at evaluating behavior of pH, drainable porosity and hydraulic conductivity and leachate species COD, TSS, calcium, magnesium that may indicate leachate characteristics and by extension, potential for clogging. Also investigated were the mineral phases that formed in the respective columns. For practical purposes, gravel media, which has traditionally been used as the drainage media in LCDS, was used as control. The practical implications of the study findings are discussed below, with respect to the limitations of the study and relative media performances.

4.4.1 Limitations of the Clogging Study

Table 4-10 gives a summary of influent concentrations of various leachate parameters, in comparison with Alberta's leachate characteristics. It is shown that column influent TSS and Ca^{2+} concentrations used in the current study were lower than Alberta's average or median values (Table 4.10). While the concentrations of these parameters may be representative of leachates in some landfills at some period of their life cycles (Chapter 2, Table 2-5), they do not represent average conditions in Alberta. Therefore, they are likely to underestimate potential of LCDS to clog.

Table 4-10. Comparison between key clogging parameters in leachate influent to the columns in this study and in 12 Alberta Class II municipal solid waste landfills.

Parameter	Column influent in current study		Alberta MSW landfills			
	Min	Max	Mean	Median	Min	Max
pH	7.8	8.7	7.5	7.4	1.9	13.0
COD ($mg \cdot L^{-1}$)	1,537	3,823	5,958	4,000	10	83,000
TSS ($mg \cdot L^{-1}$)	10	308 ‡	1743	675	3	21,940
Ca^{2+} ($mg \cdot L^{-1}$)	9.1	33.4	522	277	0.03	3,810
Mg^{2+} ($mg \cdot L^{-1}$)	24.6	354	378	215	0.05	7,170

‡ Most influent TSS measurements were under 100 $mg \cdot L^{-1}$.

It was observed that leachates applied in this study had reached methanogenic stage. However, clogging processes are expected to commence during acetogenic phase and proceed through methanogenic phase. The leachates had also passed through LCDS, implying that some pre-treatment had already taken place. Therefore, it is highly likely that clogging levels observed were lower than would actually happen in the field. The study by Rowe and McIsaac (2005) used spiked leachates to account for this effect. However, application of spiked leachates may also lead to uncertainties because addition of nutrients may enhance biological and chemical components of clogging, which would not be expected under filed conditions. The concentration of key leachates species at the interface of the waste and the LCDS before entry into the LCDS is not yet known. Consequently, it is not possible to establish appropriate spiking levels for adoption in laboratory studies for simulation of field clogging.

Leachates characteristics notwithstanding, there were aspects of the experimental set-up and operations that were not initially foreseen but may have influenced the outcome of the current study adversely. These aspects are discussed as follows.

1. Clogging was observed to occur within the feed line that connected the leachate storage tank to the test columns. The clogging may explain why COD concentrations at the storage tank outlet (To) were higher than those entering the columns. A similar observation was made for TSS whereby concentrations leaving the storage tank and those at the pumps level (0.75) were much higher than those in the column influents (Appendix C, Table C1-4 and C2-5). Settling of suspended solids in the flow lines was assumed to take place. At the time of column disassembly, it was observed that the top steel plate had accumulated substantial amounts of solids. These solids may have acted as a source of solids as the study progressed and/or sink of other leachate species such as COD and calcium. It is important that these sources of errors and uncertainties are addressed in future studies. In particular, the top steel plate should not be in contact with tire shreds, because their flat shape tends to block plate perforations.
2. In this study, an inline heater was placed at the beginning of the feed line close to the leachate storage tank to raise the temperature of the leachate

from 7 to 20°C. The arrangement was designed to achieve conditions similar to those in the field. However, the heat from the heater combined with the relatively low flow rates may have enhanced biogeochemical reactions within the feed lines, thereby causing clogging in the pipes. Consequently, it may be beneficial to place the inline heater just before the drainage media.

3. The pumping units were placed serially along the leachate feed line. Due to the low flow rates, it was possible that the characteristics leachates varied along the feed line because of clogging. It would be more prudent to place the pipes feeding the columns from the storage tank in parallel to ensure more uniform influent characteristics. An additional measure may include adopting flow conduits that allow higher velocities to minimize deposition of particulate matter. The pumps could also be avoided by installing a gravity flow system.
4. Leachates were stored in leachate holding tank for periods of about three months. Although temperatures were kept at about 7°C and the leachate stirred constantly, it was observed at the time of disassembly that the solids had settled at the bottom of the tank. The observation implied that in addition to settlement of solids, biogeochemical reactions may have taken place within the tank, thereby lowering the concentration of leachates reaching the columns. It is important that leachates are stored for much shorter periods to minimize both settling and biochemical reactions.

4.4.2 Comparison of media performances

The limitations of the experiment notwithstanding, it was possible to compare performances of different media types, considering that the limitations discussed above affected all the columns in a similar manner. However, to minimize issues associated with storage tanks, feed lines and pumping units, the media comparisons were based on normalized data. Table 4-11 gives a summary of these comparisons based on one-way ANOVA conducted for various parameters as observed for the period between 167 and 420 days (when the operations of the columns was considered more consistent than for the period between 0 and 167 days).

Table 4-11. Performance of the drainage media based on ANOVA. The parameters shown are those associated with significant differences with $p < 0.05$ and as discussed in section 4.3 (pH, COD, TSS, Ca^{2+} and drainable porosity).

	PLTT	**OTR**	**Gravel**	**OTR+PLTT**
PLTT		TSS Porosity	COD Ca^{2+} TSS Porosity	
OTR	TSS Porosity		COD	TSS Porosity
Gravel	COD TSS Ca^{2+} Porosity	COD		COD TSS Porosity
OTR+PLTT		TSS Porosity	COD TSS Porosity	

The most frequent differences occurred between gravel and PLTT (COD, TSS, Ca^{2+} and porosity), followed by gravel and OTR+PLTT (COD, TSS and porosity). The differences between OTR and PLTT, and OTR and OTR+PLTT were on TSS and porosity, while the difference between OTR and gravel was on COD levels only. The lack of significant differences between PLTT and OTR+PLTT suggests that no substantial improvement would be made by mixing OTR and PLTT on a 50:50 basis. Furthermore, significant differences on TSS and drainable porosity occurring between OTR and PLTT, and OTR and OTR+PLTT were similar (Table 4-11).

Considering that OTR had higher hydraulic conductivity than PLTT (Table 4-8), it is possible the performance of TDA-based LCDS may be improved if PLTT and OTR were placed in different horizontal sections or composite construction. Though testing of this hypothesis is required, OTR could be placed towards the lower end of leachate collection system where high leachate mounds are expected.

No significant difference in drainable porosity was detected between gravel and OTR. However, COD was significantly different between gravel and each of the TDA columns, suggesting that biological clogging may affect these media differently. The consumption of COD in the gravel column was much lower compared to the inlet levels, and also more uniform compared to TDA media. This finding implies an environment less favorable for microbial growth, for gravel and, therefore, lower tendency for gravel media to clog.

Table 4-11 also shows that TSS occurred together with high drainage porosity in cases with significant differences. Considering that drainable porosity is a more direct indicator of media clogging, this correspondence implies that suspended solids may have been the main contributor of clogging. Therefore, for clogging caused by deposition of solids, OTR media would perform similar to gravel; PLTT and OTR+PLTT would perform similarly, but different from gravel and OTR.

It was not established how the differences between the surface chemistry of TDA and gravel may affect clogging behavior. However, because pH, the master indicator of prevailing geochemical processes, did not show significant difference in any of the media types implies that the surface chemistry associated with rubber may not play a major role in the clogging processes.

References

Alberta Environment (2010). Standards for Landfills in Alberta. Government of Alberta. Alberta, Canada.

ASTM (1998). Standard practice for use of scrap tires in civil engineering applications. West Conshohocken, ASTM International.

Aydilek, A. H., Madden, E. T. and Demirkan, M. M. (2006). Field Evaluation of a Leachate Collection System Constructed with Scrap Tires. *Journal of Geotechnical and Geoenvironmental engineering* **132:** 990-1000.

Beaven, R. P., Powrie, W., Hudson, A. P. and Parkes, D. J. (2006). Compressibility of tyres for use in landfill drainage systems. *Waste and Resource Management* **159:** 173-180.

Brovelli, A., Malaguerra, F. and Barry, D. A. (2009). Bioclogging in porous media: Model development and sensitivity to initial conditions. *Environmental Modelling & Software* **24:** 611-626.

Chu, L. M., Cheung, K. C. and Wong, M. H. (1994). Variations in the Chemical Landfill Leachate. *Environmental Management* **18:** 105-117.

Cooke, A. J. and Rowe, R. K. (2008). 2D modelling of clogging in landfill leachate collection systems. *Canadian Geotechnical Journal* **45:** 1393-1409.

Cooke, A. J., Rowe, R. K., Rittimann, B. E., et al. (2001). Biofilm growth and mineral precipitation in synthetic leachate columns. *Journal of Geotechnical and Geoenviornmental Engineering* **127:** 849-856.

Cooke, A. J., Rowe, R. K. and Rittmann, B. E. (2005). Modelling species fate and porous media effects for landfill leachate flow. *Canadian Geotechnical Journal* **42:** 116-1132.

Cooke, A. J., Rowe, R. K., Rittmann, B. E. and Fleming, I. R. (1999). Modeling Biochemically Driven Mineral Precipitation in Anaerobic Films. *Water Science Technology* **39:** 57-64.

Cooke, A. J., Rowe, R. K., Rittmann, B. E., et al. (2001). Biofilm growth and mineral precipitation in synthetic leachate columns. *Journal of Geotechnical and Geoenvironmental Engineering* **127:** 849-856.

Cooke, A. J., Rowe, R. K., Rittmann, B. E., et al. (2001). Biofilm growth and mineral precipitation in synthetic leachate columns. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* **127:** 849-856.

Cozzarelli, I. M., B¨ohlke, J. K., Masoner, J., et al. (2011). Biogeochemical Evolution of a Landfill Leachate Plume, Norman, Oklahoma. *GROUND WATER* **49:** 663-687.

EWMCE (2009). Implications of Using Tire Derived Aggregate for Landfill Leachate Collection Systems – Literature Review. Edmonton, Alberta Recycling Management Authority (ARMA).

Fleming, I., Rowe, R. and Cullimore, D. (1999). Field observations of clogging in a landfill leachate collection systems. *Canadian Goetechnical Journal* **36:** 685-707.

Fleming, I. and Rowe, R. K. (2004). Laboratory studies of clogging of landfill leachate collection and drainage systems. *Canadian Goetechnical Journal* **41:** 134-153.

Hudson, A. P., Beaven, R. P., K.Knox and Powrie, W. (2009) Investigation of the clogging of Landfill tyre drainage layers. Twelfth International Waste Management and Landfill Symposium. S. Margherita di Pula, Cagliari, Italy, CISA Publisher.

Hudson, A. P., Beaven, R. P., Powrie, W., et al. (2008) Clogging potential of methanogenic leachate on tyre and aggregate drainage layers. In Proceedings Waste 2008: Waste and Resource Management- a shared responsibility. Stratford-upon-Avon, Warwickshire, England, pp. 16-17.

Hudson, A. P., Beaven, R. P., Powrie, W. and Parkes, D. (2007). Hydraulic conductivity of tyres in landfill drainage systems. *Waste and Resource Management* **160:** 63-70.

Koerner, G. R. and Koerner, G. R. (2004). Leachate clogging assessment of geotextile and soil landfill filters. Cincinnati, Ohio, Geosynthetic Research Institute, Drexel University.

Manning, D. A. C. (2000). Carbonates and oxalates in sediments and landfill: monitors of death and decay in natural and artificial systems. *Journal of the Geological Society, London* **157:** 229-238.

McIsaac, R. and Rowe, R. K. (2005). Change in leachate chemistry and porosity as leachate permeates through tire shreds and gravel. *Canadian Goetechnical Journal* **42:** 1173-1188.

McIssac, R. S. (2007). An Experimental Investigation of Clogging in Landfill Leachate Collection Systems. Department of Civil and Environmental Engineering The University of Western Ontario, Canada. **PhD**.

Meles, D., Bayat, A. and Soleymani, H. (2013). Compression Behaviour of Large-Sized Tire-Derived Aggregate for Embankment Application. *Journal of Materials in Civil Engineering* **25:** 1285-1290.

Mostafa, M. and Van Geel, P. J. (2007). Conceptual Models and Simulations for Biological Clogging in Unsaturated Soils. *Vadose Zone Journal* **6:** 175-185.

Qian, X., Gray, D. H. and Koerner, R. M. (2004). Estimation of Maximum Liquid Head over Landfill Barriers *Journal of Geotechnical and Geoenviornmental Engineering* **130:** 488-497.

Reinhart, D. R., McCreanor, P. T., Townsend, T. G. and Craven, W. J. (1998). Assessment of Leachate Collection System Clogging at Florida Municipal Solid Waste Landfills, Florida Center for Solid and Hazardous Waste Management, Gainesville, FL

Rowe, K. R., Armstrong, M. D. and Cullimore, D. R. (2000). Particle size and clogging of granular media permeated with leachate. *Journal of Geotechnical and Geoenvironmental Engineering* **126:** 775-786.

Rowe, K. R. and Babcock, D. (2007). Modelling the clogging of coarse gravel and tire shreds in column tests. *Canadian Goetechnical Journal* **44:** 1273-1285.

Rowe, R. K. (2005). Long-term performance of contaminant barrier systems. *Geotechnique* **55:** 631-678.

VanGulck, J. F. and Rowe, R. K. (2004). Evolution of clog formation with time in columns permeated with synthetic landfill leachate. *Journal of Contaminant Hydrology* **75:** 115-139.

VanGulck, J. F. and Rowe, R. K. (2004). Influence of landfill leachate suspended solids on clog (biorock) formation. *Waste Management* **24:** 723-738.

VanGulck, J. F., Rowe, R. K., Ritmann, B. E. and Cooke, A. J. (2003). Predicting biogeochemical calcium precipitation in landfill leachate collection systems. *Biodegradation* **14:** 331-346.

Warith, M., Evgin, P., Benson, P. and Rao, S. (2005). Evaluation of permeability of tire shreds under vertical loading. *Journal of Testing and Evaluation* **33:** 1-4.

Warith, M. and Sudhakar, M. R. (2006). Predicting the compressibility behaviour of tire shred samples for landfill applications. *Waste Management* **26:** 268-276.

Wartman, J., Natale, M. F. and P. M. Strenk (2007). Immediate and Time-Dependent Compression of Tire Derived Aggregate. *Journal of Geotechnical and Geoenvironmental Engineering* **133:** 245-256.

5 Conclusions and Recommendations

The objective of the current study was to evaluate the performance of TDA when used as media for leachate collection and drainage systems. Emphasis was placed on three aspects that were considered critical for the long-term performance of LCDS; namely, (i) composition and strength of landfill leachates, (ii) physical and mechanical properties of TDA, and (iii) clogging phenomenon. Based on the results and discussions presented in various sections, the following conclusions are drawn.

5.1 Composition and Strength of Leachates in Alberta Landfills and Its Implications on Performance of LCDS

Characteristics of leachates from municipal and industrial landfills in Alberta were examined based on parameters commonly associated with clogging phenomenon. A total of 12 Class II municipal and 10 industrial landfills, were studied. Leachates from Class II municipal landfill showed higher concentrations of COD and TSS compared to industrial landfills. Because COD and TSS are commonly associated with clogging, it was concluded that municipal landfills were more susceptible to clogging than industrial landfills. Out of 12 municipal sanitary landfills studied, 10 exhibited pH values of between 6.6 and 7.5 implying that they were relatively young landfills and most likely transiting from acetogenic to methanogenic phases. Such landfills may be undergoing active clogging processes. All leachate species studied showed high variability, not only across different jurisdictions but also within sanitary landfill themselves. Based on the observations, it was recommended that interpretation of leachate characterisation data takes account of site specific issues such as climate, hydrogeology and type of landfill.

This study did not show clear correlations between rainfall amounts and concentration of COD, TSS and Ca^{2+} contrary to the expectation that high rainfall would have diluted the leachates. A qualitative assessment based on relative duration of acidogenic and methanogenic phases of a landfill, Alberta landfills were considered generally not susceptible to clogging. The following recommendations are made:

i) Spatial variability of the leachate characteristics could not be evaluated due to lack of site specific rainfall data. There is a need to conduct further investigations and obtain sufficient rainfall data to enable evaluation of spatial variability of leachate composition and characteristics.

ii) Since susceptibility of Alberta landfills to clogging was based on a preliminary and basic assessment, there is a need to conduct further studies and confirm that landfills in Alberta are not susceptible to clogging.

5.2 Characterization of TDA Processed in Alberta

Experimental data on particle size distribution, specific gravity, compressibility, porosity, and hydraulic conductivity was obtained for PLTT, MTT, OTR and OTR+PLTT. The four products had uniform particle size distributions. The specific gravities were lower than those of gravel, and therefore suitable for light-weight construction. Although OTR originates from tires used on heavy equipment, effects of media compression on porosity and hydraulic conductivity were not significantly different from those of PLTT, MTT, and OTR+PLTT. Additionally, no advantage, with respect to hydraulic conductivity, was achieved by mixing OTR and PLTT on 50:50 weight basis. Both PLTT and OTR were found to exhibit strains of between 40 and 50% at overburden pressures of about 150 kPa. The following recommendations are made:

i) Based on factors of safety of 1.5, it is recommended that the as-spread thickness of PLTT layer be 820-900 mm for landfills expected to reach 20 m height. In case of OTR, the as-spread thickness should be 740-805 mm for a 20 m landfill.

ii) The hydraulic conductivity tests did not take account of horizontal component; there is a need to conduct further tests to determine horizontal hydraulic conductivity of TDA materials processed in Alberta.

iii) The factors of safety were based on media clogging. However, there is a need to conduct field scale experiments to check if factors of safety based on clogging conditions also take of other field conditions such as measurement errors and differing loading conditions.

iv) It was hypothesised that a composite construction based on OTR and PLTT may be advantageous compared to mixing them on 50:50 weight basis. There a need to conduct further tests to test this hypothesis.

5.3 Long-term Clogging Tests

The main objective of the long-term clogging tests was to evaluate the clogging behavior of TDA when used as media for LCDS. The experimental set-up and process controls simulated saturated section of LCDS. Changes in chemistries for leachate species COD, TSS, calcium, and magnesium that are closely associated with clogging phenomenon were monitored for a period of 420 days. The following conclusions and recommendations were made:

i. Observed clogging levels were lower than those of the field which was attributed to use of leachates from an old landfill, which were, therefore, biologically stable. Additionally, the leachates had passed through LCDS and therefore received some pre-treatment which reduced their strength. Consequently, further studies that take into account the field strength of leachates of both acetogenic and methanogenic phases of landfill processes are required.

ii. There is need to review the experimental set-up and procedures that may influence the clogging tests; namely,

   a) Clogging of leachate within the feed pipes and retention of substantial amounts of solid matter at the top steel plate. Retained and released matter may have may have caused differences in COD, TSS, and calcium concentration of the leachates entering the drainage media. Further work should review the arrangement and size of leachate feed pipes and the scour velocities required to minimize clogging within the pipes.
   b) Positioning of the inline heater just before the leachates reach the drainage media to limit biogeochemical reactions in the chilling of leachates.
   c) Use of parallel piping and pumping from the holding tanks in place of serial arrangement to ensure uniform leachate characteristics in each of the columns.
   d) Leachates storage periods and appropriate storage temperatures in holding tanks that minimize both settlement and biogeochemical reactions

iii. No significant differences were observed between PLTT and OTR+PLTT; therefore, drainage efficiency of LCDS may not be improved by mixing OTR and PLTT on a 50:50 basis.

Appendix A

Landfills operating in Alberta

Table A1-1. Landfills in Alberta with active approvals. Only industrial, hazardous, and municpal landfills accepting more than 10,000 tonnes/yr were contacted for leachate data. Not all of the contacted landfills actually provided data.

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
18787	Grassy Lake/wmf/municipal landfill	Municipal District of Taber	4900B 50 ST	Taber	T1G 1T2	Municipal Sanitary Landfill	< 10,000 t/yr	II
18985	Taber/wmf/municipal landfill	Town of Taber	4900A 50 ST	Taber	T1G 1T1	Municipal Sanitary Landfill	< 10,000 t/yr	II
19150	Long Lake, regional /wmf/municipal landfill	Long Lake Regional Waste Management Services Commission	BOX 178	Grimshaw	T0H 1W0	Municipal Sanitary Landfill	< 10,000 t/yr	II
19769	Whitemud/wmf/ municipal landfill	Municipal District of Smoky River No. 130	BOX 210	Falher	T0H 1M0	Municipal Sanitary Landfill	< 10,000 t/yr	II
19884	Guy/wmf/municipal landfill	Municipal District of Smoky River No. 130	BOX 210	Falher	T0H 1M0	Municipal Sanitary Landfill	< 10,000 t/yr	II
19911	Jean Cote/wmf/municipal landfill	Municipal District of Smoky River No. 130	BOX 210	Falher	T0H 1M0	Municipal Sanitary Landfill	< 10,000 t/yr	II

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
20007	Falher/wmf/municipal landfill	Smoky River Regional Waste Management Commission	BOX 155	Falher	T0H 1M0	Municipal Sanitary Landfill	< 10,000 t/yr	II
20575	Conklin/wmf/municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	< 10,000 t/yr	II
20614	Craigend/wmf/municipal landfill	Lac La Biche County	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1. (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
20660	Fort MacKay/wmf/ municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	< 10,000 t/yr	II
20677	Grassland/wmf/municipal landfill	County of Athabasca No. 12	3602 48 AVE	Athabasca	T9S 1M8	Municipal Sanitary Landfill	< 10,000 t/yr	II
20708	Hylo/wmf/municipal landfill	Lac La Biche County	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
20713	Janvier/wmf/municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	< 10,000 t/yr	II
20774	Plamondon/wmf/ municipal landfill	Lac La Biche county	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
20943	Iron Creek/wmf/ municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
20969	High	Town of High Prairie	BOX 179	High Prairie	T0G 1E0	Municipal	< 10,000 t/yr	II

	prairie/wmf/municipal landfill					Sanitary Landfill		
46818	Sexsmith/wmf/municipal landfill	Town of Sexsmith	BOX 420	Sexsmith	T0H 3C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
47058	Elizabeth/wmf/municipal landfill, Metis	Elizabeth Metis Settlement	BOX 420	Cold Lake	T9M 1P1	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
47198	Ashmont/wmf/municipal landfill	County of St. Paul No. 19	5015 49 AVE	St. Paul	T0A 3A4	Municipal Sanitary Landfill	< 10,000 t/yr	II
47339	Boyle/wmf/municipal landfill, expansion	Village of Boyle	5010 3 ST	Boyle	T0A 0M0	Municipal Sanitary Landfill	< 10,000 t/yr	II
47354	Two Hills/wmf/municipal landfill, regional	County of Two Hills Regional Waste Management Commission	BOX 8	Two Hills	T0B 4K0	Municipal Sanitary Landfill	< 10,000 t/yr	II
47450	Lac Ste. Anne/wmf/ municipal landfill, Highway 43 East	Highway 43 East Waste Commission	BOX 219	Sangudo	T0E 2A0	Municipal Sanitary Landfill	< 10,000 t/yr	II
47596	Wandering River/wmf/ municipal landfill	County of Athabasca No. 12	3602 48 AVE	Athabasca	T9S 1M8	Municipal Sanitary Landfill	< 10,000 t/yr	II
47624	Bluffton/wmf/municipal landfill, NE 6	Ponoka County	4205 HIGHWAY 2A	Ponoka	T4J 1V9	Municipal Sanitary Landfill	< 10,000 t/yr	II

47716	Beaver Dam/wmf/ municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
47746	Muriel Lake/wmf/ municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
47784	Springbank/wmf/ municipal landfill	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
47785	Westlock/wmf/municipal landfill	Westlock County	10336 106 ST	Westlock	T7P 2G1	Municipal Sanitary Landfill	< 10,000 t/yr	II
47816	Athabasca/wmf/ municipal landfill, Lawrence Lake, regional	Athabasca Regional Waste Management Services Commission	4705-49 Avenue	Athabasca	T9S 1B7	Municipal Sanitary Landfill	< 10,000 t/yr	II
47833	Stettler/wmf/regional municipal landfill	Stettler Regional Waste Management Authority	BOX 1270	Stettler	T0C 2L0	Municipal Sanitary Landfill	< 10,000 t/yr	II
47860	Swan Hills/wmf/ municipal landfill	Town of Swan Hills	BOX 149	Swan Hills	T0G 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
48135	Peers/wmf/municipal landfill-reclassification (class III)	Yellowhead County	2716 1 AVE	Edson	T7E 1N9	Municipal Sanitary Landfill	< 10,000 t/yr	III (previously accepted MSW, currently accepts only inerts)

48276	Flagstaff/wmf/municipal landfill/regional	Flagstaff Regional Solid Waste Management Association	BOX 309	Sedgewick	T0B 4C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
48305	Bonnyville/wmf/ municipal landfill	Town of Bonnyville	BAG 1006	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
48329	Goodridge/wmf/ municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
48482	Mallaig/wmf/municipal landfill	Evergreen Regional Waste Management Services Commission	5015 49 AVE	St. Paul	T0A 3A4	Municipal Sanitary Landfill	< 10,000 t/yr	II
49898	Vegreville/wmf/ municipal landfill	Town of Vegreville	BOX 640	Vegreville	T9C 1R7	Municipal Sanitary Landfill	< 10,000 t/yr	II
49909	Lamont area/wmf/ municipal landfill, regional, St. Michael	Lamont County Regional Solid Waste Commission	BOX 556	Lamont	T0B 2R0	Municipal Sanitary Landfill	< 10,000 t/yr	II
49920	Rich Lake/wmf/ municipal landfill	Lac La Biche county	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
49932	Wainwright/wmf/ municipal landfill	Wainwright Regional Waste to Energy Authority	1018 2 AVE	Wainwright	T9W 1R1	Municipal Sanitary Landfill	< 10,000 t/yr	II
50079	Marianna Lakes/wmf/ municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	< 10,000 t/yr	II
50110	Claresholm/wmf/	Town of Claresholm	BOX 1000	Claresholm	T0L 0T0	Municipal	< 10,000 t/yr	II

	municipal landfill					Sanitary Landfill		
69992	Grande Prairie/wmf/ municipal landfill, West County	West Grande Prairie County Solid Waste Authority	8611 108 ST	Grande Prairie	T8V 4L5	Municipal Sanitary Landfill	< 10,000 t/yr	II
70567	Carstairs/wmf/municipal landfill, SE 13 - closure	Town of Carstairs	1119 OSLER ST	Carstairs	T0M 0N0	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
71127	Red Earth Creek/wmf/ municipal landfill	Municipal District of Opportunity No. 17	BOX 60	Wabasca	T0G 2K0	Municipal Sanitary Landfill	< 10,000 t/yr	II
71277	Provost/wmf/municipal landfill, regional	M.D. 52 Regional Waste Management Authority	BOX 300	Provost	T0B 3S0	Municipal Sanitary Landfill	< 10,000 t/yr	II
71610	Owl River/wmf/ municipal landfill	Lac La Biche County	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
72953	Radway/wmf/landfill	Hamlet of Radway	BOX 280	Radway	T0A 2V0	Municipal Sanitary Landfill	< 10,000 t/yr	II
73850	Ardmore/wmf/municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST/Bag 1010	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
74405	Hilda Lake (Moore Lake)/wmf/municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
74624	Wildwood/wmf/	Yellowhead County	2716 1 AVE	Edson	T7E 1N9	Municipal	< 10,000 t/yr	II

	municipal landfill - reclassification (class III)					Sanitary Landfill		
74661	La Corey/wmf/municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST/Bag 1010	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
77849	Claresholm/wmf/Willow Creek regional landfill, dry waste	Willow Creek Regional Waste Management Commission	Box 2820	Claresholm	T0L 0T0	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
78514	Didsbury/wmf/municipal landfill	Mountain View Regional Waste Management Commission	BOX 2130	Didsbury	T0M 0W0	Municipal Sanitary Landfill	< 10,000 t/yr	II
78773	Elinor Lake/wmf/ municipal landfill	Lac La Biche County	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
80109	Cardston/wmf/Chief Mountain regional landfill	Chief Mountain Regional Solid Waste Authority	BOX 280	Cardston	T0K 0K0	Municipal Sanitary Landfill	< 10,000 t/yr	II
137316	Newbrook/wmf/ municipal landfill	Thorhild Regional Waste Management Services Commission	BOX 10	Thorhild	T0A 3J0	Municipal Sanitary Landfill	< 10,000 t/yr	II
137508	Hays/wmf/municipal landfill	Municipal District of Taber	4900B 50 ST	Taber	T1G 1T2	Municipal Sanitary Landfill	< 10,000 t/yr	II
142941	Rocky Mountain House/wmf/municipal landfill	Rocky Mountain Regional Solid Waste Authority	5313 44 ST	Rocky Mountain House	T4T 1A3	Municipal Sanitary Landfill	< 10,000 t/yr	II

143656	Fort Chipewyan municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	< 10,000 t/yr	II
149727	Youngstown/wmf/class II landfill	Big Country Regional Waste Management Commission	BOX 1906	Hanna	T0J 1P0	Municipal Sanitary Landfill	< 10,000 t/yr	II
151259	Ponoka/wmf/municipal landfill, SE 10-43-25-w4	Town of Ponoka	5102 48 AVE	Ponoka	T4J 1P7	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
152403	Thorhild/wmf/municipal landfill	Thorhild Regional Waste Management Services Commission	BOX 10	Thorhild	T0A 3J0	Municipal Sanitary Landfill	< 10,000 t/yr	II
154814	Beaver Lake/wmf/ municipal landfill	Lac La Biche County	BOX 1679	Lac La Biche	T0A 2C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
154862	Smoky Lake County (Spedden)/wmf/municipal landfill, NW 8-60-12-w4	Evergreen Regional Waste Management Services Commission	5015 49 AVE	St. Paul	T0A 3A4	Municipal Sanitary Landfill	< 10,000 t/yr	II
154862	Smoky Lake County (Spedden)/wmf/municipal landfill, NW 8-60-12-w4	Smoky Lake County	BOX 310	Smoky Lake	T0A 3C0	Municipal Sanitary Landfill	< 10,000 t/yr	II
155394	Fort Kent/wmf/municipal landfill	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II
155506	Athabasca/wmf/ municipal landfill - closure	County of Athabasca No. 12	3602 48 AVE	Athabasca	T9S 1M8	Municipal Sanitary Landfill	< 10,000 t/yr	II
155817	Fork Lake/wmf/	Lac La Biche County	BOX 1679	Lac La	T0A 2C0	Municipal	< 10,000 t/yr	II

	municipal landfill			Biche		Sanitary Landfill		
157722	Long Lake/wmf/ municipal landfill	Thorhild Regional Waste Management Services Commission	BOX 10	Thorhild	T0A 3J0	Municipal Sanitary Landfill	< 10,000 t/yr	II
158156	Marie Lake/wmf/ municipal landfill, NW 32-64-2-w4	Municipal District of Bonnyville No. 87	5211 47 ST	Bonnyville	T9N 2J7	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
182198	Foothills/wmf/municipal landfill, SE lsd 2, 29-22-3-w5	Municipal District of Foothills No. 31	BOX 5605	High River	T1V 1M7	Municipal Sanitary Landfill	< 10,000 t/yr	II
182201	Burnstick Lake/wmf/ municipal landfill	Clearwater County	BOX 550	Rocky Mountain House	T4T 1A4	Municipal Sanitary Landfill	< 10,000 t/yr	II
198911	Greenview/wmf/ Greenview regional landfill	Greenview Regional Waste Management Commission	BOX 1079	Valleyview	T0H 3N0	Municipal Sanitary Landfill	< 10,000 t/yr	II
200427	Wetaskiwin/wmf/landfill, regional	City of Wetaskiwin	BOX 6210	Wetaskiwin	T9A 2E9	Municipal Sanitary Landfill	< 10,000 t/yr	II
224508	Midlandvale/wmf/landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II
224509	Jean Cote/wmf/landfill	Municipal District of Smoky River No. 130	BOX 210	Falher	T0H 1M0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224511	Waiparous/wmf/landfill	Alberta Municipal	9405 - 50 St.	Edmonton	T6B 2T4	Municipal	< 10,000 t/yr	II

		Affairs				Sanitary Landfill		
224512	Faust/wmf/landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II
224514	Wrentham/wmf/landfill	County of Warner No. 5	BOX 90	Warner	T0K 2L0	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1- (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
224515	North Drumheller/wmf/ landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II
224516	Westward Ho/wmf/ landfill	Mountain View County	1601 15 AVE	Didsbury	T0M 0W0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224517	Central Park/wmf/landfill	Red Deer County	38106 RANGE RD 275	Red Deer County	T4S 2L9	Municipal Sanitary Landfill	< 10,000 t/yr	II
224518	Forest Lawn/wmf/landfill	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	< 10,000 t/yr	II
224519	Barons/wmf/landfill	Village of Barons	BOX 129	Barons	T0L 0G0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224520	Willow Creek/wmf/ landfill, Parkland	Municipal District of Willow Creek No. 26	BOX 550	Claresholm	T0L 0T0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224521	James River/wmf/landfill	Alberta Municipal	9405 - 50 St.	Edmonton	T6B 2T4	Municipal	< 10,000 t/yr	II

		Affairs				Sanitary Landfill		
224524	Buffalo Lakes/wmf/ landfill	County of Grande Prairie No. 1	10001 84 AVE	Clairmont	T0H 0W0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224527	Deadwood/wmf/landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
224529	Alberta Beach/wmf/ landfill	Summer Village of Val Quentin	PO BOX 128	Alberta Beach	T0E 0A0	Municipal Sanitary Landfill	< 10,000 t/yr	II
224545	Champion/wmf/landfill	Vulcan County	BOX 180	Vulcan	T0L 2B0	Municipal Sanitary Landfill	< 10,000 t/yr	II
225525	Calgary/wmf/municipal landfill	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	< 10,000 t/yr	II
225527	Calgary/wmf/landfill	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	< 10,000 t/yr	II
225529	County of Athabasca/wmf/ municipal landfill	County of Athabasca No. 12	3602 48 AVE	Athabasca	T9S 1M8	Municipal Sanitary Landfill	< 10,000 t/yr	II
225530	Rosedale/wmf/landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II
225533	M.D. of Lesser Slave	Municipal District of	BOX 722	Slave Lake	T0G 2A0	Municipal	< 10,000 t/yr	II

	Lake/wmf/municipal landfill	Lesser Slave River No. 124				Sanitary Landfill		
225539	County of Thorhild/wmf/ municipal landfill	County of Thorhild No. 7	BOX 10	Thorhild	T0A 3J0	Municipal Sanitary Landfill	< 10,000 t/yr	II
225540	Nacmine/wmf/municipal landfill	Alberta Municipal Affairs	9405 - 50 St.	Edmonton	T6B 2T4	Municipal Sanitary Landfill	< 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
227604	Smoky Lake/wmf/ municipal, regional landfill	Evergreen Regional Waste Management Services Commission	5015 49 AVE	St. Paul	T0A 3A4	Municipal Sanitary Landfill	< 10,000 t/yr	II
232383	Fishing Lake/wmf/ municipal landfill, Metis	Fishing Lake Metis Settlement	GD	Fishing Lake Metis Settlement	T0A 3G0	Municipal Sanitary Landfill	< 10,000 t/yr	II
236142	Deadman's Flat/wmf/ municipal landfill	Alberta Transportation	803 MANNING RD NE	Calgary	T2E 7M8	Municipal Sanitary Landfill	< 10,000 t/yr	II
11216	Calgary/wmf/municipal landfill, Shepard	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	> 10,000 t/yr	II
19028	Lethbridge/wmf/ municipal landfill	City of Lethbridge	910 4 AVE S	Lethbridge	T1J 0P6	Municipal Sanitary Landfill	> 10,000 t/yr	II
19090	Calgary/wmf/municipal landfill, hazardous waste transfer station, East Calgary	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	> 10,000 t/yr	II

19101	Calgary/wmf/municipal landfill, Spyhill	City of Calgary	BOX 2100 STN M	Calgary	T2P 2M5	Municipal Sanitary Landfill	> 10,000 t/yr	II
20252	Peace River/wmf/ municipal landfill, East Peace regional	East Peace Regional Landfill Authority	BAG 1300	Peace River	T8S 1Y9	Municipal Sanitary Landfill	> 10,000 t/yr	II
20670	Fort McMurray/wmf/ municipal landfill	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	> 10,000 t/yr	II

Table A1-1(continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
20754	Ryley regional/wmf/ municipal landfill, Beaver	Beaver Regional Waste Management Services Commission	BOX 322	Ryley	T0B 4A0	Municipal Sanitary Landfill	> 10,000 t/yr	II
20954	Grande Prairie\wmf\ municipal landfill	Aquatera Utilities Inc.	BAG 4000	Grande Prairie	T8V 6V3	Municipal Sanitary Landfill	> 10,000 t/yr	II
46896	Ridgeview/wmf/ municipal landfill, regional	Central Alberta Regional Waste Management Commission	c/o 200 5214 47 AVE	Red Deer	T4N 3P7	Municipal Sanitary Landfill	> 10,000 t/yr	II
47061	Roseridge/wmf/municipal landfill/regional	Roseridge Waste Management Services Commission	BOX 19 SITE 1 RR 1	Morinville	T8R 1P4	Municipal Sanitary Landfill	> 10,000 t/yr	II
47073	Leduc/wmf/municipal landfill/regional	Leduc and District Regional Waste Management Authority	1 ALEXANDRA PARK	Leduc	T9E 4C4	Municipal Sanitary Landfill	> 10,000 t/yr	II
47140	Edmonton/wmf/ municipal landfill, Clover	City of Edmonton	3 FL 1 SIR WINSTON	Edmonton	T5J 2R7	Municipal Sanitary	> 10,000 t/yr	II

	Bar		CHURCHILL SQ			Landfill		
47415	Drayton Valley/wmf/ municipal landfill/ regional	Town of Drayton Valley (transferred to Aspen Waste Management Authority in 2007)	5120 52 ST	Drayton Valley	T7A 1A1	Municipal Sanitary Landfill	> 10,000 t/yr	II
47447	Foothills/wmf/regional landfill	Foothills Regional Services Commission	BOX 5605	High River	T1V 1M7	Municipal Sanitary Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
47449	Drumheller/wmf/ municipal landfill, regional	Drumheller & District Solid Waste Management Association	703 2 AVE W	Drumheller	T0J 0Y3	Municipal Sanitary Landfill	> 10,000 t/yr	II
47636	Camrose/wmf/class II municipal landfill, regional	Camrose Regional Solid Waste Authority	5204 50 AVE	Camrose	T4V 0S8	Municipal Sanitary Landfill	> 10,000 t/yr	II
47826	Seba Beach wmf municipal landfill	Parkland County	53109A SH 779	Parkland County	T7Z 1R1	Municipal Sanitary Landfill	> 10,000 t/yr	II
48050	Hinton/wmf/municipal landfill/regional	West Yellowhead Regional Waste Management Authority	2 FL 131 CIVIC CENTRE RD	Hinton	T7V 2E5	Municipal Sanitary Landfill	> 10,000 t/yr	II
48819	Edmonton/wmf/ municipal landfill, West	Waste Management of Canada Corporation	12707 170 ST	Edmonton	T5V 1L9	Municipal Sanitary Landfill	> 10,000 t/yr	II
49852	Whitecourt/wmf/ municipal landfill,	Whitecourt Regional Solid Waste	BOX 509	Whitecourt	T7S 1N6	Municipal Sanitary	> 10,000 t/yr	II

	regional	Management Authority				Landfill		
70354	Brooks/wmf/municipal landfill	Newell Regional Solid Waste Management Authority Ltd.	427 1 ST W	Brooks	T1R 0G1	Municipal Sanitary Landfill	> 10,000 t/yr	II
70686	Coronation/wmf/class II municipal landfill	Waste Services (CA) Inc.	601 1122 INTERNATIONAL BLVD	Burlington	L7L 3Z8	Municipal Sanitary Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
72856	Slave Lake/wmf/Lesser Slave regional landfill	Lesser Slave Regional Waste Management Services Commission	BOX 722	Slave Lake	T0G 2A0	Municipal Sanitary Landfill	> 10,000 t/yr	II
73493	High Level/wmf/ landfill, Mackenzie regional waste management facility	Town of High Level	9813 102 ST	High Level	T0H 1Z0	Municipal Sanitary Landfill	> 10,000 t/yr	II
74850	Redcliff/Cypress/wmf/ municipal landfill	Redcliff/Cypress Regional Waste Management Authority	BOX 40	Redcliff	T0J 2P0	Municipal Sanitary Landfill	> 10,000 t/yr	II
78246	Medicine Hat/wmf/ municipal landfill	City of Medicine Hat	580 1 ST SE	Medicine Hat	T1A 8E6	Municipal Sanitary Landfill	> 10,000 t/yr	II
78945	West Dried Meat Lake/wmf/municipal landfill, regional	West Dried Meat Lake Regional Waste Management Authority	4728 41 ST	Camrose	T4V 0Z6	Municipal Sanitary Landfill	> 10,000 t/yr	II
137872	Spirit River Class II	CCS Corporation	2400 530 8 AVE	Calgary	T2P 3S8	Municipal	> 10,000 t/yr	II

	landfill - landfill expansion and construction of a bio-remediation pad		SW			Sanitary Landfill		
146658	Fort McMurray/wmf/ regional municipal landfill, lateral landfill extension	Regional Municipality of Wood Buffalo	9909 FRANKLIN AVE	Fort McMurray	T9H 2K4	Municipal Sanitary Landfill	> 10,000 t/yr	II
154918	Red Deer waste management facility	City of Red Deer	BOX 5008	Red Deer	T4N 3T4	Municipal Sanitary Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
196002	North Peace/wmf/ regional landfill, Class II	North Peace Regional Landfill Commission	BOX 730	Fairview	T0H 1L0	Municipal Sanitary Landfill	> 10,000 t/yr	II
220236	Clairmont/wmf/municipal landfill	County of Grande Prairie No. 1	10001 84 AVE	Clairmont	T0H 0W0	Municipal Sanitary Landfill	> 10,000 t/yr	II
18746	Iron Springs/wmf/transfer station/dry waste landfill	Lethbridge Regional Waste Management Services Commission	100 905 4 AVE S	Lethbridge	T1J 4E4	Dry Waste Landfill	< 10,000 t/yr	III
20808	Ribstone/wmf/dry waste landfill - closure plan	Municipal District of Wainwright No. 61	717 14 AVE	Wainwright	T9W 1B3	Dry Waste Landfill	< 10,000 t/yr	III
46850	Wagner/wmf/municipal landfill	Municipal District of Lesser Slave River No. 124	BOX 722	Slave Lake	T0G 2A0	Dry Waste Landfill	< 10,000 t/yr	III
68468	Kneehill County/wmf/dry waste site (Class III)	Kneehill County	232 MAIN ST	Three Hills	T0M 2A0	Dry Waste Landfill	< 10,000 t/yr	III
72729	Medicine Hat/wmf/dry landfill, Westar	Westar Landfill Ltd.	BOX 24034 RPO CRESTWOOD	Medicine Hat	T1A 8M8	Dry Waste Landfill	< 10,000 t/yr	III

74237	Gift Lake/wmf/dry waste landfill	High Prairie & District Regional Solid Waste Management Authority	BOX 239	High Prairie	T0G 1E0	Dry Waste Landfill	< 10,000 t/yr	III
76108	Faust-Kinuso Class III landfill	High Prairie & District Regional Solid Waste Management Authority	BOX 239	High Prairie	T0G 1E0	Dry Waste Landfill	< 10,000 t/yr	III

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
76109	Grouard Class III landfill	High Prairie & District Regional Solid Waste Management Authority	BOX 239	High Prairie	T0G 1E0	Dry Waste Landfill	< 10,000 t/yr	III
77669	Barons/wmf/dry waste landfill, T Erdman	Thomas Erdman	BOX 128	Barons	T0L 0G0	Dry Waste Landfill	< 10,000 t/yr	III
137526	Coutts/wmf/municipal landfill	Village of Coutts	BOX 236	Coutts	T0K 0N0	Dry Waste Landfill	< 10,000 t/yr	III
143199	Bettenson/wmf/dry waste landfill	Bettenson's Sand & Gravel Co Ltd	4320 52 AVE	Red Deer	T4N 4J9	Dry Waste Landfill	< 10,000 t/yr	III
148741	Ponoka/wmf/Class III landfill	Picker People Ltd.	BOX 6 SITE 1 RR 2	Ponoka	T4J 1R7	Dry Waste Landfill	< 10,000 t/yr	III
189305	Evergreen/wmf/regional landfill	Evergreen Regional Waste Management Services Commission	5015 49 AVE	St. Paul	T0A 3A4	Dry Waste Landfill	< 10,000 t/yr	II
231403	Enchant/wmf/municipal landfill	Municipal District of Taber	4900B 50 ST	Taber	T1G 1T2	Dry Waste Landfill	< 10,000 t/yr	III

19045	Calgary/wmf/dry waste landfill, ECCO	ECCO Waste Systems Limited Partnership	10012 24 ST SE	Calgary	T2C 3X7	Dry Waste Landfill	> 10,000 t/yr	III
20686	Cholla Sand and Dry Waste Class III landfill	Cholla Sand and Dry Waste Inc.	304 9768 170 ST	Edmonton	T5T 5L4	Dry Waste Landfill	> 10,000 t/yr	III
49173	Municipal District of Big Horn/wmf/industrial dry landfill	Bow Valley Waste Management Commission	185 CAREY	Canmore	T1W 2R7	Dry Waste Landfill	> 10,000 t/yr	III

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
49589	Northland Material Handling/wmf/dry waste site	Northland Material Handling Inc.	1500 10025 102A AVE	Edmonton	T5J 2Z2	Dry Waste Landfill	> 10,000 t/yr	III
188621	Swan Hills Class II industrial landfill	Devon Canada Corporation	2000 400 3 AVE SW	Calgary	T2P 4H2	Dry Waste Landfill	> 10,000 t/yr	III
221204	Edson/wmf/municipal landfill	Town of Edson	BOX 6300	Edson	T7E 1T7	Inert (Dry) Waste Landfill	> 10,000 t/yr	III (currently accepting inert waste only)
10348	Ryley hazardous waste storage facility and landfill	Clean Harbors Canada, Inc.	7305 BLVD MARIE-VICTORIN BUREAU 200	Brossard	J4W 1A6	Hazardous Waste Landfill	> 10,000 t/yr	I
48516	Pembina hazardous waste landfill	Pembina Area Landfill Ltd.	BOX 6478	Drayton Valley	T7A 1R9	Hazardous Waste Landfill	> 10,000 t/yr	I
10052	Rocky Mountain House/wmf/industrial Class II landfill, regional	Rocky Mountain Regional Solid Waste Authority	5313 44 ST	Rocky Mountain House	T4T 1A3	Industrial Waste Landfill	> 10,000 t/yr	II

18690	Calgary/wmf/municipal landfill, NW 13-22-1-w5	BFI Canada Inc.	BOX 76068 SHAWNESSY PO	Calgary	T2Y 2Z0	Industrial Waste Landfill	> 10,000 t/yr	II
18701	Crowsnest-Pincher Creek/wmf/regional landfill	Crowsnest-Pincher Creek Regional Waste Management Authority	BOX 668	Pincher Creek	T0K 1W0	Industrial Waste Landfill	> 10,000 t/yr	II
46773	Big Valley Class II industrial landfill	Waste Management of Canada Corporation	300 5045 SOUTH SERVICE RD	Burlington	L7L 5Y7	Industrial Waste Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
75152	Spirit River hazardous recycling facility and landfill	Newalta Corporation	211 11 AVE SW	Calgary	T2R 0C6	Industrial Waste Landfill	> 10,000 t/yr	II
78246	Medicine Hat/wmf/ municipal landfill	City of Medicine Hat	580 1 ST SE	Medicine Hat	T1A 8E6	Industrial Waste Landfill (Industrial Cell in Municipal Landfill)	> 10,000 t/yr	II
149968	Horizon oil sands project	Canadian Natural Resources Limited	2500 855 2 ST SW	Calgary	T2P 4J8	Industrial Waste Landfill	> 10,000 t/yr	II
153125	Jackpine oilsands mine - phase 1	Shell Canada Limited	BOX 100 STN M	Calgary	T2P 2H5	Industrial Waste Landfill	> 10,000 t/yr	II
154484	La Glace Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II

158998	Simonette Class II oilfield waste landfill	Suncor Energy Inc.	BOX 38	Calgary	T2P 2V5	Industrial Waste Landfill	> 10,000 t/yr	II
188621	Swan Hills Class II industrial landfill	Devon Canada Corporation	2000 400 3 AVE SW	Calgary	T2P 4H2	Industrial Waste Landfill	> 10,000 t/yr	II
193262	Rainbow Lake Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
203668	Tower Road Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
204916	Bonnyville Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
207586	Fox Creek Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
208059	Elk Point Class II industrial landfill	Newalta Corporation	211 11 AVE SW	Calgary	T2R 0C6	Industrial Waste Landfill	> 10,000 t/yr	II
218419	Mitsue Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
225523	Home Oil Co/wmf/ landfill	Devon Canada Corporation	2000 400 3 AVE SW	Calgary	T2P 4H2	Industrial Waste Landfill	> 10,000 t/yr	II
228525	Judy Creek Class II	CCS Corporation	2400 530 8 AVE	Calgary	T2P 3S8	Industrial	> 10,000 t/yr	II

	industrial landfill		SW			Waste Landfill		
230814	Janvier Class II landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
232420	Zama Class II industrial landfill	Newalta Corporation	211 11 AVE SW	Calgary	T2R 0C6	Industrial Waste Landfill	> 10,000 t/yr	II

Table A1-1 (continued)

APV ID	Name	Company name	Address	City	Postal code	Activities name	Annual Waste Amounts	Class
236632	Wabasca Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
238093	South Grande Prairie Class II industrial landfill	Secure Energy Services Inc.	1201 333 7 AVE SW	Calgary	T2P 2Z1	Industrial Waste Landfill	> 10,000 t/yr	II
239576	South Grande prairie Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
245630	Willow Creek Class II industrial landfill	CCS Corporation	2400 530 8 AVE SW	Calgary	T2P 3S8	Industrial Waste Landfill	> 10,000 t/yr	II
247721	Willesden Green Class II oilfield landfill	Secure Energy Services inc.	1201 333 7 AVE SW	Calgary	T2P 2Z1	Industrial Waste Landfill	> 10,000 t/yr	II

Appendix A2

Descriptive statistics for leachate chemical parameters

Table A2-1. Descriptive statistics for various leachate parameters in municipal sanitary landfills.

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
Landfill 1	Mean	6.7	6467	9721	4383	1150	1907	2.36	8959	398	287	6.88	449.37	1250
	Max	7.9	36000	64700	16100	8030	15400	21.50	40200	4350	1640	165.00	2600.00	11600
	Min	1.9	2	10	5	1	0	0.01	1	3	0	0.07	0.20	0
	SD	1.4	12776	19379	4768	1736	4134	6.24	10864	871	398	32.94	668.36	2365
	Median	7.1	218	670	2330	736	405	0.02	4230	84	127	0.10	171.00	553
Landfill 2	Mean	6.6	5291	9504	5023	5670	1178	58.92	10054	609	291	0.88	444.40	1509
	Max	8.2	47400	66900	30900	64703	3510	885.00	65000	3270	1150	5.98	2070.00	3815
	Min	3.4	2	10	1	1	0	0.01	1	3	0	0.05	0.20	0
	SD	1.4	10934	17535	6405	15429	1123	212.87	12538	914	387	1.36	618.70	1113
	Median	7.3	171	915	3450	288	989	0.06	7835	236	122	0.35	148.00	1778
Landfill 3	Mean	7.0	5767	8124	3380	161	533	0.48	4505	313	221	0.25	328.85	366
	Max	8.1	43800	56100	12000	1250	1460	1.89	16700	1780	1040	1.60	1380.00	1350
	Min	5.7	2	10	5	1	0	0.01	1	3	0	0.07	0.20	0
	SD	0.7	12734	16803	3804	370	555	0.62	5106	445	310	0.37	416.28	380
	Median	7.2	173	540	2580	16	263	0.21	3350	85	88	0.10	195.50	210

Landfill	**Statistic**	**pH**	**BOD_5 (mg/L)**	**COD (mg O_2/L)**	**total alkalinity ($CaCO_3$) (mg/L)**	**SO_4^{2-} (mg/L)**	**Cl (mg/L)**	**PO_4^{3-} (mg/L)**	**TDS (mg/L)**	**TSS (mg/L)**	**NH_3 (mg/L)**	**NO_2 + NO_3 (mg/L)**	**TKN (mg/L)**	**Na (mg/L)**
Landfill 4	Mean	7.1		3244	3058	412	572		4666		210	0.99	161.50	392
	Max	7.7	0	11100	5850	2640	964	0.00	8950	0	446	1.90	174.00	435
	Min	6.1	0	240	909	10	89	0.00	3150	0	5	0.09	149.00	349
	SD	0.4		3898	1066	499	173		1554		74	1.28	17.68	61
	Median	7.1		620	2805	284	551		3929		207	0.99	161.50	392

Table A2-1 (continued)

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
Landfill 7	Mean	7.0	1136	2208	2472	74	614		3371	125	171		33.81	563
	Max	7.5	1690	6460	3720	284	1220	0.00	4690	222	475	0.00	51.70	847
	Min	6.4	318	720	794	3	194	0.00	1100	36	4	0.00	18.90	230
	SD	0.4	723	1799	785	95	360		1010	69	187		13.48	196
	Median	7.1	1400	1740	2530	27	653		3750	112	91		35.80	590
Landfill 5	Mean	6.9		6290	5886	73	2275		10160	617	282	20.13	331.00	2425
	Max	7.6		22000	9838	125	3500	0.00	14388	2240	640	79.00	730.00	4300
	Min	6.2		540	2255	37	700	0.00	4224	36	18	0.50	20.00	1300
	SD	0.6		10491	3847	42	1276		4961	1083	301	39.25	350.41	1315
	Median	6.9		1310	5726	64	2450		11013	96	235	0.50	287.00	2050
Landfill 8	Mean	8.6	3241	5529			1830	17.90	11213	2611	439		400.00	358
	Max	9.5	45540	20750			1830	17.90	17000	21940	888	0.00	400.00	358
	Min	7.3	218	1600			1830	17.90	7610	73	4	0.00	400.00	358
	SD	0.9	3194	2343					2669	2759	184			
	Median	8.8	2905	5290			1830	17.90	10350	1970	401		400.00	358
Landfill	Mean	7.4	431	882	1993	68	1145		3779	362	25	0.98		725

6	Max	8.1	1990	4180	3990	304	4730	0.00	11000	1210	50	2.51	0.00	3180
	Min	6.5	16	20	157	5	13	0.00	259	7	1	0.05	0.00	7
	SD	0.4	662	1221	1222	92	1336		3049	403	35	1.16		885
	Median	7.5	125	530	2250	33	705		2970	188	25	0.29		370
Landfill 9	Mean	8.6	14239	7764	2179	935	3789	1.29	21216	501	272	2.08	639.35	1842
	Max	13.0	561000	83000	13200	4720	30200	6.20	520000	5080	1900	22.00	12000.00	13000
	Min	6.1	2	70	1	1	12	0.05	626	7	0	0.05	8.70	29
	SD	1.7	72056	16355	2375	1008	6459	1.54	70271	1066	419	4.97	1872.67	2522
	Median	8.0	256	970	1900	641	945	0.99	7260	140	88	0.27	140.00	638

Table A2-1. (continued)

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
Landfill 11	Mean	7.3	193	726	1987	263	1040		3922	76	105	0.09	170.17	689
	Max	7.7	647	1220	2800	1180	1900		5490	123	206	0.19	270.00	1970
	Min	6.8	19	303	130	20	210		2060	29	0	0.01	100.00	21
	SD	0.4	257	385	956	513	553		1130		84	0.06	73.74	631
	Median	7.4	96	633	2215	31	995		4000	76	106	0.10	144.00	640
Landfill 12	Mean	7.1	5799	10327	3754	221	1292	510.00	6556		422	0.80	485.50	1229
	Max	7.8	21000	24900	6310	816	1800	510.00	11000	0	715	2.70	510.00	1720
	Min	6.4	366	2670	978	30	363	510.00	1820	0	162	0.10	461.00	537
	SD	0.5	7648	8957	2108	335	646		3729		228	1.27	34.65	516
	Median	7.1	3590	5635	3930	69	1650	510.00	6740		405	0.20	485.50	1330
Landfill 10	Mean	7.3	2320	1856	2917	126	566		4693	368	155		3784.73	721
	Max	7.8	2320	2790	4900	563	2100		6930	368	183	0.00	4900.00	1550
	Min	6.9	2320	127	1240	22	26		16	368	131	0.00	152.00	79
	SD	0.2		704	1411	141	693		2378		26		1251.61	574
	Median	7.4	2320	1955	3800	66	77		6175	368	151		4060.00	1150

Table A2-2. Descriptive statistics for additional leachate parameters in municipal sanitary landfills.

Landfill	Statistic	Acetone (mg/L)	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
Landfill 1	Mean	3.49	0.68	11421	725	263	0.00	7.97	0.266	355	0.015
	Max	21.90	10.00	42900	3710	2040	0.03	46.80	1.150	1220	0.162
	Min	0.06	0.00	3	0	0	0.00	0.00	0.000	0	0.000
	SD	6.30	2.17	11314	1052	617	0.01	13.52	0.360	322	0.033
	Median	0.20	0.10	6690	319	3	0.00	1.43	0.128	248	0.005
Landfill 2	Mean	19.19	0.51	11961	505	640	13.52	0.29	0.007	896	0.065
	Max	130.00	10.00	37700	3680	7260	129.00	2.26	0.050	7170	0.427
	Min	0.02	0.00	3	0	0	0.00	0.00	0.000	0	0.000
	SD	37.20	1.91	10405	796	1802	31.74	0.59	0.014	1761	0.123
	Median	0.30	0.10	10900	269	2	0.50	0.05	0.001	384	0.009
Landfill 3	Mean	111.18	0.54	6946	655	210	9.42	0.16	0.004	292	0.023
	Max	2000.00	5.00	23500	3810	1790	59.00	0.65	0.035	1080	0.182
	Min	0.02	0.00	3	0	0	0.00	0.00	0.000	0	0.000
	SD	434.93	1.17	7582	1083	490	18.36	0.21	0.009	319	0.050
	Median	3.00	0.10	5160	265	2	0.87	0.07	0.001	225	0.003
Landfill 4	Mean	0.01	0.01	5305	345	130	9.13	0.03	0.000		
	Max	0.01	0.01	5570	353	585	29.40	0.04	0.000	0	0.000

Landfill	Statistic	Acetone (mg/L)	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
	Min	0.01	0.00	5040	336	1	1.38	0.03	0.000	0	0.000
	SD	0.00	0.01	375	12	170	8.80	0.00	0.000		
	Median	0.01	0.01	5305	345	32	3.76	0.03	0.000		

Table A2-2. (continued)

Landfill	Statistic	Acetone (mg/L)	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
Landfill 7	Mean			6140	387	337	17.12	0.07	145.500	189	0.005
	Max			8220	628	1580	180.00	0.17	255.000	309	0.005
	Min			2100	147	14	0.23	0.01	0.000	1	0.005
	SD			1743	149	481	51.38	0.05	109.040	92	
	Median			6990	363	118	0.89	0.07	163.500	204	0.005
Landfill 5	Mean		0.01	14455	704	278	19.53	0.27	0.003	313	0.024
	Max		0.01	20500	2300	1020	71.20	0.76	0.006	610	0.071
	Min		0.00	6520	47	2	0.10	0.05	0.002	130	0.001
	SD		0.00	6159	1072	496	34.49	0.33	0.002	210	0.032
	Median		0.01	15400	235	45	3.42	0.14	0.002	255	0.011
Landfill 8	Mean			19200	520	181	3.01	0.84	0.046	226	0.045
	Max			19200	520	219	3.53	1.01	0.046	226	0.069
	Min			19200	520	149	2.42	0.57	0.046	226	0.005
	SD					35	0.56	0.24			0.035
	Median			19200	520	175	3.07	0.93	0.046	226	0.062
Landfill 6	Mean			3883	290	48	2.50	0.08	0.001	93	0.007
	Max		0.00	6380	566	128	6.02	0.24	0.001	173	0.014

	Min		0.00	454	57	0	0.19	0.01	0.001	53	0.005
	SD			2155	171	45	1.96	0.07	0.000	48	0.004
	Median			4540	307	50	2.32	0.08	0.001	70	0.005
Landfill 9	Mean		0.01	18969	407	64	1.52	0.17	0.003	266	0.061
	Max		0.05	92900	3700	2000	19.00	1.00	0.055	1000	0.674
	Min		0.00	965	11	0	0.00	0.01	0.000	0	0.001
	SD		0.01	19407	698	264	3.64	0.17	0.007	252	0.127
	Median		0.00	13850	200	2	0.30	0.13	0.001	180	0.013

Table A2-2. (continued)

Landfill	Statistic	Acetone (mg/L)	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
Landfill 11	Mean		0.01	5241	232	7	32.47	0.05	0.000	187	0.003
	Max		0.01	8110	396	26	252.00	0.11	0.000	240	0.014
	Min		0.00	6	16	0	0.61	0.01	0.000	135	0.000
	SD		0.00	2985	119	11	88.70	0.04	0.000	35	0.005
	Median		0.01	5850	256	1	1.21	0.04	0.000	193	0.002
Landfill 12	Mean		0.58	2739	906	118	7.04	0.14	0.001	170	0.002
	Max		1.50	4760	1860	228	19.40	0.42	0.001	317	0.005
	Min		0.07	7	316	37	1.20	0.05	0.000	64	0.000
	SD		0.67	2027	627	86	7.28	0.14	0.000	94	0.002
	Median		0.37	3640	661	88	5.75	0.10	0.001	150	0.002
Landfill 10	Mean			2919	285	211	2.24	0.11	0.001	269	0.003
	Max			6420	563	211	2.24	0.11	0.001	269	0.003
	Min			2300	191	211	2.24	0.11	0.001	269	0.003
	SD			1251	106						
	Median			2460	251	211	2.24	0.11	0.001	269	0.003

Table A2-3. Descriptive statistics for various leachate parameters in industrial landfills.

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	Total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
Landfill 13	Mean	11.9			1030	1640	8820		17500		0.51	0.70	5.60	3810
	Max	12.6			1030	1640	8820		17500		0.51	0.70	5.60	3810
	Max	7.2			1030	1640	8820		17500		0.51	0.70	5.60	3810
	SD	1.6												
	Median	12.3			1030	1640	8820		17500		0.51	0.70	5.60	3810
Landfill 14	Mean	7.7			331	343	2523		5182	15	0.34	0.45	0.64	1183
	Max	7.8			620	890	5800		12000	41	0.78	1.70	1.20	2900
	Max	7.5			69	130	820		1700	1	0.05	0.00	0.18	420
	SD	0.1			243	316	2026		4099	17	0.33	0.72	0.39	1027
	Median	7.7			410	190	1770		3540	9	0.18	0.09	0.65	700
Landfill 15	Mean	7.8		970	1155	131	3736		7344	141	2.16	0.22	6.82	1460
	Max	7.9		1200	1560	210	4920		9510	312	6.60	0.30	11.90	1860
	Max	7.7		739	385	30	1650		3420	54	0.39	0.10	3.70	710
	SD	0.1		326	480	92	1402		2588	148	2.56	0.11	3.27	500
	Median	7.8		970	1210	170	4250		8220	56	1.62	0.30	7.00	1690
Landfill	Mean	7.2		2510	419	287	1131	0.09	2750	1525	0.15	0.49		309

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	Total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
16	Max	7.8		3290	1060	594	3170	0.10	6410	4440	0.18	1.51	0.00	702
	Max	6.0		1730	61	28	14	0.05	136	31	0.11	0.07	0.00	13
	SD	0.7		1103	390	234	1303	0.03	2720	2525	0.05	0.59		310
	Median	7.5		2510	321	199	681	0.10	1710	103	0.15	0.30		211
Landfill 17	Mean	7.2		5	502	39	4197	0.05	6795	6	0.21	10.40	1.20	1231
	Max	7.7		5	923	50	7620	0.05	12200	6	0.36	20.70	1.20	2240
	Max	6.7		5	80	28	774	0.05	1390	6	0.05	0.10	1.20	222
	SD	0.7			596	16	4841		7644		0.22	14.57		1427
	Median	7.2		5	502	39	4197	0.05	6795	6	0.21	10.40	1.20	1231

Table A2-3 (continued)

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	Total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
Landfill 18	Mean	7.0	3894	8811		181	3518		8780	80	111.54	13.28	144.37	1772
	Max	8.4	14400	25500		656	7350		16400	540	417.00	91.00	476.00	5350
	Max	5.8	100	536		1	672		2640	3	2.20	0.10	2.80	403
	SD	0.5	4418	8239		173	2129		4384	121	135.59	27.36	170.10	1303
	Median	7.0	1560	6060		157	3255		8665	36	24.50	0.10	40.95	1665
Landfill 19	Mean	7.5			562	242	18776		31650	542	37.48	0.91	62.81	10482
	Max	11.3			1220	870	32000		52200	3290	78.30	1.30	78.00	17200
	Max	6.6			193	40	7460		13300	46	0.05	0.70	43.30	4540
	SD	1.2			320	277	8667		13835	831	22.31	0.18	10.73	4863
	Median	7.3			410	100	20600		35100	299	40.15	1.00	62.00	11400
Landfill 20	Mean	7.6		600	3064	28	1000		4374	13	236.67			797
	Max	7.9		810	4078	53	1300		5585	18	300.00	0.00	0.00	980
	Max	7.2		290	1447	14	500		2277	5	140.00	0.00	0.00	450
	SD	0.4		274	1415	22	436		1823	7	85.05			300
	Median	7.8		700	3667	17	1200		5260	16	270.00			960
Landfill	Mean	6.6	292	2510		1061	5731		13257	105	111.44			2112

Landfill	Statistic	pH	BOD_5 (mg/L)	COD (mg O_2/L)	Total alkalinity ($CaCO_3$) (mg/L)	SO_4^{2-} (mg/L)	Cl (mg/L)	PO_4^{3-} (mg/L)	TDS (mg/L)	TSS (mg/L)	NH_3 (mg/L)	NO_2 + NO_3 (mg/L)	TKN (mg/L)	Na (mg/L)
21	Max	7.0	728	7420		2130	8450		17800	343	228.00	0.00	0.00	3040
	Max	6.2	45	17		198	18		1100	31	1.41	0.00	0.00	16
	SD	0.2	237	2294		640	2847		6180	108	94.91			1025
	Median	6.6	217	1890		824	6825		16500	68	95.90			2490
Landfill 22	One sample	7.0		143		34	308		920	7	0.34			57
Landfill 23	Mean	7.7	573	1051		560	189		3282	282	25.40			518
	Max	8.1	1650	2980		1770	408		4710	884	52.20	0.00	0.00	702
	Max	7.3	27	68		5	5		1140	28	3.66	0.00	0.00	223
	SD	0.3	612	972		806	154		1165	268	19.47			187
	Median	7.7	284	701		78	147		3800	220	23.40			587

Table A2-4. Descriptive statistics for additional leachate parameters in industrial landfills.

Landfill	Statistic	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
Landfill 13	Mean	0.03	23700	8820	3.63	3.93	0.01			0.032
	Max	0.21	23700	8820	21.80	3.93	0.03			0.132
	Max	0.01	23700	8820	0.10	3.93	0.01			
	SD	0.06			7.63		0.01			0.043
	Median	0.01	23700	8820	0.10	3.93	0.01			0.019
Landfill 14	Mean		8253	445	0.47	0.00	2.25	0.015	100.00	
	Max	0.00	18000	870	1.50	0.00	3.80	0.035	200.00	
	Max	0.00	3000	130	0.10	0.00	0.65	0.002	24.00	
	SD		6012	273	0.59	0.00	1.35	0.013	64.95	
	Median		5580	420	0.14	0.00	2.60	0.011	91.00	
Landfill 15	Mean	22.00	12238	597	31.70	0.00	5.46	0.041	474.60	
	Max	39.00	15700	722	48.50	0.00	8.30	0.058	693.00	
	Max	5.00	5790	426	3.31	0.00	3.27	0.023	58.00	
	SD	13.27	4247	149	18.40	0.00	2.10	0.017	266.55	
	Median	25.00	13800	686	39.20	0.00	6.09	0.050	553.00	
Landfill	Mean		4423	532	1.00	2.30	0.01			

Landfill	Statistic	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
16	Max	0.00	10800	1290	4.63	7.30	0.02			
	Max	0.00	275	30	0.02	0.06	0.00			
	SD		4378	529	2.03	2.95	0.01			
	Median		2990	328	0.10	0.99	0.01			
Landfill 17	Mean	0.00	11495	781	16.70	16.62	0.05	0.001	92.10	0.015
	Max	0.00	20400	1370	33.30	30.40	0.09	0.001	150.00	0.015
	Max	0.00	2590	191	0.09	2.83	0.02	0.000	34.20	0.015
	SD		12594	834	23.48	19.49	0.06	0.001	81.88	
	Median	0.00	11495	781	16.70	16.62	0.05	0.001	92.10	0.015

Table A2-4 (continued)

Landfill	Statistic	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
Landfill 18	Mean		12950	1151	8.05		0.10	0.019	220.41	0.077
	Max	0.00	24700	2960	34.90	0.00	0.72	0.020	395.00	0.080
	Max	0.00	4150	53	0.21	0.00	0.03	0.002	44.90	0.008
	SD		6017	711	9.18		0.16	0.004	97.30	0.015
	Median		12900	1195	6.06		0.03	0.020	214.50	0.080
Landfill 19	Mean	0.05	44314	1340	33.35	10.65	0.14		732.71	
	Max	0.21	65700	2240	116.00	22.80	0.41	0.001	6500.00	0.009
	Max	0.00	22100	543	0.20	0.10	0.03		4.00	
	SD	0.05	17030	645	39.91	8.51	0.11		1666.97	
	Median	0.04	46150	1640	10.32	11.67	0.09		320.00	
Landfill 20	Mean	0.00	7679	147	6.70	0.07	0.15	0.002	356.67	
	Max	0.00	9470	260	6.90	0.11	0.20	0.002	440.00	
	Max	0.00	4547	87	6.49	0.03	0.10	0.002	210.00	
	SD	0.00	2722	98	0.29	0.06	0.07		127.41	
	Median	0.00	9020	94	6.70	0.07	0.15	0.002	420.00	
Landfill 21	Mean	0.01		1387	57.78	25.42	0.04		526.06	0.015
	Max	0.02		2020	207.00	64.00	0.10		698.00	0.060

Landfill	Statistic	Benzene (mg/L)	Electrical conductivity (uS/cm^2)	Ca (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	Cd (mg/L)	Mg (mg/L)	Pb (mg/L)
	Max	0.00		51	0.13	0.05	0.00		19.50	0.000
	SD	0.01		642	69.08	19.61	0.04		236.35	0.019
	Median	0.00		1590	45.10	22.15	0.04		620.00	0.010
Landfill 22										
Landfill 23	Mean		4017	255	46.81	1.97	0.03	0.002	176.06	0.036
	Max		6140	440	159.00	4.55	0.15	0.010	252.00	0.166
	Max		1720	45	2.32	0.11	0.00	0.001	66.30	0.005
	SD		1806	120	50.49	1.42	0.05	0.003	65.48	0.054
	Median		4220	271	33.10	1.70	0.02	0.001	184.00	0.005

Appendix B

Appendix B: Physical characteristics of TDA

Appendix B1. Raw Data for particle specific gravity

Table B1-1. Specific gravity tests – MTT

	Test 1	Test 2	Test 3
Mass of pail (kg)	1.035	1.035	1.035
Mass of pail + water (kg)	16.96	16.96	16.94
Mass of pail + water+TDA (kg)	22.99	23.065	22.925
Mass of TDA (kg)	6.03	6.105	5.985
Volume of water displaced (m^3)	0.004847	0.004847	0.004847
Specific gravity of TDA	1244.068	1259.542	1234.784
unit density	1.244	1.260	1.234784
mean	1.25		
SD	0.01		
Error	0.06		

Table B1-2. Specific gravity tests – PLTT

	Test 1	**Test 2**	**Test 3**
Mass of pail (kg)	1.035	1.035	1.035
Mass of pail + water (kg)	17	17	17
Mass of pail + water+TDA (kg)	22.715	22.775	22.855
Mass of TDA (kg)	5.715	5.775	5.855
Volume of water displaced (m^3)	0.004847	0.004847	0.004847
Specific gravity of TDA	1179.078	1191.459	1207.964
unit density	1.179	1.191	1.207964
mean	1.19		
SD	0.01		
Error	0.07		

Table B1-3. Specific gravity tests – OTR

	Test 1	Test 2	Test 3
Mass of pail (kg)	1.035	1.035	1.035
Mass of pail + water (kg)	17	17	17
Mass of pail + water+TDA (kg)	22.15	22.475	22.62
Mass of TDA (kg)	5.15	5.475	5.62
Volume of water displaced (m^3)	0.004847	0.004847	0.004847
Specific gravity of TDA	1062.513	1129.565	1159.48
unit density	1.063	1.130	1.15948
mean	1.12		
SD	0.05		
Error	0.13		

Table B1-4. Specific gravity tests – PLTT + OTR

	Test 1	Test 2	Test 3
Mass of pail (kg)	1.035	1.035	1.035
Mass of pail + water (kg)	16.885	16.985	16.895
Mass of pail + water+TDA (kg)	22.515	22.73	22.315
Mass of TDA (kg)	5.63	5.745	5.42
Volume of water displaced (m^3)	0.004847	0.004847	0.004847
Specific gravity of TDA	1161.543	1185.269	1118.217
unit density	1.162	1.185	1.118217
mean	1.16		
SD	0.03		
Error	0.11		

Appendix B2. Conversion of overburden to sanitary landfill height

Table B2-1. Relationship between overburden and height of sanitary landfill

Overburden Pressure (kPa)-A	Unit weight of municipal solid waste (kNm-3)-B)	Height of municipal solid waste (m) C (C=A/B)
0	8.5	0
21.91	8.5	2.58
43.81	8.5	5.15
65.72	8.5	7.73
87.62	8.5	10.31
109.53	8.5	12.89
131.43	8.5	15.46
153.34	8.5	18.04
175.25	8.5	20.62
197.15	8.5	23.19
219.06	8.5	25.77
240.96	8.5	28.35
262.87	8.5	30.93
284.77	8.5	33.50
306.68	8.5	36.08
328.59	8.5	38.66
350.49	8.5	41.23
372.4	8.5	43.81
394.3	8.5	46.39
416.21	8.5	48.97
438.11	8.5	51.54
460.02	8.5	54.12

Appendix B3. Dry Density data and compression of TDA

Table B3-1. Compression of PLTT

Overburden pressure (kPa)	Test 1		Test 2		Test 3		Average	
	1Dry density- (kg/m^3)	1height of TDA (m)	Dry density- (kg/m^3)	height of TDA (m)	Dry density- (kg/m^3)	height of TDA (m)	Average density (kg/m3)	Average height (m)
0.00	402.5	1.04	388.8	1.05	396.6	1.05	396.0	1.047
21.91	510.6	0.82	523.9	0.78	571.9	0.73	535.5	0.78
43.81	621.1	0.68	615.9	0.66	646.7	0.64	627.9	0.66
65.72	679.7	0.62	674.0	0.60	701.3	0.59	685.0	0.61
87.62	720.2	0.59	718.0	0.57	745.4	0.56	727.9	0.57
109.53	753.3	0.57	752.5	0.54	780.4	0.53	762.1	0.55
131.43	792.5	0.54	781.4	0.52	810.9	0.51	794.9	0.53
153.34	814.5	0.52	806.1	0.51	832.1	0.50	817.6	0.51
175.25	836.1	0.51	825.8	0.49			830.9	0.51
197.15	857.1	0.50						
219.06	875.3	0.49						
240.96	890.5	0.48						

ANOVA- PLTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	216035.8	7	30862.25	4.947552	0.000578	2.285235
Columns	5353402	5	1070680	171.6416	1.38E-23	2.485143
Error	218325.9	35	6237.884			
Total	5787764	47				

Table B3-2. Compression of OTR

Overburden pressure (kPa)	Test 1		Test 2		Test 3		Average	
	Dry density-kg/m3	height of TDA	Dry density-kg/m3	height of TDA	Dry density-kg/m3	height of TDA	Average density kg/m3	Average height, m
0.00	457.79	1.05	456.48	1.05	410.23	1.04	441.50	1.04
21.91	544.66	0.88	532.22	0.90	465.44	0.92	514.11	0.90
43.81	604.42	0.79	586.42	0.82	520.44	0.82	570.43	0.81
65.72	645.96	0.74	628.86	0.76	555.69	0.77	610.17	0.76
87.62	683.74	0.70	666.57	0.72	593.52	0.73	647.95	0.71
109.53	718.60	0.67	694.67	0.69	618.98	0.70	677.42	0.68
131.43	747.75	0.64	721.95	0.66	639.81	0.67	703.17	0.66
153.34	770.59	0.62	745.60	0.64	661.03	0.65	725.74	0.64
175.25	794.87	0.60	767.15	0.62	680.38	0.64	747.46	0.62
197.15	816.53	0.59	787.37	0.61	698.55	0.62	767.48	0.60
219.06	832.13	0.58	807.32	0.59	712.83	0.61	784.09	0.59
240.96	852.86	0.56	824.02	0.58	726.45	0.60	801.11	0.58
262.87	868.31	0.55			739.28	0.59	803.79	0.38
284.77	884.33	0.54			753.93	0.58	819.13	0.37
306.68	897.57	0.53			766.36	0.57	831.97	0.37
328.59	916.45	0.52			779.21	0.56	847.83	0.36

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	209882.1	11	19080.19513	4.910681812	2.96E-05	1.967547
Columns	8029234	5	1605846.898	413.2978255	2.66E-42	2.382823
Error	213699.6	55	3885.447247			
Total	8452816	71				

Table B3-3. Compression of MTT

Overburden pressure (kPa)	Test 1		Test 2		Test 3		Average	
	Dry density- (kg/m^3)	height of TDA (m)	Dry density- (kg/m^3)	height of TDA (m)	Dry density- (kg/m^3)	height of TDA (m)	Average density kg/m^3 (m)	Average height (m)
0	397.08	1.05	388.66	1.05	384.21	1.04	389.98	1.04
21.91	549.2	0.76	541.85	0.75	521.13	0.77	537.39	0.76
43.81	623.31	0.67	609.17	0.67	605.7	0.67	612.73	0.67
65.72	669.48	0.62	661.67	0.62	663.1	0.61	664.75	0.62
87.62	709.47	0.59	695.6	0.59	707.38	0.57	704.15	0.58
109.53	746.41	0.56	733.2	0.56	740.81	0.55	740.14	0.55
131.43	774.2	0.54	759.19	0.54	769.92	0.53	767.77	0.53
153.34	799.51	0.52	781.05	0.52	793.3	0.51	791.29	0.52
175.25	820.02	0.51	804.2	0.51	813.05	0.5	812.42	0.51
197.15	841.59	0.49	820.41	0.5	833.81	0.49	831.94	0.49

ANOVA- MTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	260140.7232	9	28904.52	4.965176269	0.000120091	2.095755094
Columns	7031694.586	5	1406339	241.5788069	2.57758E-31	2.422085466
Error	261965.2447	45	5821.45			
Total	7553800.553	59				

Table B3-4. Compression of OTR+PLTT

Overburden Pressure (kPa)	Test 1		Test 2		Test 3		Average	
	Dry density (kg/m3)	height of TDA (m)	Dry density (kg/m3)	height of TDA (m)	Dry density (kg/m3)	height of TDA (m)	Average Density (kg/m3)	Average height (m)
0.00	394.76	1.05	384.82	1.05	358.87	1.05	379.48	1.05
21.91	497.72	0.84	504.90	0.80	511.90	0.73	504.84	0.79
43.81	574.40	0.73	592.51	0.68	566.72	0.66	577.88	0.69
65.72	633.10	0.66	632.51	0.64	616.97	0.61	627.53	0.64
87.62	675.59	0.62	671.51	0.60	650.06	0.58	665.72	0.60
109.53	703.94	0.60	703.15	0.57	680.68	0.55	695.92	0.57
131.43	732.09	0.58	732.56	0.55	706.27	0.53	723.64	0.55
153.34	758.29	0.56	757.34	0.53	731.00	0.51	748.88	0.53
175.25	781.85	0.54	777.81	0.52	749.97	0.50	769.88	0.52
197.15	797.33	0.53	796.26	0.51				
219.06	815.09	0.52	815.60	0.49				
240.96	828.50	0.51						

ANOVA-
OTR+PLTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	193253.2575	8	24156.65719	4.945782748	0.000268189	2.180170453
Columns	5394331.245	5	1078866.249	220.8847871	5.18483E-28	2.449466426
Error	195371.7615	40	4884.294038			
Total	5782956.264	53				

Appendix B4. Raw data for porosity of TDA

Table B4-1. Porosity data as calculated for TDA products

Pressure (kPa)	PLTT	OTR	MTT	PLTT+OTR
0	0.6681	0.6048	0.6934	0.6714
21.9	0.5511	0.5398	0.5786	0.5629
43.8	0.4736	0.4894	0.5206	0.4997
65.7	0.4257	0.4538	0.4807	0.4567
87.6	0.3898	0.42	0.4505	0.4236
109.5	0.3611	0.3936	0.4227	0.3975
131.4	0.3336	0.3706	0.4016	0.3735
153.3	0.3146	0.3504	0.3835	0.3516
175.2		0.3309	0.3673	0.3334
197.2		0.313		
219.1		0.2982		
241.0		0.2829		
262.9		0.2805		
284.8		0.2668		
306.7		0.2553		
328.6		0.2411		

Appendix B5. Linear regression for Compression index of TDA

Linear Regression

Nonlinear Regression

Data Source: Copy of Data 1 in log. Figure 10 void ratio against overburden pressures
Equation: Polynomial, Linear
f=y0+a*x

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9938	0.9877	0.9856	0.0625

	Coefficient	Std. Error	t	P	VIF
y0	2.0643	0.0583	35.3818	<0.0001	6.9647<
a	-0.7236	0.0330	-21.9224	<0.0001	6.9647<

Analysis of Variance:

Uncorrected for the mean of the observations:

	DF	SS	MS
Regression	2	8.0834	4.0417
Residual	6	0.0235	0.0039
Total	8	8.1069	1.0134

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	1.8791	1.8791	480.5917	<0.0001
Residual	6	0.0235	0.0039		
Total	7	1.9026	0.2718		

Linear Regression

Nonlinear Regression

Data Source: Copy of 2OTR in log. Figure 10 void ratio against overburden pressures
Equation: Polynomial, Linear
f=y0+a*x

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9973	0.9946	0.9939	0.0417

	Coefficient	Std. Error	t	P	VIF
y0	2.3024	0.0385	59.7742	<0.0001	7.6658<
a	-0.7599	0.0211	-36.0369	<0.0001	7.6658<

Linear Regression

onlinear Regression

Data Source: 2OTR in log. Figure 10 void ratio against overburden pressures
Equation: Polynomial, Linear
f=y0+a*x

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9655	0.9322	0.9254	0.0938

	Coefficient	Std. Error	t	P	VIF
y0	1.6625	0.0840	19.7952	<0.0001	9.6147<

a	-0.5006	0.0427	-11.7258	<0.0001	9.6147<

Analysis of Variance:

Uncorrected for the mean of the observations:

	DF	SS	MS
Regression	2	7.6105	3.8052
Residual	10	0.0880	0.0088
Total	12	7.6985	0.6415

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	1.2104	1.2104	137.4948	<0.0001
Residual	10	0.0880	0.0088		
Total	11	1.2984	0.1180		

Linear Regression

Equation: Polynomial, Linear
f=y0+a*x

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9939	0.9877	0.9860	0.0582

	Coefficient	Std. Error	t	P	VIF
y0	2.1012	0.0537	39.1205	<0.0001	7.6658<
a	-0.6985	0.0294	-23.7529	<0.0001	7.6658<

Appendix B6. Raw data for porosity of TDA

Table B6-1. Porosity data as calculated for TDA products

Pressure (kPa)	PLTT	Error	OTR	Error	MTT	Error	PLTT+OTR	Error
0	0.6681	±0.0306	0.6048	±0.0140	0.6934	±0.007	0.6714	±0.0075
21.9	0.5511	±0.0252	0.5398	±0.0220	0.5786	±0.008	0.5629	±0.0020
43.8	0.4736	±0.0400	0.4894	±0.0228	0.5206	±0.004	0.4997	±0.0074
65.7	0.4257	±0.0456	0.4538	±0.0247	0.4807	±0.002	0.4567	±0.0045
87.6	0.3898	±0.0483	0.42	±0.0247	0.4505	±0.003	0.4236	±0.0062
109.5	0.3611	±0.0506	0.3936	±0.0268	0.4227	±0.005	0.3975	±0.0065
131.4	0.3336	±0.0543	0.3706	±0.0291	0.4016	±0.006	0.3735	±0.0076
153.3	0.3146	±0.0567	0.3504	±0.0296	0.3835	±0.007	0.3516	±0.0076
175.2			0.3309	±0.0308	0.3673	±0.006	0.3334	±0.0080
197.2			0.313	±0.0317				
219.1			0.2982	±0.0324				
241			0.2829	±0.0341				

Anova Tests for Porosity Data

ANOVA-PLTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	259506.5557	7	37072.3651	4.379748292	0.001007	2.23707
Columns	8684372.662	6	1447395.444	170.9960426	7.22E-28	2.323994
Error	355508.8627	42	8464.49673			

Total	9299388.08	55

ANOVA-OTR

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	210022.6	11	19092.96	4.91727	2.91778E-05	1.967546647
Columns	8036707	5	1607341	413.9605	2.54985E-42	2.382823311
Error	213556	55	3882.837			
Total	8460286	71				

ANOVA-MTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	143511.9	4	35877.99	7.948757	0.000314491	2.776289289
Columns	2878059	6	479676.5	106.2722	4.41155E-16	2.508188823
Error	108327.8	24	4513.66			
Total	3129899	34				

ANOVA-OTR+PLTT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	193425.1	8	24178.13	4.954359	0.000264	2.18017
Columns	5397889	5	1079578	221.2171	5.04E-28	2.449466
Error	195207	40	4880.174			
Total	5786521	53				

ANOVA for Porosity data

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	8	3.5176	0.4397	0.0145
Column 2	8	3.6224	0.4528	0.007691
Column 3	8	3.9316	0.49145	0.010782
Column 4	8	3.7369	0.467113	0.011561

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.011784	3	0.003928	0.352822	0.787421	2.946685
Within Groups	0.311732	28	0.011133			
Total	0.323516	31				

Appendix B7. Linear regression for Coefficient Compression

Linear Regression
Data source: Data 1 in Void ratio plots

PLTT = 2.410 - (0.393 * Pressure)

N = 7   Missing Observations = 4

R = 0.996   Rsqr = 0.993   Adj Rsqr = 0.992

Standard Error of Estimate = 0.025

	Coefficient	**Std. Error**	**t**	**P**
Constant	2.410	0.0643	37.450	<0.001
Pressure	-0.393	0.0148	-26.561	<0.001

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	1	0.434	0.434	705.495	<0.001
Residual	5	0.00308	0.000615		
Total	6	0.437	0.0729		

Normality Test (Shapiro-Wilk)   Passed   (P = 0.390)

Constant Variance Test: Passed   (P = 0.297)

Power of performed test with alpha = 0.050: 1.000

Linear Regression

Data source: Data 1 in Void ratio plots

MTT = 2.537 - (0.382 * Pressure)

N = 8   Missing Observations = 3

R = 0.999   Rsqr = 0.998   Adj Rsqr = 0.998

Standard Error of Estimate = 0.013

	Coefficient	**Std. Error**	**t**	**P**
Constant	2.537	0.0307	82.535	<0.001
Pressure	-0.382	0.00689	-55.445	<0.001

Analysis of Variance:

	DF	**SS**	**MS**	**F**	**P**
Regression	1	0.505	0.505	3074.114	<0.001
Residual	6	0.000986	0.000164		
Total	7	0.506	0.0723		

Normality Test (Shapiro-Wilk)   Passed   (P = 0.154)

Constant Variance Test: Passed   (P = 0.931)

Power of performed test with alpha = 0.050: 1.000

Linear Regression

Data source: Data 1 in Void ratio plots

OTR = 2.195 - (0.329 * Pressure)

N = 11

R = 1.000 Rsqr = 1.000 Adj Rsqr = 1.000

Standard Error of Estimate = 0.005

	Coefficient	Std. Error	t	P
Constant	2.195	0.0107	204.429	<0.001
Pressure	-0.329	0.00227	-144.836	<0.001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	0.600	0.600	20977.592	<0.001
Residual	9	0.000257	0.0000286		
Total	10	0.600	0.0600		

Normality Test (Shapiro-Wilk) Passed (P = 0.189)

Constant Variance Test: Passed (P = 0.065)

Power of performed test with alpha = 0.050: 1.000

Linear Regression

Data source: Data 1 in Void ratio plots

PLTT+OTR = 2.434 - (0.377 * Pressure)

N = 8 Missing Observations = 3

R = 0.999 Rsqr = 0.998 Adj Rsqr = 0.998

Standard Error of Estimate = 0.013

	Coefficient	Std. Error	t	P
Constant	2.434	0.0318	76.513	<0.001
Pressure	-0.377	0.00713	-52.887	<0.001

Power of performed test with alpha = 0.050: 1.000

Appendix B7 – continued

Table B7-1. Typical landfill heights in Alberta

Landfill Name	Municipal or Industrial	Landfill Depth. Max	Drainage Medium	Other information
N/A	industrial (oilfield)	typically 20-25m	N/A	"Speaking from experience the Class II oilfield landfills in Alberta are typically approved at heights of 15 - 20 m above berm height and the average depth of cell would be 5m. Total height above Leachate collection system would range between 20 - 25m."
Calgary BFI landfill	industrial	~80 m	TDA in one cell only	Note: this depth seems unusually high – I've contacted them to confirm, but have not had a response.
Horizon Oil Sands (CNRL)	industrial	~8m	TDA (in at least some cells)	n/a
Swan Hills	industrial	max 16.5m without cap. With cap, ~18m.		"From my experience, waste thickness for industrial/oilfield landfills generally range from 10 to 20m (excluding cap)."
Bonnyville landfill	industrial	currently ~24 m design depth ~ 43.2	aggregate	max design depth includes 1m of clay and 300mm of top soil capping.
ECCO landfill (Calgary)	dry waste (class III)	average ~40m	aggregate	from Ken: "You mention a compressive load. from the fill. I expect that a landfill, similar to a road fill, will see the load distributed so that some maximum load will presumably result, no matter what the depth of the fill. I would be curious to know what your analysis seems to suggest."
Calgary Shepard Calgary Spyhill Calgary East	municipal	typically 20-25m, with max depths of ~30m	TDA (in at least some cells in all three landfills)	Could also call Gary Lee @ 403-268-8479, as he designs landfills and may have more technical information at hand.
Lethbridge landfill	municipal	Cell 1 design depths: average ~ 46.4m maximum ~ 51.4m	TDA (in at least some cells)	The waste depth in cell 3 - phase IV for example would have a design depth of approximately 862.6 m with maximum elevation averaging 905 m ASL. (This would allow for elevation of approximately 910 on the westward end of the cell tying into the east footprint at approximate elevation of 898 m ASL.

Landfill Name	Municipal or Industrial	Landfill Depth. Max	Drainage Medium	Other information
		Cell 3 design depths: average ~ 47.2m maximum ~ 65.2m		The depth of cell 1 – phase IV has a design depth of approximately 848.8 m and an approximate maximum height of 892 m. The maximum elevation for the placing of waste according to our approval is 910 m ASL. Then we need to place a final cap and depending on the closure design, the actual height in some areas may increase by a minimum of 1 to as much as 4 meters. The height is somewhat restricted near the north-end of phase IV as the overhead power-line right-of-ways do not allow for us to exceed a height of 889 and 894.8 m respectively, and I believe this includes a final cover of a minimum 1 m.
Ryley landfill	municipal	Cell 3 average ~ 30m	TDA (in at least some cells)	Cell 3 uses TDA as drainage material
Grande Prairie (Aquatera) landfill	municipal	~18 - 20 m	TDA (in at least some cells)	n/a
Ridgeview landfill	municipal	~11.5 m	aggregate	n/a
Roseridge Landfill	municipal	~12.8m	TDA (in at least some cells)	n/a
Leduc landfill	municipal	approximately 20 m	TDA	n/a
Clover Bar landfill	municipal	~65 m	mainly aggregate	Assume a waste density of 800 kg/m^3
Drayton Valley (Aspen) landfill	municipal	~10 m	TDA (in at least some cells)	
Camrose landfill	municipal	~8-10m of waste plus 1m clay capping.	TDA (in at least some cells)	"We use the tire shred drainage material with an un-compacted depth of 200-300mm."
Brooks landfill	municipal	~18 to 20 m (possibly more)	TDA (in at least some cells)	The original (Golder Associates) maximum design elevation was 781.0m including the 1m cap (this elevation has been approximately attained in the special waste cell but

Landfill Name	Municipal or Industrial	Landfill Depth. Max	Drainage Medium	Other information
				not in the MSW). The cell floor design elevation in the middle of the east side is approximately 763.0m and in the middle of the west side is approximately 761.0m (we are not too concerned about achieving an exact maximum elevation as we are now approved to go higher). The floor elevations are under the 1m tire shred in both current cells.
West Dried Meat Lake landfill	municipal	~30 m	TDA (in at least some cells)	n/a
Slave Lake landfill	municipal	currently ~13 m design depth ~16 m	aggregate	
Red Deer landfill	municipal	max ~29.3m	aggregate	"At the current phase of landfilling at Red Deer's landfill, the most waste we have above the leachate collection system is approximately 22 m. Once the current phase is complete (in another 10 years or so) the largest depth of waste will be approximately 28 m plus the 1.3 m worth of final cap (clay, sub-soil and top-soil) that will be applied. Also, if it helps, the average density of our landfilled waste, which includes daily cover, is 0.65 tonnes/m3."

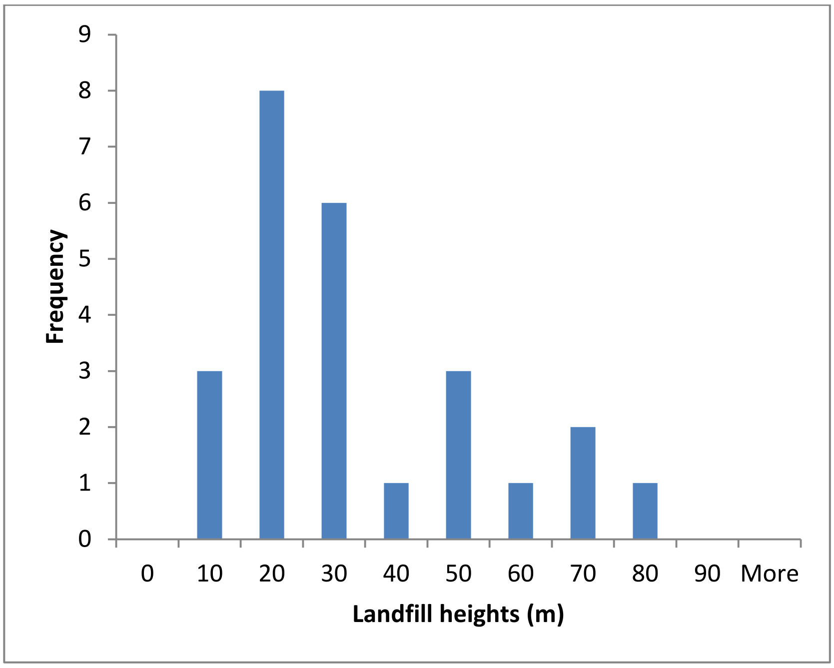


Figure B7-2. Frequency distribution of sample landfill heights in Alberta

Appendix B8

Appendix B8: Hydraulic conductivity data

Table B8-1. Computation for hydraulic conductivity of PLTT at 22 kPa (column 1).

Test No.	1		2		3		4	
Kpa	21.9057	21.9057	21.9057	21.9057	21.9057	21.9057	21.9057	21.9057
Mass of PLTT (kg)	102.680	102.680	102.680	102.680	102.680	102.680	102.680	102.680
Height of gravel layer (m)	0.774	0.774	0.774	0.774	0.774	0.774	0.774	0.774
X area of TDA sample (m^2)	0.2550	0.2550	0.2550	0.2550	0.2550	0.2550	0.2550	0.2550
Volume of PLTT ($m^{3)}$	0.1974	0.1974	0.1974	0.1974	0.1974	0.1974	0.1974	0.1974
Dry density (kg/m3)	520.1463	520.1463	520.1463	520.1463	520.1463	520.1463	520.1463	520.1463
Temperature	10	10	10	10	9	9	9	9
Total porosity	0.5948	0.5948	0.5948	0.5948	0.5948	0.5948	0.5948	0.5948
Drainable Porosity, ε	0.5918	0.5918	0.5918	0.5918	0.5918	0.5918	0.5918	0.5918
Void ratio, e	1.4606	1.4606	1.4606	1.4606	1.4606	1.4606	1.4606	1.4606
Yield factor	0.8487	0.8487	0.8487	0.8487	0.8487	0.8487	0.8487	0.8487
Q (L)	0.622	0.638	1.149		1.41	1.41	2.1	
Quantity of water discharged (m^3)	0.00062	0.00064	0.00115	0.00115	0.00141	0.00141	0.00210	0.00210
time in seconds	42.1	32.09	29.21	29.21	18.94	18.94	16.18	16.18
Flow in m3/sec	0.0000148	0.0000199	0.0000393	0.0000393	0.0000744	0.0000744	0.0001298	0.0001298
velocity (m/sec)	5.79281E-05	7.7953E-05	0.00015423	0.00015423	0.00029189	0.0002919	0.00050889	0.0005089
Average velocity (m/sec)	6.79404E-05		0.00015423		0.00029189		0.000508887	
Pz1	101.9	101.9	102.1	102.1	102.4	102.4	102.9	102.9
Pz6	101.7	101.7	101.9	101.9	102.3	102.3	102.7	102.7
i(1-6)	0.003076923	0.00307692	0.003076923	0.00307692	0.00153846	0.0015385	0.00307692	0.0030769
average i	0.003076923		0.003076923		0.001538462		0.003076923	

Table B8-2. Computation for hydraulic conductivity of PLTT at 44 kPa (column 1)

Test No	1		2		3		4		5	
Kpa	43.8114	43.8114	43.8114	43.8114	43.8114	43.8114	43.8114	43.8114	43.8114	43.8114
Mass of PLTT (kg)	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68
Height of gravel layer (m)	0.658	0.658	0.658	0.658	0.658	0.658	0.658	0.658	0.658	0.658
X- area of TDA - m^2	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047
Volume of PLTT (m3)	0.167821	0.167821	0.167821	0.167821	0.167821	0.167821	0.167821	0.167821	0.167821	0.167821
Dry density (kg/m3)	611.8438	611.8438	611.8438	611.8438	611.8438	611.8438	611.8438	611.8438	611.8438	611.8438
Temperature	9	9	9	9	8	8	8	8	8	8
Total porosity	0.523375	0.523375	0.523375	0.523375	0.523375	0.523375	0.523375	0.523375	0.523375	0.523375
Drainable Porosity, ε	0.51985	0.51985	0.51985	0.51985	0.51985	0.51985	0.51985	0.51985	0.51985	0.51985
Void ratio, e	1.090689	1.090689	1.090689	1.090689	1.090689	1.090689	1.090689	1.090689	1.090689	1.090689
Yield factor	0.745518	0.745518	0.745518	0.745518	0.745518	0.745518	0.745518	0.745518	0.745518	0.745518
Q (L)	1.6	1.005	0.15805	0.16527	0.267399	0.26659	0.4111	0.4111	0.177815	0.176446
Quantity of water discharged (m3)	0.0016	0.001005	0.000158	0.000165	0.000267	0.000267	0.000411	0.000411	0.000178	0.000176
time in seconds	31.81	19.79	1	1	1	1	1	1	1	1
Flow in m3/sec	5.03E-05	5.08E-05	0.000158	0.000165	0.000267	0.000267	0.000411	0.000411	0.000178	0.000176
velocity (m/sec)	0.000197	0.000199	0.00062	0.000648	0.001048	0.001045	0.001612	0.001612	0.000697	0.000692
Average velocity (m/sec)	0.000198164		0.000633845		0.001046846		0.001611863		0.000694503	
Re	24.52968	24.52968	78.46052	78.46052	125.8441	125.8441	193.7662	193.7662	83.48795	83.48795
Pz1	102	102	103.2	103.2	104	104	104.7	104.9	103.4	103.4
Pz6	101.8	101.9	102.9	102.9	103.4	103.4	103.7	103.7	103.1	103.1
i(1-6 L= 65cm	0.003077	0.001538	0.004615	0.004615	0.009231	0.009231	0.015385	0.018462	0.004615	0.004615
average i	0.002307692		0.004615385		0.009230769		0.033846154		0.009230769	

Table B8-3. Computation for hydraulic conductivity of PLTT at 110 kPa (column 1)

Test No	1		2		3		4	
Kpa	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285
Mass of PLTT (kg)	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68
Height of PLTT layer (m)	0.524	0.524	0.524	0.524	0.524	0.524	0.524	0.524
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.255047	0.255047	0.255047
Volume of PLTT (m3)	0.133644366	0.133644366	0.133644366	0.133644366	0.133644366	0.133644	0.133644	0.133644
Dry density (kg/m3)	768.307734	768.307734	768.307734	768.307734	768.307734	768.3077	768.3077	768.3077
Temp	13	13	11	11	8	8	8	8
Total porosity	0.401489652	0.401489652	0.401489652	0.401489652	0.401489652	0.40149	0.40149	0.40149
Drainable Porosity, ε	0.404319326	0.404319326	0.404319326	0.404319326	0.404319326	0.404319	0.404319	0.404319
Void ratio, e	0.675542749	0.675542749	0.675542749	0.675542749	0.675542749	0.675543	0.675543	0.675543
Yield factor	0.579835546	0.579835546	0.579835546	0.579835546	0.579835546	0.579836	0.579836	0.579836
Q (L)	0.0762775	0.0809751	0.128763	0.1302899	0.187633	0.181582	0.268684	0.27217
Quantity of water discharged (m3)	7.62775E-05	8.09751E-05	0.000128763	0.00013029	0.000187633	0.000182	0.000269	0.000272
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	7.62775E-05	8.09751E-05	0.000128763	0.00013029	0.000187633	0.000182	0.000269	0.000272
velocity (m/sec)	0.000299073	0.000317492	0.000504861	0.000510848	0.000735682	0.000712	0.001053	0.001067
Average velocity (m/sec)	0.000308282		0.000507854		0.000723819		0.001060305	
Re	34.44454721		53.66239119		70.13635947		102.741	
Pz1	102.5	102.5	103	103	103.7	103.8	104.4	104.4
Pz6	102.25	102.3	102.6	102.6	103	103	103.5	103.5
i(1-6)	0.004770992	0.003816794	0.007633588	0.007633588	0.013358779	0.015267	0.017176	0.017176
average i	0.004293893		0.007633588		0.014312977		0.017175573	

Table B8-4. Computation for hydraulic conductivity of PLTT at 142 kPa (column 1)

Test No	1		2		3		4		5	
Kpa	142.3871	142.38705	142.3871	142.3871	142.3871	142.38705	142.3871	142.38705	142.38705	142.38705
Mass of PLTT (kg)	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68	102.68
Height of PLTT layer (m)	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491	0.491
X- area of TDA (m2)	0.255047	0.2550465	0.255047	0.255047	0.255047	0.2550465	0.255047	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.125228	0.12522783	0.125228	0.125228	0.125228	0.1252278	0.125228	0.12522783	0.1252278	0.125227832
Dry density (kg/m3)	819.9455	819.945525	819.9455	819.9455	819.9455	819.94552	819.9455	819.945525	819.94552	819.9455246
temp	8	8	8	8	8	8	8	8	8	8
Total porosity	0.361264	0.36126391	0.361264	0.361264	0.361264	0.3612639	0.361264	0.36126391	0.3612639	0.361263905
Drainable Porosity, ε	0.365432	0.36543218	0.365432	0.365432	0.365432	0.3654322	0.365432	0.36543218	0.3654322	0.365432177
Void ratio, e	0.572118	0.57211762	0.572118	0.572118	0.572118	0.5721176	0.572118	0.57211762	0.5721176	0.572117625
Yield factor	0.524067	0.52406737	0.524067	0.524067	0.524067	0.5240674	0.524067	0.52406737	0.5240674	0.52406737
Q (L)	0.67	1.31	0.1045	0.10213	0.137509	0.1392	0.179609	0.1814299	0.26869	0.264458
Quantity of water discharged (m3)	0.00067	0.00131	0.000105	0.000102	0.000138	0.0001392	0.00018	0.00018143	0.0002687	0.000264458
time in seconds	16.87	32.54	1	1	1	1	1	1	1	1
Flow in m3/sec	3.97E-05	4.0258E-05	0.000105	0.000102	0.000138	0.0001392	0.00018	0.00018143	0.0002687	0.000264458
velocity (m/sec)	0.000156	0.00015785	0.00041	0.0004	0.000539	0.0005458	0.000704	0.00071136	0.0010535	0.001036901
Average velocity (m/sec)	0.000156782		0.000405083		0.000542467		0.00070779		0.001045198	
Re	14.26087176		36.84620146		49.34259701		64.38035156		95.07079618	
Pz1	101.9	102	102.7	102.8	103.1	103.1	103.65	103.6	104.4	104.4
Pz6	101.6	101.8	102.4	102.4	102.65	102.7	103	103	103.2	103.2
i(1-6)	0.00611	0.00407332	0.00611	0.008147	0.009165	0.0081466	0.013238	0.01221996	0.0244399	0.024439919
average i	0.00509165		0.00712831		0.008655804		0.012729124		0.024439919	

Table B8-5. Computation for hydraulic conductivity of PLTT at 66 kPa (column 4)

Test No	1		2		3		4	
Kpa	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171
Mass of PLTT (kg)	116.97	116.97	116.97	116.97	116.97	116.97	116.97	116.97
Height of PLTT layer (m)	0.757	0.757	0.757	0.757	0.757	0.757	0.757	0.757
X area of TDA (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.193070201	0.193070201	0.193070201	0.193070201	0.193070201	0.193070201	0.193070201	0.193070201
Dry density (kg/m3)	605.8418114	605.8418114	605.8418114	605.8418114	605.8418114	605.8418114	605.8418114	605.8418114
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314
Drainable Porosity, ε	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314	0.528050314
Void ratio, e	1.118869936	1.118869936	1.118869936	1.118869936	1.118869936	1.118869936	1.118869936	1.118869936
Yield factor	0.757278523	0.757278523	0.757278523	0.757278523	0.757278523	0.757278523	0.757278523	0.757278523
Temperature	4	4	4.5	4.5	4	4	4	4
Q (L)	1.43	1.4	3.06	2.98	5.23	5.34	7.465	7.57
Quantity of water discharged (m3)	0.00143	0.0014	0.00306	0.00298	0.00523	0.00534	0.007465	0.00757
time in seconds	20.69	20.6	20.4	20.21	19.73	20.79	20.58	20.42
Flow in m3/sec	6.91155E-05	6.79612E-05	0.00015	0.000147452	0.000265079	0.000256854	0.000362731	0.000370715
velocity (m/sec)	0.000270992	0.000266466	0.000588128	0.000578137	0.001039334	0.001007088	0.001422214	0.001453519
Average velocity (m/sec)	0.000268729		0.000583132		0.001023211		0.001437867	
Pz1	102.3	102.3	103.1	103.1	104.1	104.1	105	104.5
Pz6	102.1	102.1	102.7	102.7	103.5	103.5	104	103.8
i(1-6)	0.003100775	0.003100775	0.00620155	0.00620155	0.009302326	0.009302326	0.015503876	0.010852713
average i	0.003100775		0.00620155		0.009302326		0.013178295	

Table B8-6. Computation for hydraulic conductivity of PLTT at 88 kPa (column 4)

Test No	1		2		3	
Kpa	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228
Mass of PLTT (kg)	116.97	116.97	116.97	116.97	116.97	116.97
Height of PLTT layer (m)	0.635	0.635	0.635	0.635	0.635	0.635
X- area of TDA (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.161954528	0.161954528	0.161954528	0.161954528	0.161954528	0.161954528
Dry density (kg/m3)	722.2397657	722.2397657	722.2397657	722.2397657	722.2397657	722.2397657
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.437376517	0.437376517	0.437376517	0.437376517	0.437376517	0.437376517
Drainable Porosity, ε	0.437376517	0.437376517	0.437376517	0.437376517	0.437376517	0.437376517
Void ratio, e	0.777387595	0.777387595	0.777387595	0.777387595	0.777387595	0.777387595
Yield factor	0.627242961	0.627242961	0.627242961	0.627242961	0.627242961	0.627242961
Temperature	4.2	4.5	4.5	4.5	4.5	4.5
Q (L)	4.575	3.45	5.375	4.945	8.36	9.3
Quantity of water discharged (m3)	0.004575	0.00345	0.005375	0.004945	0.00836	0.0093
time in seconds	26.91	20.43	20.72	20.43	20.4	20.6
Flow in m3/sec	0.000170011	0.000168869	0.000259411	0.000242046	0.000409804	0.000451456
velocity (m/sec)	0.000666589	0.000662112	0.001017113	0.000949027	0.001606781	0.001770094
Average velocity (m/sec)	0.00066435		0.00098307		0.001688438	
Pz1	103.3	103.3	104.4	104.4	105.4	105.6
Pz6	102.8	102.8	103.6	103.5	104	104.2
i(1-6)	0.007874016	0.007874016	0.012598425	0.014173228	0.022047244	0.022047244
average i	0.007874016		0.013385827		0.022047244	

Table B8-7. Computation for hydraulic conductivity of PLTT at 131 kPa (column 4)

Test No	1		2		3		4	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of PLTT (kg)	116.97	116.97	116.97	116.97	116.97	116.97	116.97	116.97
Height of PLTT layer (m)	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.14792697	0.14792697	0.14792697	0.14792697	0.14792697	0.14792697	0.14792697	0.14792697
Dry density (kg/m3)	790.7280194	790.7280194	790.7280194	790.7280194	790.7280194	790.7280194	790.7280194	790.7280194
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429
Drainable Porosity, ε	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429	0.38402429
Void ratio, e	0.623440638	0.623440638	0.623440638	0.623440638	0.623440638	0.623440638	0.623440638	0.623440638
Yield factor	0.550730374	0.550730374	0.550730374	0.550730374	0.550730374	0.550730374	0.550730374	0.550730374
Temperature	5.2	5.2	5.2	5.5	5	4.8	4	4
Q (L)	2.35	2.35	4.88	4.465	6.2	6.16	7.005	7.005
Quantity of water discharged (m3)	0.00235	0.00235	0.00488	0.004465	0.0062	0.00616	0.007005	0.007005
time in seconds	20.49	20.42	22.07	20.52	20.48	20.48	20.42	20.42
Flow in m3/sec	0.00011469	0.000115083	0.000221115	0.000217593	0.000302734	0.000300781	0.000343046	0.000343046
velocity (m/sec)	0.000449683	0.000451225	0.000866958	0.000853149	0.001186977	0.001179319	0.001345033	0.001345033
Average velocity (m/sec)	0.000450454		0.000860053		0.001183148		0.001345033	
Pz1	102.9	102.9	104	104.1	105	105.1	105.6	105.6
Pz6	102.6	102.5	103.15	103.2	103.7	103.9	103.8	103.8
i(1-6)	0.005172414	0.006896552	0.014655172	0.015517241	0.022413793	0.020689655	0.031034483	0.031034483
average i	0.006034483		0.015086207		0.021551724		0.031034483	

Table B8-8. Computation for hydraulic conductivity of PLTT at 175 kPa (column 4)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of PLTT (kg)	116.97	116.97	116.97	116.97	116.97	116.97
Height of PLTT layer (m)	0.545	0.545	0.545	0.545	0.545	0.545
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.139000343	0.139000343	0.139000343	0.139000343	0.139000343	0.139000343
Dry density (kg/m3)	841.5087179	841.5087179	841.5087179	841.5087179	841.5087179	841.5087179
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.344466217	0.344466217	0.344466217	0.344466217	0.344466217	0.344466217
Drainable Porosity, ε	0.344466217	0.344466217	0.344466217	0.344466217	0.344466217	0.344466217
Void ratio, e	0.525474392	0.525474392	0.525474392	0.525474392	0.525474392	0.525474392
Yield factor	0.494000024	0.494000024	0.494000024	0.494000024	0.494000024	0.494000024
Temperature	4	4	4	4	4	4
Q (L)	2.88	2.88	5.55	5.535	7.395	7.395
Quantity of water discharged (m3)	0.00288	0.00288	0.00555	0.005535	0.007395	0.007395
time in seconds	20.46	20.46	20.39	20.49	20.84	20.84
Flow in m3/sec	0.000140762	0.000140762	0.000272192	0.000270132	0.000354846	0.000354846
velocity (m/sec)	0.000551909	0.000551909	0.001067226	0.001059147	0.001391301	0.001391301
Average velocity (m/sec)	0.000551909		0.001063187		0.001391301	
Pz1	103.1	103.1	104.8	104.9	106.2	106.2
Pz6	102.6	102.6	103.6	103.6	104	104
i(1-6)	0.009174312	0.009174312	0.022018349	0.023853211	0.040366972	0.040366972
average i	0.009174312		0.02293578		0.040366972	

Table B8-9. Computation for hydraulic conductivity of PLTT at 252 kPa (column 4)

Test No	1		2		3	
Kpa	251.91555	251.91555	251.91555	251.91555	251.91555	251.91555
Mass of PLTT (kg)	116.97	116.97	116.97	116.97	116.97	116.97
Height of PLTT layer (m)	0.485	0.485	0.485	0.485	0.485	0.485
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.123697553	0.123697553	0.123697553	0.123697553	0.123697553	0.123697553
Dry density (kg/m3)	945.6128891	945.6128891	945.6128891	945.6128891	945.6128891	945.6128891
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.263369254	0.263369254	0.263369254	0.263369254	0.263369254	0.263369254
Drainable Porosity, ε	0.235203427	0.235203427	0.235203427	0.235203427	0.235203427	0.235203427
Void ratio, e	0.31929624	0.31929624	0.31929624	0.31929624	0.31929624	0.31929624
Yield factor	0.337305934	0.337305934	0.337305934	0.337305934	0.337305934	0.337305934
Temperature	14.5	14.5	11.8	11.8	6.2	5.5
Q (L)	0.28	0.28	2.865	2.83	5.14	5.1
Quantity of water discharged (m3)	0.00028	0.00028	0.002865	0.00283	0.00514	0.0051
time in seconds	22.25	22.25	20.54	20.73	20.58	20.58
Flow in m3/sec	1.25843E-05	1.25843E-05	0.000139484	0.000136517	0.000249757	0.000247813
velocity (m/sec)	4.93411E-05	4.93411E-05	0.000546896	0.000535264	0.000979261	0.00097164
Average velocity (m/sec)	4.93411E-05		0.00054108		0.00097545	
Pz1	102.2	102.2	103.5	103.6	105.6	105.6
Pz6	101.6	101.6	102.7	102.7	103.5	103.5
i(1-6)	0.012371134	0.012371134	0.016494845	0.018556701	0.043298969	0.043298969
average i	0.012371134		0.017525773		0.043298969	

Table B8-10. Computation for hydraulic conductivity of PLTT at 131 kPa (column 1)

Test No	1		2		3	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of PLTT (kg)	108.9	108.9	108.9	108.9	108.9	108.9
Height of PLTT layer (m)	0.544	0.544	0.544	0.544	0.544	0.544
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.138745296	0.138745296	0.138745296	0.138745296	0.138745296	0.138745296
Dry density (kg/m3)	784.8914748	784.8914748	784.8914748	784.8914748	784.8914748	784.8914748
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.388570947	0.388570947	0.388570947	0.388570947	0.388570947	0.388570947
Drainable Porosity, ε	0.3691424	0.3691424	0.3691424	0.3691424	0.3691424	0.3691424
Void ratio, e	0.603737095	0.603737095	0.603737095	0.603737095	0.603737095	0.603737095
Yield factor	0.529388212	0.529388212	0.529388212	0.529388212	0.529388212	0.529388212
Temperature	3.5	3.5	3.5	3.5	3.5	3.5
Q (L)	5.835	5.875	8.075	9.33	10.27	10.35
Quantity of water discharged (m3)	0.005835	0.005875	0.008075	0.00933	0.01027	0.01035
time in seconds	20.48	20.43	20.7	20.49	20.78	20.67
Flow in m3/sec	0.000284912	0.000287567	0.000390097	0.000455344	0.000494225	0.000500726
velocity (m/sec)	0.001117099	0.001127509	0.001529512	0.001785337	0.001937785	0.001963272
Average velocity (m/sec)	0.001122304		0.001657425		0.001950528	
Pz1	103.2	103.1	103.9	103.9	104.3	104.3
Pz6	103.1	103	103.5	103.5	103.7	103.85
i(1-6)	0.001838235	0.001838235	0.007352941	0.007352941	0.011029412	0.008272059
average i	0.001838235		0.007352941		0.009650735	

Table B8-11. Computation for hydraulic conductivity of PLTT at 175 kPa (column 1)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of PLTT (kg)	108.9	108.9	108.9	108.9	108.9	108.9
Height of PLTT layer (m)	0.51	0.51	0.51	0.51	0.51	0.51
X area of TDA (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.130073715	0.130073715	0.130073715	0.130073715	0.130073715	0.130073715
Dry density (kg/m3)	837.2175731	837.2175731	837.2175731	837.2175731	837.2175731	837.2175731
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.347809011	0.347809011	0.347809011	0.347809011	0.347809011	0.347809011
Drainable Porosity, ε	0.31302811	0.31302811	0.31302811	0.31302811	0.31302811	0.31302811
Void ratio, e	0.31302811	0.479963867	0.479963867	0.479963867	0.479963867	0.479963867
Yield factor	0.448914541	0.448914541	0.448914541	0.448914541	0.448914541	0.448914541
Temperature	4	4	4	4	3.6	3.6
Q (L)	7.185	7.025	9.27	9.14	9.975	10.135
Quantity of water discharged (m3)	0.007185	0.007025	0.00927	0.00914	0.009975	0.010135
time in seconds	20.88	20.49	21.09	20.54	20.46	20.73
Flow in m3/sec	0.000344109	0.00034285	0.000439545	0.000444985	0.000487537	0.000488905
velocity (m/sec)	0.001349202	0.001344265	0.001723391	0.001744723	0.00191156	0.001916925
Average velocity (m/sec)	0.001346734		0.001734057		0.001914242	
Pz1	103.8	103.8	104.3	104.3	104.65	104.65
Pz6	103.3	103.3	103.5	103.6	103.7	103.8
i(1-6)	0.009803922	0.009803922	0.015686275	0.01372549	0.018627451	0.016666667
average i	0.009803922		0.014705882		0.017647059	

Table B8-12. Computation for hydraulic conductivity of PLTT at 175 kPa (column 1)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of PLTT (kg)	108.9	108.9	108.9	108.9	108.9	108.9
Height of PLTT layer (m)	0.51	0.51	0.51	0.51	0.51	0.51
X area of TDA (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.130073715	0.130073715	0.130073715	0.130073715	0.130073715	0.130073715
Dry density (kg/m3)	837.2175731	837.2175731	837.2175731	837.2175731	837.2175731	837.2175731
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.347809011	0.347809011	0.347809011	0.347809011	0.347809011	0.347809011
Drainable Porosity, ε	0.31302811	0.31302811	0.31302811	0.31302811	0.31302811	0.31302811
Void ratio, e	0.31302811	0.479963867	0.479963867	0.479963867	0.479963867	0.479963867
Yield factor	0.448914541	0.448914541	0.448914541	0.448914541	0.448914541	0.448914541
Temperature	4	4	4	4	3.6	3.6
Q (L)	7.185	7.025	9.27	9.14	9.975	10.135
Quantity of water discharged (m3)	0.007185	0.007025	0.00927	0.00914	0.009975	0.010135
time in seconds	20.88	20.49	21.09	20.54	20.46	20.73
Flow in m3/sec	0.000344109	0.00034285	0.000439545	0.000444985	0.000487537	0.000488905
velocity (m/sec)	0.001349202	0.001344265	0.001723391	0.001744723	0.00191156	0.001916925
Average velocity (m/sec)	0.001346734		0.001734057		0.001914242	
Pz1	103.8	103.8	104.3	104.3	104.65	104.65
Pz6	103.3	103.3	103.5	103.6	103.7	103.8
i(1-6)	0.009803922	0.009803922	0.015686275	0.01372549	0.018627451	0.016666667
average i	0.009803922		0.014705882		0.017647059	

Table B8-13. Computation for hydraulic conductivity of PLTT at 208 kPa (column 1)

Test No	1		2		3	
Kpa	208.10415	208.10415	208.10415	208.10415	208.10415	208.10415
Mass of PLTT (kg)	108.9	108.9	108.9	108.9	108.9	108.9
Height of PLTT layer (m)	0.49	0.49	0.49	0.49	0.49	0.49
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of PLTT (m3)	0.124972785	0.124972785	0.124972785	0.124972785	0.124972785	0.124972785
Dry density (kg/m3)	871.389719	871.389719	871.389719	871.389719	871.389719	871.389719
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.32118897	0.32118897	0.32118897	0.32118897	0.32118897	0.32118897
Drainable Porosity, ε	0.289070073	0.289070073	0.289070073	0.289070073	0.289070073	0.289070073
Void ratio, e	0.425847637	0.425847637	0.425847637	0.425847637	0.425847637	0.425847637
Yield factor	0.41455625	0.41455625	0.41455625	0.41455625	0.41455625	0.41455625
Temperature	4	4	4	4	3.6	3.6
Q (L)	6.51	6.55	8.675	8.69	10.13	10.215
Quantity of water discharged (m3)	0.00651	0.00655	0.008675	0.00869	0.01013	0.010215
time in seconds	20.52	20.73	21.21	20.48	20.43	20.63
Flow in m3/sec	0.000317251	0.000315967	0.000409005	0.000424316	0.000495839	0.000495153
velocity (m/sec)	0.001243897	0.001238861	0.001603649	0.001663683	0.001944114	0.001941421
Average velocity (m/sec)	0.001241379		0.001633666		0.001942768	
Pz1	103.6	103.7	104.6	104.9	105	105.2
Pz6	103.1	103.2	103.6	103.9	103.7	103.8
i(1-6)	0.010204082	0.010204082	0.020408163	0.020408163	0.026530612	0.028571429
average i	0.010204082		0.020408163		0.02755102	

Table B8-14. Computation for hydraulic conductivity of OTR at 110 kPa (column 3)

Test No	1		2		3		4	
Kpa	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285
Mass of OTR (kg)	128.24	128.24	128.24	128.24	128.24	128.24	128.24	128.24
Height of gravel layer (m)	0.735	0.735	0.735	0.735	0.737	0.737	0.737	0.737
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.187459178	0.187459178	0.187459178	0.187459178	0.187969271	0.187969271	0.187969271	0.187969271
Dry density (kg/m3)	684.095608	684.095608	684.095608	684.095608	682.2391748	682.2391748	682.2391748	682.2391748
Temperature	8	8	7.8	7.8	7	7	7	7
Total porosity	0.431185938	0.431185938	0.431185938	0.431185938	0.432729531	0.432729531	0.432729531	0.432729531
Drainable Porosity, ε	0.420678257	0.420678257	0.420678257	0.420678257	0.41953666	0.41953666	0.41953666	0.41953666
Void ratio, e	0.739570775	0.739570775	0.739570775	0.739570775	0.739570775	0.739570775	0.739570775	0.739570775
Yield factor	0.603295937	0.603295937	0.603295937	0.603295937	0.60165877	0.60165877	0.60165877	0.60165877
Q (L)	0.234093537	0.19803865	0.30235326	0.304530497	0.351298027	0.350035718	0.427329198	0.427329198
Quantity of water discharged (m3)	0.000234094	0.000198039	0.000302353	0.00030453	0.000351298	0.000350036	0.000427329	0.000427329
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000234094	0.000198039	0.000302353	0.00030453	0.000351298	0.000350036	0.000427329	0.000427329
velocity (m/sec)	0.000917846	0.000776481	0.001185483	0.00119402	0.001377388	0.001372439	0.001675495	0.001675495
Average velocity (m/sec)	0.000847164		0.001189751		0.001374913		0.001675495	
Re	94.95693793		133.3569336		149.180087		181.7936393	181.7936393
Pz1	103.5	103.5	104.4	104.4	104.75	104.8	105.1	105.1
Pz6	103.3	103.35	104.05	104.2	104.5	104.5	104.8	104.8
i(1-6)	0.003076923	0.002307692	0.005384615	0.003076923	0.003846154	0.004615385	0.004615385	0.004615385
average i	0.002692308		0.004230769		0.004230769		0.004615385	

Table B8-15. Computation for hydraulic conductivity of OTR at 136 kPa (column 3)

Test No	1		2		3		4	
Kpa	135.81534	135.81534	135.81534	135.81534	135.81534	135.81534	135.81534	135.81534
Mass of OTR (kg)	128.24	128.24	128.24	128.24	128.24	128.24	128.24	128.24
Height of gravel layer (m)	0.703	0.703	0.703	0.703	0.703	0.703	0.703	0.703
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.17929769	0.17929769	0.17929769	0.17929769	0.17929769	0.17929769	0.17929769	0.17929769
Dry density (kg/m3)	715.2350951	715.2350951	715.2350951	715.2350951	715.2350951	715.2350951	715.2350951	715.2350951
Temperature	8	8	7.2	7.2	7	7	6.8	6.8
Total porosity	0.405293975	0.405293975	0.405293975	0.405293975	0.405293975	0.405293975	0.405293975	0.405293975
Drainable Porosity, ε	0.40045134	0.40045134	0.40045134	0.40045134	0.40045134	0.40045134	0.40045134	0.40045134
Void ratio, e	0.673360153	0.673360153	0.673360153	0.673360153	0.673360153	0.673360153	0.673360153	0.673360153
Yield factor	0.574288455	0.574288455	0.574288455	0.574288455	0.574288455	0.574288455	0.574288455	0.574288455
Q (L)	0.267488641	0.266209448	0.304775926	0.292797546	0.382568505	0.375932105	0.413329684	
Quantity of water discharged (m3)	0.000267489	0.000266209	0.000304776	0.000292798	0.000382569	0.000375932	0.00041333	0.00041333
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000267489	0.000266209	0.000304776	0.000292798	0.000382569	0.000375932	0.00041333	0.00041333
velocity (m/sec)	0.001048784	0.001043768	0.001194982	0.001148016	0.001499995	0.001473975	0.001620605	0.001620605
Average velocity (m/sec)	0.001046276		0.001171499		0.001486985		0.001620605	
Re	113.3185808		123.0630827		156.2040949		170.2405728	170.2405728
Pz1	104.1	104.1	104.4	104.4	105	105	105.2	105.2
Pz6	103.9	103.9	104.1	104.1	104.6	104.7	104.9	104.9
i(1-6)	0.003076923	0.003076923	0.004615385	0.004615385	0.006153846	0.004615385	0.004615385	0.004615385
average i	0.003076923		0.004615385		0.005384615		0.004615385	

Table B8-16. Computation for hydraulic conductivity of OTR at 230 kPa (column 3)

Test No	1		2		3		4	
Kpa	230.00985	230.00985	230.00985	230.00985	230.00985	230.00985	230.00985	230.00985
Mass of OTR (kg)	128.24	128.24	128.24	128.24	128.24	128.24	128.24	128.24
Height of gravel layer (m)	0.665	0.665	0.665	0.665	0.665	0.665	0.665	0.665
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.169605923	0.169605923	0.169605923	0.169605923	0.169605923	0.169605923	0.169605923	0.169605923
Dry density (kg/m3)	756.105672	756.105672	756.105672	756.105672	756.105672	756.105672	756.105672	756.105672
Temperature	7.8	7.8	7.5	7.5	7.2	7.2	7	7
Total porosity	0.371310774	0.371310774	0.371310774	0.371310774	0.371310774	0.371310774	0.371310774	0.371310774
Drainable Porosity, ε	0.365346912	0.365346912	0.365346912	0.365346912	0.365346912	0.365346912	0.365346912	0.365346912
Void ratio, e	0.581124817	0.581124817	0.581124817	0.581124817	0.581124817	0.581124817	0.581124817	0.581124817
Yield factor	0.523945091	0.523945091	0.523945091	0.523945091	0.523945091	0.523945091	0.523945091	0.523945091
Q (L)	0.195494419	0.193907774	0.264847943	0.267303797	0.32263089	0.317326987	0.402160487	0.387048466
Quantity of water discharged (m3)	0.000195494	0.000193908	0.000264848	0.000267304	0.000322631	0.000317327	0.00040216	0.000387048
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000195494	0.000193908	0.000264848	0.000267304	0.000322631	0.000317327	0.00040216	0.000387048
velocity (m/sec)	0.000766505	0.000760284	0.00103843	0.001048059	0.001264989	0.001244193	0.001576812	0.00151756
Average velocity (m/sec)	0.000763395		0.001043245		0.001254591		0.001547186	
Re	78.1073512		106.7404438		124.5018797		153.5382274	
Pz1	103.4	103.6	104.1	104.15	104.7	104.6	105.2	105.2
Pz6	103.3	103.4	103.8	103.85	104.3	104.3	104.7	104.7
i(1-6)	0.001538462	0.003076923	0.004615385	0.004615385	0.006153846	0.004615385	0.007692308	0.007692308
average i	0.002307692		0.004615385		0.005384615		0.007692308	

Table B8-17. Computation for hydraulic conductivity of OTR at 262 kPa (column 3)

Test No	1		2		3		4	
Kpa	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684
Mass of OTR (kg)	128.24	128.24	128.24	128.24	128.24	128.24	128.24	128.24
Height of gravel layer (m)	0.595	0.595	0.595	0.595	0.595	0.595	0.595	0.595
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.151752668	0.151752668	0.151752668	0.151752668	0.151752668	0.151752668	0.151752668	0.151752668
Dry density (kg/m3)	845.0592804	845.0592804	845.0592804	845.0592804	845.0592804	845.0592804	845.0592804	845.0592804
Head level (m)	7.8	7.8	7.8	7.8	7	7	6.6	6.6
Total porosity	0.297347335	0.297347335	0.297347335	0.297347335	0.297347335	0.297347335	0.297347335	0.297347335
Drainable Porosity, ε	0.272943813	0.272943813	0.272943813	0.272943813	0.272943813	0.272943813	0.272943813	0.272943813
Void ratio, e	0.388447702	0.388447702	0.388447702	0.388447702	0.388447702	0.388447702	0.388447702	0.388447702
Yield factor	0.391429533	0.391429533	0.391429533	0.391429533	0.391429533	0.391429533	0.391429533	0.391429533
Q (L)	0.152198657	0.159105402	0.236539386	0.237441059	0.311280513	0.315642513	0.417065046	0.418499951
Quantity of water discharged (m3)	0.000152199	0.000159105	0.000236539	0.000237441	0.000311281	0.000315643	0.000417065	0.0004185
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000152199	0.000159105	0.000236539	0.000237441	0.000311281	0.000315643	0.000417065	0.0004185
velocity (m/sec)	0.000596749	0.000623829	0.000927436	0.000930972	0.001220485	0.001237588	0.001635251	0.001640877
Average velocity (m/sec)	0.000610289		0.000929204		0.001229037		0.001638064	
Re	54.50630274		82.98935047		106.4650749		141.8969893	
Pz1	103.5	103.4	104	104.1	104.7	104.8	105.7	105.7
Pz6	103.3	103.25	103.6	103.6	104.1	104.1	104.6	104.8
i(1-6)	0.003361345	0.002521008	0.006722689	0.008403361	0.010084034	0.011764706	0.018487395	0.01512605
average i	0.002941176		0.007563025		0.01092437		0.016806723	

Table B8-18. Computation for hydraulic conductivity of OTR at 66 kPa (column 1)

Test No	1		2		3		4	
Kpa	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171
Mass of OTR (kg)	138.045	138.045	138.045	138.045	138.045	138.045	138.045	138.045
Height of ORT layer (m)	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.216789525	0.216789525	0.216789525	0.216789525	0.216789525	0.216789525	0.216789525	0.216789525
Dry density (kg/m3)	636.7696963	636.7696963	636.7696963	636.7696963	636.7696963	636.7696963	636.7696963	636.7696963
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642
Drainable Porosity, ε	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642	0.470536642
Void ratio, e	0.888704828	0.888704828	0.888704828	0.888704828	0.888704828	0.888704828	0.888704828	0.888704828
Yield factor	0.674797996	0.674797996	0.674797996	0.674797996	0.674797996	0.674797996	0.674797996	0.674797996
Temperature	3.8	3.8	5	5	4	4	3.8	3.8
Q (L)	5.56	5.715	4.905	4.855	6.36	6.275	8.33	8.91
Quantity of water discharged (m3)	0.00556	0.005715	0.004905	0.004855	0.00636	0.006275	0.00833	0.00891
time in seconds	20.45	20.93	20.52	20.67	20.49	20.64	20.69	22.01
Flow in m3/sec	0.000271883	0.000273053	0.000239035	0.000234881	0.000310395	0.000304021	0.00040261	0.000404816
velocity (m/sec)	0.001066012	0.001070601	0.000937222	0.000920936	0.001217015	0.001192023	0.001578575	0.001587224
Average velocity (m/sec)	0.001068307		0.000929079		0.001204519		0.001582899	
Pz1	103.7	103.8	103.7	103.7	104.3	104.3	104.2	104.2
Pz6	103.5	103.7	103.5	103.5	104	104	103.9	103.85
i(2-6 L= 51.5cm	0.003883495	0.001941748	0.003883495	0.003883495	0.005825243	0.005825243	0.005825243	0.006796117
average i	0.002912621		0.003883495		0.005825243		0.00631068	

Table B8-19. Computation for hydraulic conductivity of OTR at 99 kPa (column 1)

Test No	1		2		3	
Kpa	98.57565	98.57565	98.57565	98.57565	98.57565	98.57565
Mass of OTR (kg)	138.045	138.045	138.045	138.045	138.045	138.045
Height of ORT layer (m)	0.8	0.8	0.8	0.8	0.8	0.8
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.2040372	0.2040372	0.2040372	0.2040372	0.2040372	0.2040372
Dry density (kg/m3)	676.5678023	676.5678023	676.5678023	676.5678023	676.5678023	676.5678023
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.437445183	0.437445183	0.437445183	0.437445183	0.437445183	0.437445183
Drainable Porosity, ε	0.437445183	0.437445183	0.437445183	0.437445183	0.437445183	0.437445183
Void ratio, e	0.777604544	0.777604544	0.777604544	0.777604544	0.777604544	0.777604544
Yield factor	0.627341435	0.627341435	0.627341435	0.627341435	0.627341435	0.627341435
Temperature	4	4	3.8	3.8	3.8	3.8
Q (L)	6.6	6.65	7.62	7.115	8.965	8.655
Quantity of water discharged (m3)	0.0066	0.00665	0.00762	0.007115	0.008965	0.008655
time in seconds	20.61	20.54	21.34	20.04	20.4	20.31
Flow in m3/sec	0.000320233	0.000323759	0.000357076	0.00035504	0.000439461	0.000426145
velocity (m/sec)	0.001255586	0.00126941	0.001400042	0.00139206	0.001723061	0.001670851
Average velocity (m/sec)	0.001262498		0.001396051		0.001696956	
Pz1	104.2	104.4	104.7	104.7	105	105.2
Pz6	104	104.1	104.3	104.3	104.6	104.7
i(2-6)	0.003868472	0.005802708	0.007736944	0.007736944	0.007736944	0.00967118
average i	0.00483559		0.007736944		0.008704062	

Table B8-20. Computation for hydraulic conductivity of OTR at 131 kPa (column 1)

Test No	1		2		3	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of OTR (kg)	138.045	138.045	138.045	138.045	138.045	138.045
Height of ORT layer (m)	0.753	0.753	0.753	0.753	0.753	0.753
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.192050015	0.192050015	0.192050015	0.192050015	0.192050015	0.192050015
Dry density (kg/m3)	718.797134	718.797134	718.797134	718.797134	718.797134	718.797134
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.402332199	0.402332199	0.402332199	0.402332199	0.402332199	0.402332199
Drainable Porosity, ε	0.576821202	0.576821202	0.576821202	0.576821202	0.576821202	0.576821202
Void ratio, e	0.965120091	0.965120091	0.965120091	0.965120091	0.965120091	0.965120091
Yield factor	0.827220998	0.827220998	0.827220998	0.827220998	0.827220998	0.827220998
Temperature	9.8		8.8		7.2	
Q (L)	5.195	5.05	7.3	7.3	10.415	10.415
Quantity of water discharged (m3)	0.005195	0.00505	0.0073	0.0073	0.010415	0.010415
time in seconds	20.75	20.64	20.49	20.49	20.07	20.07
Flow in m3/sec	0.000250361	0.000244671	0.000356271	0.000356271	0.000518934	0.000518934
velocity (m/sec)	0.000981631	0.000959317	0.001396888	0.001396888	0.002034663	0.002034663
Average velocity (m/sec)	0.000970474		0.001396888		0.002034663	
Pz1	103.5	103.5	104.5	104.5	104.9	104.9
Pz6	103.4	103.4	104.2	104.2	104.6	104.6
i(2-6)	0.001934236	0.001934236	0.005802708	0.005802708	0.005802708	0.005802708
average i	0.001934236		0.005802708		0.005802708	

Table B8-21. Computation for hydraulic conductivity of OTR at 175 kPa (column 1)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of OTR (kg)	138.045	138.045	138.045	138.045	138.045	138.045
Height of ORT layer (m)	0.8	0.8	0.8	0.8	0.8	0.8
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.2040372	0.2040372	0.2040372	0.2040372	0.2040372	0.2040372
Dry density (kg/m3)	676.5678023	676.5678023	676.567802	676.567802	676.5678023	676.5678023
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.437445183	0.437445183	0.43744518	0.43744518	0.437445183	0.437445183
Drainable Porosity, ε	0.437445183	0.437445183	0.43744518	0.43744518	0.437445183	0.437445183
Void ratio, e	0.777604544	0.777604544	0.77760454	0.77760454	0.777604544	0.777604544
Yield factor	0.627341435	0.627341435	0.62734143	0.62734143	0.627341435	0.627341435
Temperature	9.8		8.8		7.2	
Q (L)	5.195	5.05	7.3	7.3	10.415	10.415
Quantity of water discharged (m3)	0.005195	0.00505	0.0073	0.0073	0.010415	0.010415
time in seconds	20.75	20.64	20.49	20.49	20.07	20.07
Flow in m3/sec	0.000250361	0.000244671	0.00035627	0.00035627	0.000518934	0.000518934
velocity (m/sec)	0.000981631	0.000959317	0.00139689	0.00139689	0.002034663	0.002034663
Average velocity (m/sec)	0.000970474		0.001396888		0.002034663	
Pz1	104.1	104.2	105.9	105.9	107	107
Pz6	103.4	103.4	104.2	104.2	104.6	104.6
i(2-6)	0.010852713	0.012403101	0.02635659	0.02635659	0.037209302	0.037209302
average i	0.011627907		0.026356589		0.037209302	

Table B8-22. Computation for hydraulic conductivity of OTR at 88 kPa (column 4)

Test No	1		2		3	
Kpa	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228
Mass of OTR (kg)	141.66	141.66	141.66	141.66	141.66	141.66
Height of OTR layer (cm)	83	83	83	83	83	83
Height of ORT layer (m)	0.83	0.83	0.83	0.83	0.83	0.83
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.211688595	0.211688595	0.211688595	0.211688595	0.211688595	0.211688595
Dry density (kg/m3)	669.1905154	669.1905154	669.1905154	669.1905154	669.1905154	669.1905154
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.443579273	0.443579273	0.443579273	0.443579273	0.443579273	0.443579273
Drainable Porosity, ε	0.443579273	0.443579273	0.443579273	0.443579273	0.443579273	0.443579273
Void ratio, e	0.797201204	0.797201204	0.797201204	0.797201204	0.797201204	0.797201204
Yield factor	0.636138353	0.636138353	0.636138353	0.636138353	0.636138353	0.636138353
Temperature	4	4	3.8	3.8	3.6	3.6
Q (L)	5.935	5.93	8.16	8.2	10.225	10.345
Quantity of water discharged (m3)	0.005935	0.00593	0.00816	0.0082	0.010225	0.010345
time in seconds	20.73	20.63	20.61	20.73	20.49	20.84
Flow in m3/sec	0.0002863	0.000287445	0.000395924	0.000395562	0.000499024	0.000496401
velocity (m/sec)	0.001122541	0.001127032	0.001552361	0.001550941	0.0019566	0.001946316
Average velocity (m/sec)	0.001124786		0.001551651		0.001951458	
Pz1	103.8	103.8	104.6	104.6	104.8	104.8
Pz6	103.6	103.6	104.2	104.2	104.2	104.3
i(1-6 L= 65cm	0.003100775	0.003100775	0.00620155	0.00620155	0.009302326	0.007751938
average i	0.003100775		0.00620155		0.008527132	

Table B8-23. Computation for hydraulic conductivity of OTR at 131 kPa (column 4)

Test No	1		2		3	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of OTR (kg)	141.66	141.66	141.66	141.66	141.66	141.66
Height of ORT layer (m)	0.77	0.77	0.77	0.77	0.77	0.77
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.196385805	0.196385805	0.196385805	0.196385805	0.196385805	0.196385805
Dry density (kg/m3)	721.3352309	721.3352309	721.3352309	721.3352309	721.3352309	721.3352309
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.400221814	0.400221814	0.400221814	0.400221814	0.400221814	0.400221814
Drainable Porosity, ε	0.395433862	0.395433862	0.395433862	0.395433862	0.395433862	0.395433862
Void ratio, e	0.659300173	0.659300173	0.659300173	0.659300173	0.659300173	0.659300173
Yield factor	0.567092875	0.567092875	0.567092875	0.567092875	0.567092875	0.567092875
Temperature	3.8	3.8	4	4	4	4
Q (L)	4.165	4.45	6.955	6.975	9.055	9.035
Quantity of water discharged (m3)	0.004165	0.00445	0.006955	0.006975	0.009055	0.009035
time in seconds	21.3	20.78	20.52	20.61	20.52	20.42
Flow in m3/sec	0.00019554	0.000214148	0.000338938	0.000338428	0.000441277	0.000442458
velocity (m/sec)	0.000766683	0.000839644	0.001328925	0.001326926	0.001730182	0.001734815
Average velocity (m/sec)	0.000803164		0.001327926		0.001732498	
Pz1	103.2	103.2	104.2	104.2	104.7	104.8
Pz6	103	103	103.8	103.8	104	104.1
i(1-6)	0.003100775	0.003100775	0.00620155	0.00620155	0.010852713	0.010852713
average i	0.003100775		0.00620155		0.010852713	

Table B8-24. Computation for hydraulic conductivity of OTR at 175 kPa (column 4)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of OTR (kg)	141.66	141.66	141.66	141.66	141.66	141.66
Height of ORT layer (m)	0.72	0.72	0.72	0.72	0.72	0.72
Cross section area of TDA sample (D= 0.570m) (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348
Dry density (kg/m3)	771.4279553	771.4279553	771.4279553	771.4279553	771.4279553	771.4279553
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.358570551	0.358570551	0.358570551	0.358570551	0.358570551	0.358570551
Drainable Porosity, ε	0.358570551	0.358570551	0.358570551	0.358570551	0.358570551	0.358570551
Void ratio, e	0.559017912	0.559017912	0.559017912	0.559017912	0.559017912	0.559017912
Yield factor	0.514227092	0.514227092	0.514227092	0.514227092	0.514227092	0.514227092
Temperature	3.5	3.5	5	5	4	4
Q (L)	3.175	2.915	6.485	6.395	8.185	8.35
Quantity of water discharged (m3)	0.003175	0.002915	0.006485	0.006395	0.008185	0.00835
time in seconds	20.57	20.45	20.54	20.48	20.75	20.55
Flow in m3/sec	0.000154351	0.000142543	0.000315725	0.000312256	0.000394458	0.000406326
velocity (m/sec)	0.000605188	0.000558889	0.001237913	0.00122431	0.001546611	0.001593145
Average velocity (m/sec)	0.000582039		0.001231111		0.001569878	
Pz1	103.3	103.3	104.5	104.4	105	105
Pz6	103.1	103.1	103.9	103.8	103.9	103.9
i(1-6)	0.003100775	0.003100775	0.009302326	0.009302326	0.017054264	0.017054264
average i	0.003100775		0.009302326		0.017054264	

Table B8-25. Computation for hydraulic conductivity of MTT at 65.7 kPa (column 2)

Test No	1		2		3		4	
Kpa	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171
Mass of MTT (kg)	125.95	125.95	125.95	125.95	125.95	125.95	125.95	125.95
Height of MTT layer (m)	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348	0.18363348
Dry density (kg/m3)	685.8771069	685.8771069	685.8771069	685.8771069	685.8771069	685.8771069	685.8771069	685.8771069
Temperature	8	8	7.8	7.8	7	7	6.8	6.8
Total porosity	0.454440736	0.454440736	0.454440736	0.454440736	0.454440736	0.454440736	0.454440736	0.454440736
Drainable Porosity, ε	0.434071173	0.434071173	0.434071173	0.434071173	0.434071173	0.434071173	0.434071173	0.434071173
Void ratio, e	0.795644399	0.795644399	0.795644399	0.795644399	0.795644399	0.795644399	0.795644399	0.795644399
Yield factor	0.622502757	0.622502757	0.622502757	0.622502757	0.622502757	0.622502757	0.622502757	0.622502757
Q (L)	0.186936937	0.184580934	0.235204755	0.233788795	0.266775477	0.269398294	0.293124915	0.310742878
Quantity of water discharged (m3)	0.000186937	0.000184581	0.000235205	0.000233789	0.000266775	0.000269398	0.000293125	0.000310743
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000186937	0.000184581	0.000235205	0.000233789	0.000266775	0.000269398	0.000293125	0.000310743
velocity (m/sec)	0.000732952	0.000723715	0.000922203	0.000916652	0.001045988	0.001056271	0.0011493	0.001218377
Average velocity (m/sec)	0.000728334		0.000919428		0.001051129		0.001183839	
Re	83.56950084		105.4957511		116.9781275		131.7470707	
Pz1	102.9	103.1	103.5	103.5	103.9	103.9	104.2	104.2
Pz6	102.8	102.8	103.3	103.3	103.4	103.4	103.6	103.75
i(1-6)	0.001538462	0.004615385	0.003076923	0.003076923	0.007692308	0.007692308	0.009230769	0.006923077
average i	0.003076923		0.003076923		0.007692308		0.008076923	

Table B8-26. Computation for hydraulic conductivity of MTT at 87.6 kPa (column 2)

Test No	1		2		3		4	
Kpa	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228
Mass of MTT (kg)	125.95	125.95	125.95	125.95	125.95	125.95	125.95	125.95
Height of MTT layer (m)	0.668	0.668	0.668	0.668	0.668	0.668	0.668	0.668
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.170371062	0.170371062	0.170371062	0.17037106	0.170371062	0.170371062	0.170371062	0.170371062
Dry density (kg/m3)	739.268738	739.268738	739.268738	739.268738	739.268738	739.268738	739.268738	739.268738
Temperature	13	13	12.8	12.8	8	8	6.5	6.5
Total porosity	0.411972051	0.411972051	0.411972051	0.41197205	0.411972051	0.411972051	0.411972051	0.411972051
Drainable Porosity, ε	0.420708634	0.420708634	0.420708634	0.42070863	0.420708634	0.420708634	0.420708634	0.420708634
Void ratio, e	0.715456867	0.715456867	0.715456867	0.71545687	0.715456867	0.715456867	0.715456867	0.715456867
Yield factor	0.603339501	0.603339501	0.603339501	0.6033395	0.603339501	0.603339501	0.603339501	0.603339501
Q (L)	0.176015474	0.175394322	0.250360352	0.2530607	0.306971474	0.30908992	0.358177776	0.369421595
Quantity of water discharged (m3)	0.000176015	0.000175394	0.00025036	0.00025306	0.000306971	0.00030909	0.000358178	0.000369422
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000176015	0.000175394	0.00025036	0.00025306	0.000306971	0.00030909	0.000358178	0.000369422
velocity (m/sec)	0.000690131	0.000687695	0.000981626	0.00099221	0.00120359	0.001211896	0.001404363	0.001448448
Average velocity (m/sec)	0.000688913		0.00098692		0.001207743		0.001426405	
Re	89.04416917		127.562492		135.3807308		155.0801372	
Pz1	102.9	103	103.6	103.9	104.5	104.5	105.3	105.3
Pz6	102.8	102.8	103.25	103.3	103.6	103.8	103.9	104.3
i(1-6)	0.001538462	0.003076923	0.005384615	0.00923077	0.013846154	0.010769231	0.021538462	0.015384615
average i	0.002307692		0.007307692		0.012307692		0.018461538	

Table B8-27. Computation for hydraulic conductivity of MTT at 110 kPa (column 2)

Test No	1		2		3		4	
Kpa	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	87.6228
Mass of MTT (kg)	125.95	125.95	125.95	125.95	125.95	125.95	125.95	125.95
Height of MTT layer (m)	0.635	0.635	0.635	0.635	0.635	0.635	0.635	0.635
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.161954528	0.161954528	0.16195453	0.16195453	0.161954528	0.161954528	0.16195453	0.161954528
Dry density (kg/m3)	777.6874283	777.6874283	777.687428	777.687428	777.6874283	777.6874283	777.687428	777.6874283
Temperature	7	7	7	7	6.8	6.8	6.5	6.5
Total porosity	0.381413118	0.381413118	0.38141312	0.38141312	0.381413118	0.381413118	0.38141312	0.381413118
Drainable Porosity, ε	0.388228692	0.388228692	0.38822869	0.38822869	0.388228692	0.388228692	0.38822869	0.388228692
Void ratio, e	0.627605763	0.627605763	0.62760576	0.62760576	0.627605763	0.627605763	0.62760576	0.627605763
Yield factor	0.55675992	0.55675992	0.55675992	0.55675992	0.55675992	0.55675992	0.55675992	0.55675992
Q (L)	0.167961165	0.169250646	0.2044508	0.20648287	0.246344152	0.245019188	0.31628431	0.310128327
Quantity of water discharged (m3)	0.000167961	0.000169251	0.00020445	0.00020648	0.000246344	0.000245019	0.00031628	0.000310128
time in seconds	1	1	1	1	1	1	1	1
Flow in m3/sec	0.000167961	0.000169251	0.00020445	0.00020648	0.000246344	0.000245019	0.00031628	0.000310128
velocity (m/sec)	0.000658551	0.000663607	0.00080162	0.00080959	0.000965879	0.000960684	0.0012401	0.001215968
Average velocity (m/sec)	0.000661079		0.000805605		0.000963282		0.001228036	
Re	68.0572803		82.9360856		99.16868696		126.424814	
Pz1	103	103	103.5	103.5	104.1	104	104.9	104.8
Pz6	102.7	102.8	103.1	103.1	103.3	103.35	103.7	103.8
i(1-6)	0.004724409	0.003149606	0.00629921	0.00629921	0.012598425	0.01023622	0.01889764	0.015748031
average i	0.003937008		0.006299213		0.011417323		0.017322835	

Table B8-28. Computation for hydraulic conductivity of MTT at 175 kPa (column 2)

Test No	1		2		3		4	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of MTT (kg)	125.95	125.95	125.95	125.95	125.95	125.95	125.95	125.95
Height of MTT layer (m)	0.585	0.585	0.585	0.585	0.585	0.585	0.585	0.585
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203
Dry density (kg/m3)	844.1564393	844.1564393	844.1564393	844.1564393	844.1564393	844.1564393	844.1564393	844.1564393
Temperature	8	8	7.5	7.5	7	7	6.5	6.5
Total porosity	0.328542444	0.328542444	0.328542444	0.328542444	0.328542444	0.328542444	0.328542444	0.328542444
Drainable Porosity, ε	0.338000145	0.338000145	0.338000145	0.338000145	0.338000145	0.338000145	0.338000145	0.338000145
Void ratio, e	0.503382741	0.503382741	0.503382741	0.503382741	0.503382741	0.503382741	0.503382741	0.503382741
Yield factor	0.484727011	0.484727011	0.484727011	0.484727011	0.484727011	0.484727011	0.484727011	0.484727011
Q (L)	2.695	2.76	3.885	3.84	4.835	4.69	5.19	5.04
Quantity of water discharged (m3)	0.002695	0.00276	0.003885	0.00384	0.004835	0.00469	0.00519	0.00504
time in seconds	15.66	15.9	15.46	15.48	16.19	15.66	15.63	15.45
Flow in m3/sec	0.000172095	0.000173585	0.000251294	0.000248062	0.000298641	0.000299489	0.000332054	0.000326214
velocity (m/sec)	0.000674757	0.000680601	0.000985286	0.000972615	0.001170928	0.001174253	0.001301934	0.001279036
Average velocity (m/sec)	0.000677679		0.00097895		0.001172591		0.001290485	
Re	66.47303957		93.13502031		111.5575099		122.7736952	
Pz1	102.9	103	104	104	104.5	104.5	105.1	105.1
Pz6	102.7	102.8	103.2	103.2	103.3	103.5	103.6	103.7
i(1-6 L= MTT (cm)	0.003418803	0.003418803	0.013675214	0.013675214	0.020512821	0.017094017	0.025641026	0.023931624
average i	0.003418803		0.013675214		0.018803419		0.024786325	

Table B8-29. Computation for hydraulic conductivity of MTT at 263 kPa (column 2)

Test No	1		2		3		4	
Kpa	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684
Mass of MTT (kg)	125.95	125.95	125.95	125.95	125.95	125.95	125.95	125.95
Height of MTT layer (m)	0.535	0.535	0.535	0.535	0.535	0.535	0.535	0.535
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.136449878	0.136449878	0.13644988	0.136449878	0.136449878	0.136449878	0.136449878	0.136449878
Dry density (kg/m3)	923.0495645	923.0495645	923.049564	923.0495645	923.0495645	923.0495645	923.0495645	923.0495645
temperature	7.5	7.5	6.4	6.4	7	7	6.8	6.8
Total porosity	0.265789401	0.265789401	0.2657894	0.265789401	0.265789401	0.265789401	0.265789401	0.265789401
Drainable Porosity, ε	0.286576169	0.286576169	0.28657617	0.286576169	0.286576169	0.286576169	0.286576169	0.286576169
Void ratio, e	0.390318758	0.390318758	0.39031876	0.390318758	0.390318758	0.390318758	0.390318758	0.390318758
Yield factor	0.410979735	0.410979735	0.41097973	0.410979735	0.410979735	0.410979735	0.410979735	0.410979735
Q (L)	2.315	2.295	3.1	3.09	4.095	4.125	5.35	5.415
Quantity of water discharged (m3)	0.002315	0.002295	0.0031	0.00309	0.004095	0.004125	0.00535	0.005415
time in seconds	15.7	15.49	15.69	15.61	15.43	15.4	15.51	15.73
Flow in m3/sec	0.000147452	0.00014816	0.00019758	0.00019795	0.000265392	0.000267857	0.000344939	0.000344247
velocity (m/sec)	0.000578139	0.000580914	0.00077467	0.000776133	0.001040564	0.001050229	0.001352454	0.001349741
Average velocity (m/sec)	0.000579526		0.000775404		0.001045396		0.001351098	
Re	52.7478608		70.57642474		95.15082214		122.9754383	
Pz1	102.8	102.8	103.5	103.5	104.5	104.5	105.9	105.9
Pz6	102.6	102.6	102.8	102.8	103.2	103.2	103.5	103.6
i(1-6)	0.003738318	0.003738318	0.01308411	0.013084112	0.024299065	0.024299065	0.044859813	0.042990654
average i	0.003738318		0.013084112		0.024299065		0.043925234	

Table B8-30. Computation for hydraulic conductivity of MTT at 65.7 kPa (column 1)

Test No	1		2		3		4	
Kpa	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171
Mass of MTT (kg)	119.085	119.085	119.085	119.085	119.085	119.085	119.085	119.085
Height of MTT layer (m)	0.685	0.685	0.685	0.685	0.685	0.685	0.685	0.685
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.174706853	0.174706853	0.174706853	0.174706853	0.174706853	0.174706853	0.174706853	0.174706853
Dry density (kg/m3)	681.627528	681.627528	681.627528	681.627528	681.627528	681.627528	681.627528	681.627528
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929
Drainable Porosity, ε	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929	0.457820929
Void ratio, e	0.844409077	0.844409077	0.844409077	0.844409077	0.844409077	0.844409077	0.844409077	0.844409077
Yield factor	0.656562353	0.656562353	0.656562353	0.656562353	0.656562353	0.656562353	0.656562353	0.656562353
Temperature	3.4	3.4	3.8	3.8	4	4	3.6	3.6
Q (L)	1.335	1.35	3.815	3.505	6.45	6.53	9.04	9.28
Quantity of water discharged (m3)	0.001335	0.00135	0.003815	0.003505	0.00645	0.00653	0.00904	0.00928
time in seconds	20.63	21.27	22.79	20.61	20.73	20.7	20.67	20.79
Flow in m3/sec	6.47116E-05	6.34697E-05	0.000167398	0.000170063	0.000311143	0.000315459	0.000437349	0.000446368
velocity (m/sec)	0.000253725	0.000248855	0.000656343	0.000666792	0.001219947	0.001236868	0.001714781	0.001750145
Average velocity (m/sec)	0.00025129		0.000661568		0.001228408		0.001732463	
Pz1	102.4	102.4	103.1	103.1	103.9	103.8	104.3	104.3
Pz6	102	102.1	102.6	102.6	103.2	103.2	103.5	103.6
i(1-6 L= 65cm	0.006153846	0.003243243	0.005405405	0.005405405	0.010769231	0.009230769	0.012307692	0.010769231
average i	0.004698545		0.005405405		0.01		0.011538462	

Table B8-31. Computation for hydraulic conductivity of MTT at 110 kPa (column 1)

Test No	1		2		3		4	
Kpa	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285	109.5285
Mass of MTT (kg)	119.085	119.085	119.085	119.085	119.085	119.085	119.085	119.085
Height of MTT layer (m)	0.611	0.611	0.611	0.611	0.611	0.611	0.611	0.611
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.155833412	0.155833412	0.155833412	0.155833412	0.15583341	0.155833412	0.155833412	0.155833412
Dry density (kg/m3)	764.1814349	764.1814349	764.1814349	764.1814349	764.181435	764.1814349	764.1814349	764.1814349
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.392156033	0.392156033	0.392156033	0.392156033	0.39215603	0.392156033	0.392156033	0.392156033
Drainable Porosity, ε	0.392156033	0.392156033	0.392156033	0.392156033	0.39215603	0.392156033	0.392156033	0.392156033
Void ratio, e	0.645159046	0.645159046	0.645159046	0.645159046	0.64515905	0.645159046	0.645159046	0.645159046
Yield factor	0.562392132	0.562392132	0.562392132	0.562392132	0.56239213	0.562392132	0.562392132	0.562392132
Temperature	3.8	3.8	4	4	4	4	4	4
Q (L)	2.795	2.94	5.46	5.545	7.175	7.235	9.19	9.19
Quantity of water discharged (m3)	0.002795	0.00294	0.00546	0.005545	0.007175	0.007235	0.00919	0.00919
time in seconds	20.88	20.58	20.75	20.84	20.82	20.49	20.91	20.91
Flow in m3/sec	0.00013386	0.000142857	0.000263133	0.000266075	0.00034462	0.000353099	0.000439503	0.000439503
velocity (m/sec)	0.000524846	0.000560122	0.001031704	0.001043241	0.00135121	0.00138445	0.001723225	0.001723225
Average velocity (m/sec)	0.000542484		0.001037472		0.001367828		0.001723225	
Pz1	103	103.1	104.1	104.1	104.6	104.6	104.6	104.6
Pz6	102.5	102.5	103.4	103.5	103.8	103.8	103.7	103.7
i(1-6)	0.008183306	0.009819967	0.011456628	0.009819967	0.01309329	0.01309329	0.014729951	0.014729951
average i	0.009001637		0.010638298		0.01309329		0.014729951	

Table B8-32. Computation for hydraulic conductivity of MTT at 175 kPa (column 1)

Test No	1		2		3		4	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of MTT (kg)	119.085	119.085	119.085	119.085	119.085	119.085	119.085	119.085
Height of MTT layer (cm)	56	56	56	56	56	56	56	56
Height of MTT layer (m)	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.14282604	0.14282604	0.14282604	0.14282604	0.14282604	0.14282604	0.14282604	0.14282604
Dry density (kg/m3)	833.7765298	833.7765298	833.7765298	833.7765298	833.7765298	833.7765298	833.7765298	833.7765298
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815
Drainable Porosity, ε	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815	0.336798815
Void ratio, e	0.507838078	0.507838078	0.507838078	0.507838078	0.507838078	0.507838078	0.507838078	0.507838078
Yield factor	0.48300418	0.48300418	0.48300418	0.48300418	0.48300418	0.48300418	0.48300418	0.48300418
Temperature	4.4	4.4	4.4	4.4	4	4	3.8	3.8
Q (L)	2.04	2.025	4.955	4.995	7.32	7.14	9.855	9.855
Quantity of water discharged (m3)	0.00204	0.002025	0.004955	0.004995	0.00732	0.00714	0.009855	0.009855
time in seconds	20.72	20.64	20.84	20.66	20.73	20.43	20.45	20.45
Flow in m3/sec	9.84556E-05	9.81105E-05	0.000237764	0.000241772	0.000353111	0.000349486	0.000481907	0.000481907
velocity (m/sec)	0.00038603	0.000384677	0.000932238	0.000947951	0.001384498	0.001370284	0.001889487	0.001889487
Average velocity (m/sec)	0.000385353		0.000940094		0.001377391		0.001889487	
Pz1	102.2	102.2	103.5	103.5	104.3	104.3	105	105
Pz6	101.8	101.8	102.8	102.9	103.1	103.2	103.4	103.4
i(1-6)	0.007142857	0.007142857	0.0125	0.010714286	0.021428571	0.019642857	0.028571429	0.028571429
average i	0.007142857		0.011607143		0.020535714		0.028571429	

Table B8-33. Computation for hydraulic conductivity of MTT at 285 kPa (column 1)

Test No	1		2		3		4	
Kpa	284.7741	284.7741	284.7741	284.7741	284.7741	284.7741	284.7741	284.7741
Mass of MTT (kg)	119.085	119.085	119.085	119.085	119.085	119.085	119.085	119.085
Height of MTT layer (m)	0.499	0.499	0.499	0.499	0.499	0.499	0.499	0.499
X-area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of MTT (m3)	0.127268204	0.127268204	0.127268204	0.127268204	0.127268204	0.127268204	0.127268204	0.127268204
Dry density (kg/m3)	935.7011156	935.7011156	935.7011156	935.7011156	935.7011156	935.7011156	935.7011156	935.7011156
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125
Drainable Porosity, ε	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125	0.255726125
Void ratio, e	0.34359143	0.34359143	0.34359143	0.34359143	0.34359143	0.34359143	0.34359143	0.34359143
Yield factor	0.366737595	0.366737595	0.366737595	0.366737595	0.366737595	0.366737595	0.366737595	0.366737595
Temperature	4.2	4.2	4.2	4.2	3.8	3.8	3.8	3.8
Q (L)	4.845	4.695	6.525	6.535	7.545	7.765	8.96	8.985
Quantity of water discharged (m3)	0.004845	0.004695	0.006525	0.006535	0.007545	0.007765	0.00896	0.008985
time in seconds	20.58	20.58	20.91	20.43	20.69	20.42	20.46	20.81
Flow in m3/sec	0.000235423	0.000228134	0.000312052	0.000319873	0.000364669	0.000380264	0.000437928	0.000431764
velocity (m/sec)	0.000923058	0.00089448	0.001223509	0.001254174	0.001429813	0.001490961	0.00171705	0.001692882
Average velocity (m/sec)	0.000908769		0.001238842		0.001460387		0.001704966	
Pz1	103.6	103.6	104.7	104.9	105.5	105.2	106	106
Pz6	102.7	102.6	103.1	103	103.3	103.3	103.4	103.4
i(1-6)	0.018036072	0.02004008	0.032064128	0.038076152	0.044088176	0.038076152	0.052104208	0.052104208
average i	0.019038076		0.03507014		0.041082164		0.052104208	

Table B8-34. Computation for hydraulic conductivity of PLTT+OTR at 131 kPa (column 2)

Test No	1		2		3	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of OTR +PLTT(kg)	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.639	0.639	0.639	0.639	0.639	0.639
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR+PLTT (m3)	0.162974714	0.162974714	0.162974714	0.162974714	0.162974714	0.162974714
Dry density (kg/m3)	785.8887876	785.8887876	785.8887876	785.8887876	785.8887876	785.8887876
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.367167968	0.367167968	0.367167968	0.367167968	0.367167968	0.367167968
Drainable Porosity, ε	0.355411746	0.355411746	0.355411746	0.355411746	0.355411746	0.355411746
Void ratio, e	0.551377944	0.551377944	0.551377944	0.551377944	0.551377944	0.551377944
Yield factor	0.50969704	0.50969704	0.50969704	0.50969704	0.50969704	0.50969704
Temperature	9.8	10.6	7.8		5	
Q (L)	5.75	5.7	6.8	6.8	7.3	7.55
Quantity of water discharged (m3)	0.00575	0.0057	0.0068	0.0068	0.0073	0.00755
time in seconds	20.52	20.46	20.4	20.45	20.07	20.42
Flow in m3/sec	0.000280214	0.000278592	0.000333333	0.000332518	0.000363727	0.000369736
velocity (m/sec)	0.00109868	0.00109232	0.001306951	0.001303756	0.00142612	0.001449679
Average velocity (m/sec)	0.0010955		0.001305353		0.0014379	
Re	110.3593695		131.4997787		132.0824422	
Pz2	103.5	103.6	104	104.1	104.3	104.4
Pz6	103	103	103.4	103.5	103.7	103.7
i(2-6)	0.009708738	0.011650485	0.011650485	0.011650485	0.011650485	0.013592233
average i	0.010679612		0.011650485		0.012621359	

Table B8-35. Computation for hydraulic conductivity of PLTT+OTR at 153 kPa (column 2)

Test No	1		2		3	
Kpa	153.3399	153.3399	153.3399	153.3399	153.3399	153.3399
Mass of OTR +PLTT(kg)	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.62	0.62	0.62	0.62	0.62	0.62
Cross section area of TDA sample (D= 0.570m) (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR+PLTT (m3)	0.15812883	0.15812883	0.15812883	0.15812883	0.15812883	0.15812883
Dry density (kg/m3)	809.9724762	809.9724762	809.9724762	809.9724762	809.9724762	809.9724762
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.347774728	0.347774728	0.347774728	0.347774728	0.347774728	0.347774728
Drainable Porosity, ε	0.344382639	0.344382639	0.344382639	0.344382639	0.344382639	0.344382639
Void ratio, e	0.525279926	0.525279926	0.525279926	0.525279926	0.525279926	0.525279926
Yield factor	0.493880165	0.493880165	0.493880165	0.493880165	0.493880165	0.493880165
Temperature	5	4.5	4.5	4.5	4	4
Q (L)	5.55	5.55	6.85	6.85	7.85	7.55
Quantity of water discharged (m3)	0.00555	0.00555	0.00685	0.00685	0.00785	0.00755
time in seconds	20.37	20.45	20.58	20.49	20.52	19.87
Flow in m3/sec	0.000272459	0.000271394	0.000332847	0.000334309	0.000382554	0.00037997
velocity (m/sec)	0.001068274	0.001064095	0.001305046	0.001310778	0.001499937	0.001489806
Average velocity (m/sec)	0.001066184		0.001307912		0.001494871	
Pz2	103.5	103.6	104	104.2	104.7	104.6
Pz6	103.2	103.15	103.4	103.5	103.75	103.75
i(2-6)	0.006122449	0.009183673	0.012244898	0.014285714	0.019387755	0.017346939
average i	0.007653061		0.013265306		0.018367347	

Table B8-36. Computation for hydraulic conductivity of PLTT+OTR at 175 kPa (column 2)

Test No	1		2		3	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of OTR +PLTT(kg)	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.605	0.605	0.605	0.605	0.605	0.605
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR+PLTT (m3)	0.154303133	0.154303133	0.154303133	0.154303133	0.15430313	0.154303133
Dry density (kg/m3)	830.0544385	830.0544385	830.0544385	830.0544385	830.054438	830.0544385
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.331603854	0.331603854	0.331603854	0.331603854	0.33160385	0.331603854
Drainable Porosity, ε	0.344382639	0.344382639	0.344382639	0.344382639	0.34438264	0.344382639
Void ratio, e	0.525279926	0.525279926	0.525279926	0.525279926	0.52527993	0.525279926
Yield factor	0.493880165	0.493880165	0.493880165	0.493880165	0.49388017	0.493880165
Temperature	4.8	4.8	4.5	4.5	4.3	4.3
Q (L)	4.8	4.85	6	7.4	7	7.1
Quantity of water discharged (m3)	0.0048	0.00485	0.006	0.0074	0.007	0.0071
time in seconds	20.42	20.79	20.73	25.55	20.39	20.52
Flow in m3/sec	0.000235064	0.000233285	0.000289436	0.000289628	0.00034331	0.000346004
velocity (m/sec)	0.00092165	0.000914677	0.001134835	0.00113559	0.00134605	0.001356631
Average velocity (m/sec)	0.000918164		0.001135212		0.001351341	
Re	80.33212549					
Pz2	103.2	103.2	103.8	103.9	104.4	104.5
Pz6	102.8	102.8	103.3	103.1	103.5	103.5
i(2-6)	0.008421053	0.008421053	0.010526316	0.016842105	0.01894737	0.021052632
average i	0.008421053		0.013684211		0.02	

Table B8-37. Computation for hydraulic conductivity of PLTT+OTR at 208 kPa (column 2)

Test No	1		2		3	
Kpa	208.10415	208.10415	208.10415	208.10415	208.10415	208.10415
Mass of OTR +PLTT(kg)	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.59	0.59	0.59	0.59	0.59	0.59
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR+PLTT (m3)	0.150477435	0.150477435	0.15047744	0.150477435	0.150477435	0.150477435
Dry density (kg/m3)	851.1575174	851.1575174	851.157517	851.1575174	851.1575174	851.1575174
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.314610731	0.314610731	0.31461073	0.314610731	0.314610731	0.314610731
Drainable Porosity, ε	0.344382639	0.344382639	0.34438264	0.344382639	0.344382639	0.344382639
Void ratio, e	0.525279926	0.525279926	0.52527993	0.525279926	0.525279926	0.525279926
Yield factor	0.493880165	0.493880165	0.49388017	0.493880165	0.493880165	0.493880165
Temperature	4	4	4.2	4.2	4.2	4.2
Q (L)	4.65	4.5	6.1	6.05	7.2	7.15
Quantity of water discharged (m3)	0.00465	0.0045	0.0061	0.00605	0.0072	0.00715
time in seconds	20.7	20.51	20.57	20.48	20.39	20.54
Flow in m3/sec	0.000224638	0.000219405	0.00029655	0.00029541	0.000353114	0.000348101
velocity (m/sec)	0.000880771	0.000860256	0.00116272	0.00115826	0.001384509	0.001364854
Average velocity (m/sec)	0.000870514		0.001160491		0.001374682	
Re	76.16310442					
Pz2	103.1	103.1	103.8	104	104.4	104.5
Pz6	102.8	102.8	103.2	103.1	103.3	103.4
i(2-6 L= 46cm	0.006521739	0.006521739	0.01304348	0.019565217	0.023913043	0.023913043
average i	0.006521739		0.016304348		0.023913043	

Table B8-38. Computation for hydraulic conductivity of PLTT+OTR at 241 kPa (column 2)

Test No	1		2		3	
Kpa	240.9627	240.9627	240.9627	240.9627	240.9627	240.9627
Mass of OTR +PLTT(kg)	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.572	0.572	0.572	0.572	0.572	0.572
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR+PLTT (m3)	0.145886598	0.145886598	0.145886598	0.145886598	0.145886598	0.145886598
Dry density (kg/m3)	877.9421945	877.9421945	877.9421945	877.9421945	877.9421945	877.9421945
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.293042537	0.293042537	0.293042537	0.293042537	0.293042537	0.293042537
Drainable Porosity, ε	0.274288794	0.274288794	0.274288794	0.274288794	0.274288794	0.274288794
Void ratio, e	0.377958603	0.377958603	0.377958603	0.377958603	0.377958603	0.377958603
Yield factor	0.393358374	0.393358374	0.393358374	0.393358374	0.393358374	0.393358374
Temperature	4.2	4.2	4.2	4.2	4	4
Q (L)	6	6	6.6	6.6	7.75	7.75
Quantity of water discharged (m3)	0.006	0.006	0.0066	0.0066	0.00775	0.00775
time in seconds	20.4	20.42	20.43	20.43	20.61	20.55
Flow in m3/sec	0.000294118	0.00029383	0.000323054	0.000323054	0.000376031	0.000377129
velocity (m/sec)	0.001153192	0.001152063	0.001266649	0.001266649	0.001474363	0.001478667
Average velocity (m/sec)	0.001152628		0.001266649		0.001476515	
Pz2	103.7	103.9	104.2	104.3	104.5	104.8
Pz6	103.1	103.2	103.2	103.3	103.5	103.6
i(2-6)	0.013574661	0.015837104	0.022624434	0.022624434	0.022624434	0.027149321
average i	0.014705882		0.022624434		0.024886878	

Table B8-39. Computation for hydraulic conductivity of PLTT+OTR at 65.7 kPa (column 3)

Test No	1		2		3		4	
Kpa	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171	65.7171
Mass of OTR (kg)	128.08	128.08	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77
X- area of TDA sample (m2)	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047	0.255047
Volume of OTR (m3)	0.196386	0.196386	0.196386	0.196386	0.196386	0.196386	0.196386	0.196386
Dry density (kg/m3)	652.1856	652.1856	652.1856	652.1856	652.1856	652.1856	652.1856	652.1856
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.474468	0.474468	0.474468	0.474468	0.474468	0.474468	0.474468	0.474468
Drainable Porosity, ε	0.455874	0.455874	0.455874	0.455874	0.455874	0.455874	0.455874	0.455874
Void ratio, e	0.867452	0.867452	0.867452	0.867452	0.867452	0.867452	0.867452	0.867452
Yield factor	0.65377	0.65377	0.65377	0.65377	0.65377	0.65377	0.65377	0.65377
Temperature	10	10	10.2	9	6.4	5.8	4.2	3.8
Q (L)	1.615	1.59	5.24	5.29	7.225	7.135	8.235	8.49
Quantity of water discharged (m3)	0.001615	0.00159	0.00524	0.00529	0.007225	0.007135	0.008235	0.00849
time in seconds	20.45	20.48	20.46	20.49	20.82	20.45	20.76	20.45
Flow in m3/sec	7.9E-05	7.76E-05	0.000256	0.000258	0.000347	0.000349	0.000397	0.000415
velocity (m/sec)	0.00031	0.000304	0.001004	0.001012	0.001361	0.001368	0.001555	0.001628
Average velocity (m/sec)	0.000307022		0.001008217		0.001364304		0.001591544	
Pz1	102.5	102.5	103.7	103.8	104.5	104.5	104.9	104.5
Pz6	102.2	102.2	103.4	103.4	103.9	104	104.3	104.2
i(1-6 L= 64.5cm	0.004651	0.004651	0.004651	0.006202	0.009302	0.007752	0.009302	0.004651
average i	0.004651163		0.005426357		0.008527132		0.006976744	

Table B8-40. Computation for hydraulic conductivity of PLTT+OTR at 87.6 kPa (column 3)

Kpa	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228
Test No	1		2		3		4	
Mass of OTR (kg)	128.08	128.08	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.715	0.715	0.715	0.715	0.715	0.715	0.715	0.715
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.255047
Volume of OTR (m3)	0.182358248	0.182358248	0.18235825	0.182358248	0.182358248	0.182358248	0.182358248	0.182358
Dry density (kg/m3)	702.3537556	702.3537556	702.353756	702.3537556	702.3537556	702.3537556	702.3537556	702.3538
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.434042099	0.434042099	0.4340421	0.434042099	0.434042099	0.434042099	0.434042099	0.434042
Drainable Porosity, ε	0.434610814	0.434610814	0.43461081	0.434610814	0.434610814	0.434610814	0.434610814	0.434611
Void ratio, e	0.767920746	0.767920746	0.76792075	0.767920746	0.767920746	0.767920746	0.767920746	0.767921
Yield factor	0.623276659	0.623276659	0.62327666	0.623276659	0.623276659	0.623276659	0.623276659	0.623277
Temperature	5.4	5.4	5	4.8	4.2	4.2	4	4
Q (L)	4.195	4.205	6.31	6.385	6.925	7.555	8.87	8.87
Quantity of water discharged (m3)	0.004195	0.004205	0.00631	0.006385	0.006925	0.007555	0.00887	0.00887
time in seconds	20.45	20.4	20.45	20.4	20.43	20.63	20.42	20.42
Flow in m3/sec	0.000205134	0.000206127	0.00030856	0.00031299	0.000338962	0.000366214	0.000434378	0.000434
velocity (m/sec)	0.000804302	0.000808196	0.00120981	0.001227189	0.001329022	0.001435872	0.001703133	0.001703
Average velocity (m/sec)	0.000806249		0.001218499		0.001382447		0.001703133	
Pz1	103.6	103.6	104.2	104.2	104.7	104.7	105.2	105.2
Pz6	103.4	103.4	103.8	103.8	104.1	104.1	104.5	104.5
i(1-6)	0.003100775	0.003100775	0.00620155	0.00620155	0.009302326	0.009302326	0.010852713	0.010853
average i	0.003100775		0.00620155		0.009302326		0.010852713	

Table B8-41. Computation for hydraulic conductivity of PLTT+OTR at 131.4 kPa (column 3)

Test No	1		2		3		4	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of OTR (kg)	128.08	128.08	128.08	128.08	128.08	128.08	128.08	128.08
Height of OTR layer (cm)	66	66	66	66	66	66	66	66
Height of ORT+PLTT layer (m)	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.16833069	0.16833069	0.16833069	0.16833069	0.16833069	0.16833069	0.16833069	0.16833069
Dry density (kg/m3)	760.8832353	760.8832353	760.8832353	760.8832353	760.8832353	760.8832353	760.8832353	760.8832353
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.38687894	0.38687894	0.38687894	0.38687894	0.38687894	0.38687894	0.38687894	0.38687894
Drainable Porosity, ε	0.367534993	0.367534993	0.367534993	0.367534993	0.367534993	0.367534993	0.367534993	0.367534993
Void ratio, e	0.599449305	0.599449305	0.599449305	0.599449305	0.599449305	0.599449305	0.599449305	0.599449305
Yield factor	0.527083025	0.527083025	0.527083025	0.527083025	0.527083025	0.527083025	0.527083025	0.527083025
Temperature	5	5	5	5	5	5	4.8	4.8
Q (L)	2.565	2.59	4.535	4.48	6.51	6.535	7.4	7.4
Quantity of water discharged (m3)	0.002565	0.00259	0.004535	0.00448	0.00651	0.006535	0.0074	0.0074
time in seconds	20.61	20.42	20.46	20.38	20.37	20.49	20.66	20.66
Flow in m3/sec	0.000124454	0.000126836	0.000221652	0.000219823	0.000319588	0.000318936	0.00035818	0.00035818
velocity (m/sec)	0.000487967	0.000497307	0.000869065	0.000861895	0.001253056	0.001250502	0.001404372	0.001404372
Average velocity (m/sec)	0.000492637		0.00086548		0.001251779		0.001404372	
Pz1	102.9	102.9	103.5	104.4	104.3	104.4	104.7	104.7
Pz6	102.7	102.7	103.2	103.2	103.8	103.9	104	104
i(1-6 L= 64.5cm	0.003100775	0.003100775	0.004651163	0.018604651	0.007751938	0.007751938	0.010852713	0.010852713
average i	0.003100775		0.011627907		0.007751938		0.010852713	

Table B8-42. Computation for hydraulic conductivity of PLTT+OTR at 175 kPa (column 3)

Test No	1		2		3		4	
Kpa	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456	175.2456
Mass of OTR (kg)	128.08	128.08	128.08	128.08	128.08	128.08	128.08	128.08
Height of ORT+PLTT layer (m)	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625
X- area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.159404063	0.159404063	0.159404063	0.159404063	0.159404063	0.159404063	0.15940406	0.159404063
Dry density (kg/m3)	803.4926964	803.4926964	803.4926964	803.4926964	803.4926964	803.4926964	803.492696	803.4926964
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.352544161	0.352544161	0.352544161	0.352544161	0.352544161	0.352544161	0.35254416	0.352544161
Drainable Porosity, ε	0.334916953	0.334916953	0.334916953	0.334916953	0.334916953	0.334916953	0.33491695	0.334916953
Void ratio, e	0.517281539	0.517281539	0.517281539	0.517281539	0.517281539	0.517281539	0.51728154	0.517281539
Yield factor	0.480305396	0.480305396	0.480305396	0.480305396	0.480305396	0.480305396	0.4803054	0.480305396
Temperature	4.5	4.8	4.8	4.8	4.8	4.8	4.2	4.2
Q (L)	3.925	3.915	5.67	5.635	6.945	6.895	9.075	8.96
Quantity of water discharged (m3)	0.003925	0.003915	0.00567	0.005635	0.006945	0.006895	0.009075	0.00896
time in seconds	20.4	20.39	20.52	20.49	20.36	20.4	20.67	20.39
Flow in m3/sec	0.000192402	0.000192006	0.000276316	0.000275012	0.00034111	0.00033799	0.00043904	0.000439431
velocity (m/sec)	0.00075438	0.000752827	0.001083394	0.001078283	0.001337442	0.00132521	0.00172142	0.001722945
Average velocity (m/sec)	0.000753603		0.001080838		0.001331326		0.001722182	
Pz1	103.5	103.5	104	104.2	104.6	104.7	105.5	105.6
Pz6	103.2	103.2	103.6	103.6	103.9	103.9	104.4	104.6
i(1-6)	0.0048	0.0048	0.0064	0.0096	0.0112	0.0128	0.0176	0.016
average i	0.0048		0.008		0.012		0.0168	

Table B8-43. Computation for hydraulic conductivity of PLTT+OTR at 87.6 kPa (column 4)

Test No	1		2		3		4	
Kpa	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228	87.6228
Mass of OTR (kg)	123.21	123.21	123.21	123.21	123.21	123.21	123.21	123.21
Height of ORT layer (m)	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.175982085	0.175982085	0.175982085	0.175982085	0.175982085	0.175982085	0.175982085	0.175982085
Dry density (kg/m3)	700.1280841	700.1280841	700.1280841	700.1280841	700.1280841	700.1280841	700.1280841	700.1280841
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539
Drainable Porosity, ε	0.472993539	0.6312	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539	0.472993539
Void ratio, e	0.897509942	1.197708275	0.897509942	0.897509942	0.897509942	0.897509942	0.897509942	0.897509942
Yield factor	0.678321438	0.905205794	0.678321438	0.678321438	0.678321438	0.678321438	0.678321438	0.678321438
Temperature	4.2		4.2		4.2		4.2	
Q (L)	2.235	2.235	3.665	3.785	6.6	6.535	9.08	9.08
Quantity of water discharged (m3)	0.002235	0.002235	0.003665	0.003785	0.0066	0.006535	0.00908	0.00908
time in seconds	21.67	21.67	20.73	20.73	20.76	20.57	20.93	20.93
Flow in m3/sec	0.000103138	0.000103138	0.000176797	0.000182586	0.000317919	0.000317696	0.000433827	0.000433827
velocity (m/sec)	0.000404389	0.000404389	0.000693195	0.000715892	0.001246514	0.001245638	0.001700972	0.001700972
Average velocity (m/sec)	0.000404389		0.000704543		0.001246076		0.001700972	
Pz1	103	103	103.4	103.4	104.5	104.5	105.5	105.5
Pz6	102.8	102.8	103.1	103.1	103.9	103.9	104.5	104.5
i(1-6 L= 65cm	0.003076923	0.003076923	0.004615385	0.004615385	0.009230769	0.009230769	0.015384615	0.015384615
average i	0.003076923		0.004615385		0.009230769		0.015384615	

Table B8-44. Computation for hydraulic conductivity of PLTT+OTR at 131.4 kPa (column 4)

Test No	1		2		3	
Kpa	131.4342	131.4342	131.4342	131.4342	131.4342	131.4342
Mass of OTR (kg)	123.21	123.21	123.21	123.21	123.21	123.21
Height of ORT layer (m)	0.634	0.634	0.634	0.634	0.634	0.634
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.161699481	0.161699481	0.161699481	0.161699481	0.161699481	0.161699481
Dry density (kg/m3)	761.9690505	761.9690505	761.9690505	761.9690505	761.9690505	761.9690505
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.426444072	0.426444072	0.426444072	0.426444072	0.426444072	0.426444072
Drainable Porosity, ε	0.38757878	0.38757878	0.38757878	0.38757878	0.38757878	0.38757878
Void ratio, e	0.675747143	0.675747143	0.675747143	0.675747143	0.675747143	0.675747143
Yield factor	0.555827878	0.555827878	0.555827878	0.555827878	0.555827878	0.555827878
Temperature	4		4		3.8	
Q (L)	3.575	3.51	6.02	5.745	7.93	6.695
Quantity of water discharged (m3)	0.003575	0.00351	0.00602	0.005745	0.00793	0.006695
time in seconds	20.9	20.51	21.46	20.46	20.61	20.45
Flow in m3/sec	0.000171053	0.000171136	0.000280522	0.000280792	0.000384765	0.000327384
velocity (m/sec)	0.000670672	0.000670999	0.001099885	0.001100944	0.001508606	0.001283624
Average velocity (m/sec)	0.000670836		0.001100414		0.001396115	
Pz1	103.4	103.4	104.3	104.2	105.1	104.9
Pz6	103	102.9	103.8	103.7	104.5	104.3
i(1-6 L= 65cm	0.006309148	0.007886435	0.007886435	0.007886435	0.009463722	0.009463722
average i	0.006309148		0.007886435		0.009463722	

Table B8-45. Computation for hydraulic conductivity of PLTT+OTR at 197 kPa (column 4)

Test No	1		2		3	
Kpa	197.1513	197.1513	197.1513	197.1513	197.1513	197.1513
Mass of OTR (kg)	123.21	123.21	123.21	123.21	123.21	123.21
Height of OTR layer (cm)	58.5	58.5	58.5	58.5	58.5	58.5
Height of ORT layer (m)	0.585	0.585	0.585	0.585	0.585	0.585
Cross section area of TDA sample (D= 0.570m) (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203	0.149202203
Dry density (kg/m3)	825.7920991	825.7920991	825.7920991	825.7920991	825.7920991	825.7920991
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.378402635	0.378402635	0.378402635	0.378402635	0.378402635	0.378402635
Drainable Porosity, ε	0.378402635	0.378402635	0.378402635	0.378402635	0.378402635	0.378402635
Void ratio, e	0.608758429	0.608758429	0.608758429	0.608758429	0.608758429	0.608758429
Yield factor	0.542668342	0.542668342	0.542668342	0.542668342	0.542668342	0.542668342
Temperature	4		4		4	
Q (L)	3	3	5.255	5.38	7.395	7.875
Quantity of water discharged (m3)	0.003	0.003	0.005255	0.00538	0.007395	0.007875
time in seconds	20.75	20.57	20.63	20.66	20.87	20.42
Flow in m3/sec	0.000144578	0.000145843	0.000254726	0.000260407	0.000354336	0.000385651
velocity (m/sec)	0.00056687	0.000571831	0.000998744	0.001021016	0.001389301	0.001512082
Average velocity (m/sec)	0.000569351		0.00100988		0.001450692	
Pz1	103.3	103.3	104.2	104.2	104.6	104.6
Pz6	102.9	103	103.6	103.6	104	104
i(1-6)	0.006837607	0.005128205	0.01025641	0.01025641	0.01025641	0.01025641
average i	0.006837607		0.01025641		0.01025641	

Table B8-46. Computation for hydraulic conductivity of PLTT+OTR at 262.8 kPa (column 4)

Test No	1		2		3	
Kpa	262.8684	262.8684	262.8684	262.8684	262.8684	262.8684
Mass of OTR (kg)	123.21	123.21	123.21	123.21	123.21	123.21
Height of OTR layer (cm)	53.5	53.5	53.5	53.5	53.5	53.5
Height of ORT layer (m)	0.535	0.535	0.535	0.535	0.535	0.535
X area of TDA sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of OTR (m3)	0.136449878	0.136449878	0.136449878	0.136449878	0.136449878	0.136449878
Dry density (kg/m3)	902.9689308	902.9689308	902.9689308	902.9689308	902.9689308	902.9689308
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Total porosity	0.320309424	0.320309424	0.320309424	0.320309424	0.320309424	0.320309424
Drainable Porosity, ε	0.270051221	0.270051221	0.270051221	0.270051221	0.270051221	0.270051221
Void ratio, e	0.397314941	0.397314941	0.397314941	0.397314941	0.397314941	0.397314941
Yield factor	0.387281258	0.387281258	0.387281258	0.387281258	0.387281258	0.387281258
Temperature	6		4.8		4.7	4.8
Q (L)	2.685	2.595	5.665	5.66	7.31	7.225
Quantity of water discharged (m3)	0.002685	0.002595	0.005665	0.00566	0.00731	0.007225
time in seconds	20.72	20.54	20.79	20.76	20.87	20.72
Flow in m3/sec	0.000129585	0.000126339	0.000272487	0.00027264	0.000350264	0.000348697
velocity (m/sec)	0.000508084	0.000495356	0.001068381	0.00106898	0.001373332	0.00136719
Average velocity (m/sec)	0.00050172		0.001068681		0.001370261	
Pz1	103.3	103.3	104.5	104.6	105.3	105.2
Pz6	102.9	102.9	103.5	103.6	104	104
i(1-6 L= 65cm	0.007476636	0.007476636	0.018691589	0.018691589	0.024299065	0.022429907
average i	0.007476636		0.018691589		0.023364486	

Table B8-47. Computation for hydraulic conductivity of Gravel (column 3)

Test No	1		2		3	
Height of Gravel layer (m)	0.65	0.65	0.65	0.65	0.65	0.65
X area of Gravel sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of Gravel (m3)	0.165780225	0.165780225	0.165780225	0.165780225	0.165780225	0.165780225
Dry density (kg/m3)	0	0	0	0	0	0
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Drainable Porosity, ε	0.4	0.4	0.4	0.4	0.4	0.4
Temperature	13		13		13	
Q (L)	2.635	2.68	5.67	5.56	7.62	7.655
Quantity of water discharged (m3)	0.002635	0.00268	0.00567	0.00556	0.00762	0.007655
time in seconds	20.52	20.61	21.09	20.46	20.52	20.76
Flow in m3/sec	0.000128411	0.000130034	0.000268848	0.00027175	0.000371345	0.000368738
velocity (m/sec)	0.000503482	0.000509844	0.001054113	0.001065491	0.00145599	0.001445768
Average velocity (m/sec)	0.000506663		0.001059802		0.001450879	
Pz1	103.3	103.2	104.3	104.4	105.1	105
Pz6	103	102.9	103.7	103.8	104	104
i(1-6)	0.004761905	0.004761905	0.00952381	0.00952381	0.017460317	0.015873016
average i	0.004761905		0.00952381		0.016666667	

Table B8-48. Computation for hydraulic conductivity of Gravel (column 3)

Test No	1		2		3	
Height of gravel layer (cm)	51.5	51.5	51.5	51.5	51.5	51.5
Height of Gravel layer (m)	0.515	0.515	0.515	0.515	0.515	0.515
X area of Gravel sample (m2)	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465	0.2550465
Volume of Gravel (m3)	0.131348948	0.131348948	0.131348948	0.131348948	0.131348948	0.131348948
Dry density (kg/m3)	0	0	0	0	0	0
Head level (m)	104.1	104.1	104.1	104.1	104.1	104.1
Drainable Porosity, ε	0.4	0.4	0.4	0.4	0.4	0.4
Temperature	13		13		13	
Q (L)	4.425	4.425	6.69	6.69	8.125	8.125
Quantity of water discharged (m3)	0.004425	0.004425	0.00669	0.00669	0.008125	0.008125
time in seconds	20.45	20.45	20.58	20.58	20.81	20.81
Flow in m3/sec	0.000216381	0.000216381	0.000325073	0.000325073	0.000390437	0.000390437
velocity (m/sec)	0.0008484	0.0008484	0.001274563	0.001274563	0.001530847	0.001530847
Average velocity (m/sec)	0.0008484		0.001274563		0.001530847	
Pz2	103.7	103.7	104.1	104.1	104.4	104.4
Pz6	103.5	103.5	103.8	103.8	103.9	103.9
i(2-6)	0.003883495	0.003883495	0.005825243	0.005825243	0.009708738	0.009708738
average i	0.003883495		0.005825243		0.009708738	

APPENDIX C

Appendic C: Long-term Clogging Study

Appendix C1- Changes in Leachate Chemistry – Day 0-127

Table C1.1- Leachate chemistry-pH

			pH	pH	pH	pH	pH	pH	pH	pH	pH	Average (0-167) days				
Media	Sampling point	Point id	6th Sep 2011	20th Sep 2011	4th October 2011	18th October 2011	17th Nov 2011	30th Nov2011	11th Jan 2012	24 th Jan 2012	7 th Feb 2012	Average	error	Normalised (Average/C6 *)	Max	Min
PLTT	0.75	C17					7.76	7.85	7.97	7.97	8.03	7.92	0.05	0.98	8.03	7.76
	0.625	C16	7.94	8.13	8.18	8.22	7.76	8.2	8.12	8.22	8.29	8.12	0.06	1.00	8.29	7.76
	0.5	C15	7.93	8.12	8.19	8.22	7.95	8.19	8.11	8.23	8.28	8.14	0.04	1.00	8.28	7.95
	0.375	C14	7.95	8.11	7.94	7.97	7.92	8.18	8.1	8.14	8.33	8.07	0.05	0.99	8.33	7.92
	0.25	C13	7.93	8.09	7.8	7.83	7.88	8.09	8.08	8.08	8.21	8.00	0.05	0.99	8.21	7.88
	0.125	C12	7.93	8.07	7.8	7.84	7.84	8.03	8.08	8.08	8.17	7.98	0.04	0.98	8.17	7.84
	0	C11	7.95	7.85	7.79	7.82	7.76	7.98	8.11	7.96	8.09	7.92	0.04	0.98	8.11	7.76
OTR	0.75	C27					7.82	7.85	7.9	7.97	8.03	7.91	0.04	0.97	8.03	7.82
	0.625	C26	7.93	8.09	8.11	8.17	7.97	8.31	8.26	8.38	8.31	8.17	0.05	1.00	8.38	7.97
	0.5	C25	7.91	8.02	7.97	8	7.92	8.29	8.23	8.25	8.15	8.08	0.05	0.99	8.29	7.92
	0.375	C24	7.93	7.94	7.9	7.93	7.92	8.27	8.23	8.22	8.12	8.05	0.05	0.99	8.27	7.92
	0.25	C23	7.91	7.99	7.82	7.89	7.89	8.17	8.23	8.21	8.1	8.02	0.05	0.98	8.23	7.89
	0.125	C22	7.91	7.78	7.77	7.84	7.88	8.08	8.24	8.21	8.08	7.98	0.06	0.98	8.24	7.88
	0	C21	7.9	7.72	7.78	7.85	7.84	7.97	8.32	8.21	8.03	7.96	0.07	0.97	8.32	7.84
Gravel	0.75	C37					7.77	7.81	7.91	8	8.01	7.90	0.05	0.99	8.01	7.77
	0.625	C36	7.75	7.78	7.82	7.96	7.9	8.23	8.04	8.21	8.16	7.98	0.06	1.00	8.23	7.9
	0.5	C35	7.74	7.68	7.77	7.94	7.85	8.2	8.03	8.14	8.07	7.94	0.06	0.99	8.2	7.85
	0.375	C34	7.76	7.64	7.79	7.95	7.86	8.18	8.04	7.98	8.02	7.91	0.06	0.99	8.18	7.86
	0.25	C33	7.78	7.67	7.79	7.95	7.88	8.12	8.04	7.89	7.96	7.90	0.05	0.99	8.12	7.88
	0.125	C32	7.81	7.63	7.79	7.94	7.84	8.02	8.03	7.83	7.94	7.87	0.04	0.99	8.03	7.83
	0	C31	7.88	7.61	7.77	7.85	7.83	7.9	8.05	7.84	7.97	7.86	0.04	0.98	8.05	7.83
OTR+PLTT	0.75	C47					7.68	7.81	7.85	7.98	7.99	7.86	0.06	0.96	7.99	7.68
	0.625	C46	7.9	8.15	8.16	8.21	7.9	8.39	8.37	8.44	8.29	8.20	0.07	1.00	8.44	7.9
	0.5	C45	7.91	8.05	8.1	8.03	7.85	8.37	8.18	8.19	8	8.08	0.05	0.98	8.37	7.85
	0.375	C44	7.91	7.84	7.86	7.87	7.81	8.32	8.08	8.04	7.89	7.96	0.05	0.97	8.32	7.81
	0.25	C43	7.89	7.81	7.83	7.86	7.81	8.21	8.03	7.96	7.88	7.92	0.04	0.97	8.21	7.81
	0.125	C42	7.9	7.79	7.81	7.84	7.83	8.03	7.97	7.91	7.86	7.88	0.03	0.96	8.03	7.83
	0	C41	7.92	7.68	7.8	7.86	7.82	7.87	7.89	7.9	7.86	7.84	0.02	0.96	7.9	7.82
Tank-outlet	0.75	To	8.06	8.1	8.11	8.23	7.9	8.01	7.98	8	8.03	8.05	0.03	1.00	8.03	7.9

Table C1.2. Leachate chemistry-Temperature

Media	Sampling point	Point id	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC	Temp oC		Temp oC	Temp oC
			6th Sep 2011	20th Sep 2011	4th Oct 2011	18th Oct 2011	15th Nov 2011	30th Nov 2011	11th Jan 2012	24th Jan 2012	7th Feb 2012	Average	error	Normalised (Average/C 6*)	Max	Min
PLTT	0.75	C17					16.6	15.6	16.1	16.7	16.2	16.2	0.2	0.9	16.7	15.6
	0.625	C16	20.9	19.5	18.8	17.6	17.2	17.4	16.2	17.2	17.6	18.0	0.5	1.0	20.9	16.2
	0.5	C15	20.9	19.6	18.6	17.5	17.2	17.2	16.3	17.1	17.5	18.0	0.5	1.0	20.9	16.3
	0.375	C14	20.4	19.4	18.6	17.7	17.2	17	16.5	17.2	17.6	18.0	0.4	1.0	20.4	16.5
	0.25	C13	20.2	19.5	18.7	18	16.9	17	16.5	17.4	17.6	18.0	0.4	1.0	20.2	16.5
	0.125	C12	20.1	19.4	18.8	18	17	17.8	16.8	17.4	17.8	18.1	0.4	1.0	20.1	16.8
	0	C11	20.3	19.2	18.6	17.5	18.5	18.5	18.8	18.6	18.3	18.7	0.3	1.0	20.3	17.5
OTR	0.75	C27					12.5	15.7	13.6	16.9	16.6	15.1	0.9	0.9	16.9	12.5
	0.625	C26	21.1	19	18.6	18.1	16.5	17.1	17.2	17.3	17.1	18.0	0.5	1.0	21.1	16.5
	0.5	C25	21	19.3	18.5	18.1	16.8	17.1	17	17.1	17.8	18.1	0.5	1.0	21	16.8
	0.375	C24	20.9	19.2	18.4	18	16.8	17	16.9	17	17.4	18.0	0.5	1.0	20.9	16.8
	0.25	C23	20.8	19	18.4	17.7	16.7	17.1	16.9	17.1	17.2	17.9	0.4	1.0	20.8	16.7
	0.125	C22	20.3	18.1	18.7	17.5	16.7	16.8	16.5	16.9	16.8	17.6	0.4	1.0	20.3	16.5
	0	C21	20.3	18.1	18.7	16.5	15.9	16.2	18.5	16.6	15.7	17.4	0.5	1.0	20.3	15.7
Gravel	0.75	C37					16.8	15.6	15.6	17.3	17.6	16.6	0.4	0.9	17.6	15.6
	0.625	C36	20.6	18.6	18.4	17.8	16.1	16.9	17	17.4	17.6	17.8	0.4	1.0	20.6	16.1
	0.5	C35	20.9	18.7	18.5	17.6	16.2	16.9	17	17.1	17.5	17.8	0.5	1.0	20.9	16.2
	0.375	C34	20.9	19	18.7	17.9	16.3	17	17	16.9	17.4	17.9	0.5	1.0	20.9	16.3
	0.25	C33	20.7	19.1	18.7	17.8	16.3	16.8	16.9	16.8	17.4	17.8	0.5	1.0	20.7	16.3
	0.125	C32	20.6	18.6	18.5	18	16.6	16.7	16.7	16.7	17.02	17.7	0.5	1.0	20.6	16.6
	0	C31	20.5	17.8	18.4	18.5	16.8	15.8	15.8	16.5	16.9	17.4	0.5	1.0	20.5	15.8
OTR+PLTT	0.75	C47						15.6	16.4	17.2	17.2	16.6	0.4	0.9	17.2	15.6
	0.625	C46	21.2	19.1	18.6	17.9	16.2	17.3	17.1	17.1	17.6	18.0	0.5	1.0	21.2	16.2
	0.5	C45	21.2	19	18.1	17.6	16.3	17.2	16.9	17.2	17.6	17.9	0.5	1.0	21.2	16.3
	0.375	C44	20.9	18.9	18.3	17.9	16.1	17.2	17	17.2	17.7	17.9	0.5	1.0	20.9	16.1
	0.25	C43	20.7	19.1	18.6	17.9	16.3	17.1	16.9	17	17.5	17.9	0.5	1.0	20.7	16.3
	0.125	C42	20.5	19	18.7	17.9	15.8	16.8	16.3	16.8	17.2	17.7	0.5	1.0	20.5	15.8
	0	C41	20.2	18.8	18.4	17.7	15.5	15.8	14.7	16.7	16.7	17.2	0.6	1.0	20.2	14.7
Tank-outlet	0	To	12.6	13.3	11.2	11.6	11.9	12.9	13.4	11.5	10.2	12.1	0.4	1.0	13.4	10.2

Table C1.3. Leachate chemistry- Conductivity

Media	Sampling point	Point id	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Conduct, mS	Normalised (Average/C6*)	Conduct, mS	Conduct, mS
			6th Sep 2011	20th Sep 2011	4th oct 2011	18th Oct 2011	19th Oct 2011	30th Nov 2011	11th Jan 2012	24th Jan 2012	7th Feb 2012	Average	error		Max	Min
PLTT	0.75	C17						14.18	14.56	13.79	14.52	14.26	0.18	0.99	14.56	13.79
	0.625	C16	14.57	14.6	14.7	14.29	14.41	14.27	14.47	14.32	13.5	14.35	0.12	1.00	14.7	13.5
	0.5	C15	14.66	14.62	14.75	14.58	14.66	14.43	14.63	14.29	13.57	14.47	0.12	1.01	14.75	13.57
	0.375	C14	14.7	14.51	14.84	14.34	14.37	14.4	14.59	14.66	13.68	14.45	0.11	1.01	14.84	13.68
	0.25	C13	14.39	14.48	14.85	14.34	14.4	14.53	14.5	14.7	13.45	14.40	0.13	1.00	14.85	13.45
	0.125	C12	14.23	14.44	14.8	14.53	14.55	14.44	14.13	14.63	13.92	14.41	0.09	1.00	14.8	13.92
	0	C11	14.7	14.36	14.69	14.73	14.34	14.56	14.34	14.92	13.63	14.47	0.13	1.01	14.92	13.63
OTR	0.75	C27						14.2	14.19	14.24	14.23	14.22	0.01	0.99	14.24	14.19
	0.625	C26	14.7	14.85	14.61	14.41		14.35	13.9	14.24	13.93	14.37	0.12	1.00	14.85	13.9
	0.5	C25	14.64	14.86	14.79	14.58		14.28	14	14.08	13.85	14.39	0.14	1.00	14.86	13.85
	0.375	C24	14.66	14.98	14.78	14.6	14.68	14.11	14.1	13.98	13.83	14.41	0.14	1.00	14.98	13.83
	0.25	C23	14.65	14.97	14.99	14.58	14.7	14.33	14.4	14.03	14.02	14.52	0.12	1.01	14.99	14.02
	0.125	C22	14.36	15.17	14.97	14.64	14.6	14.49	14.5	14.15	14.09	14.55	0.12	1.01	15.17	14.09
	0	C21	14.52	15.15	15.04	14.64	14.84	14.56	13.53	14.08	14.28	14.52	0.17	1.01	15.15	13.53
Gravel	0.75	C37						14.41	14.07	13.84	13.37	13.92	0.22	0.98	14.41	13.37
	0.625	C36	14.61	14.8	14.65	14.6	14.52	13.72	14.38	13.84	13.14	14.25	0.19	1.00	14.8	13.14
	0.5	C35	14.67	14.68	14.51	14.27	14.55	13.97	14.72	14.07	13.81	14.36	0.11	1.01	14.72	13.81
	0.375	C34	14.59	14.98	14.65	14.33	14.55	13.88	14.43	13.94	13.92	14.36	0.13	1.01	14.98	13.88
	0.25	C33	14.77	15.16	14.54	14.52	14.78	14.27	14.44	13.94	14.13	14.51	0.12	1.02	15.16	13.94
	0.125	C32	14.78	15.07	14.49	14.09	14.26	14.53	14.48	14.34	14.06	14.46	0.11	1.01	15.07	14.06
	0	C31	14.54	15.17	15.05	14.14	14.53	14.41	15.2	14.26	14.36	14.63	0.13	1.03	15.2	14.14
OTR+PLTT	0.75	C47						14.6	14.76	13.9	13.38	14.16	0.32	1.00	14.76	13.38
	0.625	C46	14.68	14.28	14.75	14.49	14.26	14	14.54	13.54	13.42	14.22	0.16	1.00	14.75	13.42
	0.5	C45	14.6	14.45	14.83	14.61	14.38	13.69	14.46	13.86	13.62	14.28	0.15	1.00	14.83	13.62
	0.375	C44	14.68	14.8	14.56	14.64	14.84	14.21	14.29	14.17	13.29	14.39	0.16	1.01	14.84	13.29
	0.25	C43	14.74	14.51	14.77	14.66	14.71	14.31	14.64	13.95	13.2	14.39	0.17	1.01	14.77	13.2
	0.125	C42	14.67	14.36	14.79	14.6	14.39	14.49	14.77	13.81	14.02	14.43	0.11	1.02	14.79	13.81
	0	C41	14.91	14.93	15.01	14.63	14.38	14.69	15.5	14.34	14.04	14.71	0.14	1.03	15.5	14.04
Tank-outlet	0.75	T0	14.92	14.28	14.75	14.46	14.1	13.3	13.71	13.34	13.67	14.06	0.20	1.00	14.92	13.3

Table C1.4. Leachate chemistry- COD

Media	Sampling point	Point id	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	COD, mg/L	
			24/08/2011	06/09/2011	20/09/2011	04/10/2011	18/10/2011	15/11/2011	11/01/2012	25/01/2012	07/02/2012	Average	error	Max	Min	Normalised, (Average/C*6)
PLTT	0.75	C17							5233	3829	2106	3723	904	5233	2106	0.97
	0.625	C16	3457	4495	5161	3367	2677	3605	3986	6022	1636	3823	434	6022	1636	1.00
	0.5	C15	4075	4495	3778	3415	2748	3415	4448	4002	1636	3557	302	4495	1636	0.93
	0.375	C14	4075	4396	4174	3248	2701	3629	4633	4060	1871	3643	298	4633	1871	0.95
	0.25	C13	3852	4322	4223	3177	2510	3677	4402	4695	1659	3613	332	4695	1659	0.95
	0.125	C12	3927	4396	4470	3415	2701	1844	4910	4983	2035	3631	400	4983	1844	0.95
	0	C11	3852	4643	4075	3082	2272	2748	4910	3887	1471	3438	377	4910	1471	0.90
OTR	0.75	C27							5649	4406	2012	4022	1067	5649	2012	1.27
	0.625	C26	3778	4272	3630	3391	2963	3343	3479	1924	1612	3155	288	4272	1612	1.00
	0.5	C25	3778	4322	3606	3248	2867	3558	3340	2905	1471	3233	266	4322	1471	1.02
	0.375	C24	3803	4322	4050	3415	2844	3439	3109	3483	1495	3329	274	4322	1495	1.06
	0.25	C23	3976	4396	4174	3248	2891	3462	3202	3194	1424	3330	292	4396	1424	1.06
	0.125	C22	4667	4223	4223	3320	2701	3558	3017	2444	1354	3278	346	4667	1354	1.04
	0	C21	3581	4149	4001	3248	2177	3367	3202	1809	1542	3008	314	4149	1542	0.95
Gravel	0.75	C37							5233	4983	2247	4154	956	5233	2247	1.32
	0.625	C36	3655	4272	3235	2867	1725	3962	3940	3136	1612	3156	318	4272	1612	1.00
	0.5	C35	4174	4198	3581	2772	1796	3415	3340	2963	1213	3050	336	4198	1213	0.97
	0.375	C34	3581	4248	3581	2891	1606	2748	2971	2617	1330	2841	311	4248	1330	0.90
	0.25	C33	3828	4322	3433	2629	1534	1749	3571	2559	1283	2768	362	4322	1283	0.88
	0.125	C32	3828	4050	3877	2558	1558	1725	4125	1636	1095	2717	417	4125	1095	0.86
	0	C31	3704	4272	3606	2272	1487	1320	3802	1578	1166	2579	418	4272	1166	0.82
OTR+PLTT	0.75	C47							4725	4348	2153	3742	802	4725	2153	1.13
	0.625	C46	4248	4865	3902	3050	2475	3841	3294	2501	1542	3302	343	4865	1542	1.00
	0.5	C45	4396	4445	3507	3146	2523	3817	3109	3309	1424	3297	312	4445	1424	1.00
	0.375	C44	5680	4495	3235	3002	2715	3218	3432	3252	1518	3394	385	5680	1518	1.03
	0.25	C43	3852	4495	3531	3338	2882	3625	3386	3540	1589	3360	264	4495	1589	1.02
	0.125	C42	4099	4495	3704	3122	2547	2739	2232	2444	1213	2955	340	4495	1213	0.89
	0	C41	4544	4396	3383	2595	1733	2164	2186	1289	1260	2617	412	4544	1260	0.79
Tank-outlet	0.75	T1	4223			4870	3481	5086	5649	8330	3530	5024	629	8330	3481	1.00

Table C1.5. Leachate chemistry-TSS

Media	Sampling level	Point id	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	TSS, mg/L	
			24th Aug 2011	6th Sep 2011	20th sep 2011	4th Oct 2011	18th Oct 2011	15th Nov 2011	30th Nov 2011	11th Jan 2012	24th Jan 2012	7th Feb 2012	Mean	Error	Max	Min	normalised (Average/ C*6)
PLTT	0.75	C17						8312	13224	544	192	3320	5118	2493	13224	192	66.30
	0.625	C16	24	30	30	20	22	38	88	294	102	124	77	27	294	20	1.00
	0.5	C15	32	40	36	30	22	46	70	180	80	100	64	15	180	22	0.82
	0.375	C14	28	22	32	18	10	24	76	186	80	136	61	19	186	10	0.79
	0.25	C13	30	36	28	2	18	24	62	158	58	88	50	14	158	2	0.65
	0.125	C12	103	32	16	14	8	18	36	140	44	92	50	14	140	8	0.65
	0	C11	63	64	10	12	20	6	22	150	8	82	44	15	150	6	0.57
OTR	0.75	C27						3445	1800	630	360	580	1363	578	3445	360	15.85
	0.625	C26	38	38	22	50	14	68	92	116	114	308	86	27	308	14	1.00
	0.5	C25	24	38	12	20	16	76	84	128	92	314	80	29	314	12	0.93
	0.375	C24	34	4	22	8	8	70	88	110	100	72	52	13	110	4	0.60
	0.25	C23	32	34	10	28	12	60	84	110	88	64	52	11	110	10	0.61
	0.125	C22	34	44	26	22	22	88	98	98	96	74	60	11	98	22	0.70
	0	C21	20	76	20	14	6	48	90	156	118	20	57	16	156	6	0.66
Gravel	0.75	C37						6570	14892	400	410	820	4618	2822	14892	400	113.20
	0.625	C36	20	20	10	0	40	58	32	126	50	52	41	11	126	0	1.00
	0.5	C35	18	22	16	4	2	24	30	108	50	32	31	10	108	2	0.75
	0.375	C34	44	20	12	18	10	10	28	114	18	28	30	10	114	10	0.74
	0.25	C33	22	20	30	4	12	10	24	116	22	40	30	10	116	4	0.74
	0.125	C32	30	52	32	28	6	20	42	114	18	26	37	9	114	6	0.90
	0	C31	28	94	26	14	14	18	24	136	10	20	38	13	136	10	0.94
OTR+PLTT	0.75	C47						7667	75	310	1580	600	2046	1428	7666.5	75	40.93
	0.625	C46			16	24	34	38	74	16	98	100	50	13	100	16	1.00
	0.5	C45	52	18	16	12	18	30	60	66	90	68	43	9	90	12	0.86
	0.375	C44	58	18	10	16	6	32	66	82	60	42	39	8	82	6	0.78
	0.25	C43	42	30	16	10	22	40	66	50	140	100	52	13	140	10	1.03
	0.125	C42	40	50	14	26	12	34	30	50	50	52	36	5	52	12	0.72
	0	C41	44	78	28	10	14	10	16	16	38	28	28	7	78	10	0.56
Tank-outlet	0.75	T1				5980	5740	11005	964	648	652	2680	3953	1459	11005	648	1.00

Table C1.6. Leachate chemistry- TS

Sampling level	Sample id	TS, mg/L 24th Aug 2011	TS, mg/L 6th Sep 2011	TS, mg/L 18th Oct 2011	TS, mg/L 11th Jan 2012	TS, mg/L 24th Feb 2012	TS, mg/L 7th Feb 2012	TS, mg/L Average	TS, mg/L Error	TS, mg/L Max	TS, mg/L Min
0.75	C17				9725	9460	9405	**9530**	99	9725	9405
0.625	C16	9505	8540	8540	9795	9455	8580	**9069**	236	9795	8540
0.5	C15	9555	8450	8450	9755	8840	8560	**8935**	236	9755	8450
0.375	C14	9430	8320	8320	9290	8890	8660	**8818**	194	9430	8320
0.25	C13	9555	8660	8660	9200	8715	8565	**8893**	161	9555	8565
0.125	C12	9525	8605	8605	9160	8770	8540	**8868**	160	9525	8540
0	C11	9520	8720	8720	9225	8710	8480	**8896**	160	9520	8480
0.75	C27				5080	9620	9410	**8037**	1480	9620	5080
0.625	C26	9585	8590	8590	8520	8360	8480	**8688**	183	9585	8360
0.5	C25	9575	8485	8485	8560	8365	8400	**8645**	188	9575	8365
0.375	C24	9645	8715	8715	8470	8305	8465	**8719**	196	9645	8305
0.25	C23	9600	8485	8485	8420	8270	8370	**8605**	202	9600	8270
0.125	C22	9625	8540	8540	8520	8315	8355	**8649**	199	9625	8315
0	C21	9630	8590	8590	8530	8405	8230	**8663**	201	9630	8230
0.75	C37				9465	9560	9455	**9493**	33	9560	9455
0.625	C36	8845	8645	8645	8805	8835	8490	**8711**	58	8845	8490
0.5	C35	9750	8590	8590	8745	8770	8475	**8820**	191	9750	8475
0.375	C34	9955	8710	8710	8720	8400	8220	**8786**	248	9955	8220
0.25	C33	9755	8710	8710	8760	8390	8405	**8788**	204	9755	8390
0.125	C32	9520	8550	8550	8735	8340	8265	**8660**	185	9520	8265
0	C31	9790	8560	8560	8775	8420	8380	**8748**	216	9790	8380
0.75	C47				9385	13950	9300	**10878**	1536	13950	9300
0.625	C46	9735	8620	8620	8790	8630	8410	**8801**	193	9735	8410
0.5	C45	9760	8580	8580	8725	8655	8430	**8788**	198	9760	8430
0.375	C44	9640	8650	8650	8315	8470	8235	**8660**	208	9640	8235
0.25	C43	9675	8540	8540	8400	8485	8470	**8685**	199	9675	8400
0.125	C42	9650	8620	8620	8305	8345	8490	**8672**	203	9650	8305
0	C41	9980	8680	8680	8180	8320	8420	**8710**	267	9980	8180
0.75	T1				14175	11885	10575	**12212**	1052	14175	10575

Table C1.7. Leachate chemistry-Calcium

Media	Sampling point	Point id	Calcium, mg/L 24th Aug 2011	Calcium, mg/L 06th Sep 2011	Calcium, mg/L 20th Sep 2011	Calcium, mg/L 4th Oct 2011	Calcium, mg/L 24th Jan 2012	Calcium, mg/L 7th Feb 2012	Calcium, mg/L Average	Calcium, mg/L Error	Calcium, mg/L Max	Calcium, mg/L Min	Normalised (Average/C*6)
PLTT	0.75	C17					34.871	39.906	37.389	2.518	39.906	34.871	1.19
	0.625	C16	34.614	25.735	31.839	31.839	39.22	25.982	31.538	2.107	39.220	25.735	1.00
	0.5	C15	34.062	26.163	33.388	33.388	34.646	27.943	31.598	1.468	34.646	26.163	1.00
	0.375	C14	33.448	25.728	31.478	31.478	34.466	25.154	30.292	1.606	34.466	25.154	0.96
	0.25	C13	32.59	31.835	30.256	30.256	34.409	24.689	30.673	1.356	34.409	24.689	0.97
	0.125	C12	33.29	26.605	34.969	34.969	34.0685	26.899	31.800	1.617	34.969	26.605	1.01
	0	C11	24.222	28.079	26.341	26.341	33.728	27.713	27.737	1.320	33.728	24.222	0.88
OTR	0.75	C27					39	42.330	40.665	1.665	42.330	39.000	1.47
	0.625	C26	33.806	24.561	31.203	31.203	21.501	23.194	27.578	2.084	33.806	21.501	1.00
	0.5	C25	23.236	23.104	30.528	30.528	20.405	16.151	23.992	2.318	30.528	16.151	0.87
	0.375	C24	38.594	25.89	31.052	31.052	20.001	24.383	28.495	2.651	38.594	20.001	1.03
	0.25	C23	31.304	25.812	31.576	31.576	20.209	18.252	26.455	2.468	31.576	18.252	0.96
	0.125	C22	29.92	27.508	32.822	32.822	20.549	19.985	27.268	2.359	32.822	19.985	0.99
	0	C21	31.574	27.67	26	26	25.314	20.858	26.236	1.419	31.574	20.858	0.95
Gravel	0.75	C37					37.908	36.170	37.039	0.869	37.908	36.170	1.11
	0.625	C36	48.292	28.977	33.332	33.332	30.121	26.387	33.407	3.169	48.292	26.387	1.00
	0.5	C35	40.524	29.816	32.862	32.862	28.067	26.846	31.830	2.006	40.524	26.846	0.95
	0.375	C34	41.212	30.038	31.65	31.65	26.581	27.542	31.446	2.132	41.212	26.581	0.94
	0.25	C33	42.108	28.841	30.498	30.498	28.256	25.602	30.967	2.347	42.108	25.602	0.93
	0.125	C32	40.898	30.69	31.747	31.747	27.704	25.655	31.407	2.142	40.898	25.655	0.94
	0	C31	40.304	29.758	30.273	30.273	27.932	25.458	30.666	2.071	40.304	25.458	0.92
OTR+PLTT	0.75	C47					39.16	36.863	38.012	1.149	39.160	36.863	1.31
	0.625	C46	22.966	23.825	42.36	42.36	21.972	20.536	29.003	4.247	42.360	20.536	1.00
	0.5	C45	34.174	25.939	31.366	31.366	32.069	22.455	29.562	1.805	34.174	22.455	1.02
	0.375	C44	37.936	24.178	39.408	39.408	25.774	23.263	31.661	3.269	39.408	23.263	1.09
	0.25	C43	37.88	24.783	33.473	33.473	31.81	23.949	30.895	2.225	37.880	23.949	1.07
	0.125	C42	37.946	25.694	27.055	27.055	24.484	24.468	27.784	2.086	37.946	24.468	0.96
	0	C41	24.228	26.333	34.669	34.669	24.516	24.661	28.179	2.074	34.669	24.228	0.97
Tank-outlet	0.75	T1	25.796	28.602	29.926	29.926	24.516	105.454	40.703	12.982	105.454	24.516	1.00

Table C1.8-Leachate chemistry- Magnesium

Media	Sampling point	Point id	magnesium, mg/L 24th Aug 2011	magnesium, mg/L 24th Aug 2011	magnesium, mg/L 06th Sep 2011	magnesium, mg/L 20th Sep 2011	magnesium, mg/L 25th Jan 2012	magnesium, mg/L 30thJan 2012	magnesium, mg/L 7th feb 2012	magnesium, mg/L Average	magnesium, mg/L Error	magnesium, mg/L Max	magnesium, mg/L Min	Normalised (Average. C*6)
PLTT	0.75	C17						327.697	231.811	279.754	47.943	327.697	231.811	1.366
	0.625	C16	1.7307	34.614	287.232	276.108	276.108	336.263	221.061	204.731	49.931	336.263	1.7307	1.000
	0.5	C15	1.7031	34.062	312.674	273.974	273.974	329.013	235.763	208.738	50.682	329.013	1.7031	1.020
	0.375	C14	1.6724	33.448	279.686	270.575	270.575	322.817	219.344	199.731	48.512	322.817	1.6724	0.976
	0.25	C13	1.6295	32.59	300.739	269.159	269.159	322.69	207.336	200.472	49.328	322.69	1.6295	0.979
	0.125	C12	1.6645	33.29	268.928	262.025	262.025	324.739	233.864	198.077	47.873	324.739	1.6645	0.967
	0	C11	1.2111	24.222	255.872	263.514	263.514	320.101	242.372	195.829	48.231	320.101	1.2111	0.957
OTR	0.75	C27						551.537	235.098	393.318	158.220	551.537	235.098	1.915
	0.625	C26	1.6903	33.806	295.771	276.034	276.034	321.556	232.467	205.337	49.597	321.556	1.6903	1.000
	0.5	C25	1.1618	23.236	242.181	279.073	279.073	325.489	171.108	188.760	48.981	325.489	1.1618	0.919
	0.375	C24	1.9297	38.594	289.941	274.343	274.343	320.203	223.564	203.274	48.638	320.203	1.9297	0.990
	0.25	C23	1.5652	31.304	309.468	270.316	270.316	318.671	199.83	200.210	49.711	318.671	1.5652	0.975
	0.125	C22	1.496	29.92	298.085	273.688	273.688	319.009	229.279	203.595	49.699	319.009	1.496	0.992
	0	C21	1.5787	31.574	309.641	271.627	271.627	320.17	241.495	206.816	50.204	320.17	1.5787	1.007
Gravel	0.75	C37						357.475	203.424	280.450	77.026	357.475	203.424	1.295
	0.625	C36	2.4146	48.292	283.452	302.269	302.269	337.777	239.622	216.585	50.842	337.777	2.4146	1.000
	0.5	C35	2.0262	40.524	292.818	289.182	289.182	338.421	238.8	212.993	50.857	338.421	2.0262	0.983
	0.375	C34	2.0606	41.212	290.739	285.088	285.088	333.519	236.912	210.660	50.119	333.519	2.0606	0.973
	0.25	C33	2.1054	42.108	288.229	289.485	289.485	336.566	235.311	211.898	50.426	336.566	2.1054	0.978
	0.125	C32	2.0449	40.898	283.745	280.931	280.931	333.182	237.812	208.506	49.587	333.182	2.0449	0.963
	0	C31	2.0152	40.304	321.185	265.713	265.713	335.345	241.287	210.223	50.548	335.345	2.0152	0.971
OTR+PLTT	0.75	C47						351.524	247.365	299.445	52.080	351.524	247.365	1.476
	0.625	C46	1.1483	22.966	286.755	272.45	272.45	330.903	233.53	202.886	50.500	330.903	1.1483	1.000
	0.5	C45	1.7087	34.174	297.068	272.409	272.409	338.653	234.935	207.337	50.425	338.653	1.7087	1.022
	0.375	C44	1.8968	37.936	300.703	271.827	271.827	331.898	233.307	207.056	49.792	331.898	1.8968	1.021
	0.25	C43	1.894	37.88	275.996	271.231	271.231	335.304	233.406	203.849	48.983	335.304	1.894	1.005
	0.125	C42	1.8973	37.946	305.187	220.368	220.368	331.179	238.559	193.643	47.762	331.179	1.8973	0.954
	0	C41	1.2114	24.228	301.013	256.448	256.448	338.078	237.8	202.175	50.580	338.078	1.2114	0.996
Tank	0.75	T1	1.2898	25.796	304.196	280.86	280.86	357.187		208.365	62.731	357.187	1.2898	1.000

Table C1.9. Leachate chemistry- Sodium

Media	Sampling point	Sample id	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	Sodium, mg/L	
			24th Aug 2011	06th Sep 2011	20th Jan 2012	30th Jan 2012	07 th Feb 2012	Average	Error	Max	Min	Normalised (Average/C*6)
PLTT	0.75	C17			1873.374	1841.545	1740.942	1818.620	39.911	1873.374	1740.942	1.277
	0.625	C16	34.614	1787.583	1769.534	1809.593	1718.209	1423.907	347.651	1809.593	34.614	1.000
	0.5	C15	34.062	1858.851	1815.677	1831.828	1795.103	1467.104	358.412	1858.851	34.062	1.030
	0.375	C14	33.448	1677.661	1748.865	1798.379	1708.315	1393.334	340.574	1798.379	33.448	0.979
	0.25	C13	32.59	1854.474	1838.903	1805.777	1631.755	1432.700	352.279	1854.474	32.59	1.006
	0.125	C12	33.29	1773.432	1945.882	1820.888	1827.437	1480.186	362.838	1945.882	33.29	1.040
	0	C11	24.222	1851.755	2147.908	1830.271	1871.102	1545.052	384.583	2147.908	24.222	1.085
OTR	0.75	C27			1965.405	2984.527	1801.619	2250.517	370.038	2984.527	1801.619	1.557
	0.625	C26	33.806	1802.597	1791.546	1784.324	1815.633	1445.581	352.983	1815.633	33.806	1.000
	0.5	C25	23.236	1610.774	1716.8	1815.27	1373.109	1307.838	329.467	1815.27	23.236	0.905
	0.375	C24	38.594	1765.974	1796.203	1802.49	1775.698	1435.792	349.362	1802.49	38.594	0.993
	0.25	C23	31.304	1798.021	1785.039	1788.303	1610.102	1402.554	344.594	1798.021	31.304	0.970
	0.125	C22	29.92	1850.302	1660.957	1783.416	1849.571	1434.833	352.920	1850.302	29.92	0.993
	0	C21	31.574	1820.548	1821.939	1791.7	1846.584	1462.469	357.829	1846.584	31.574	1.012
Gravel	0.75	C37			1826.187	1842.578	1580.393	1749.719	84.795	1842.578	1580.393	1.143
	0.625	C36	48.292	1705.207	2147.694	1846.059	1903.895	1530.229	377.319	2147.694	48.292	1.000
	0.5	C35	40.524	1778.982	1729.953	1856.573	1898.487	1460.904	356.306	1898.487	40.524	0.955
	0.375	C34	41.212	1800.436	1584.217	1833.346	1894.321	1430.706	351.285	1894.321	41.212	0.935
	0.25	C33	42.108	1756.145	1904.423	1850.427	1879.616	1486.544	361.982	1904.423	42.108	0.971
	0.125	C32	40.898	1779.04	2010.225	1822.694	1896.853	1509.942	369.344	2010.225	40.898	0.987
	0	C31	40.304	1926.859	2035.726	1847.663	1906.307	1551.372	378.991	2035.726	40.304	1.014
OTR+PLTT	0.75	C47			1655.23	1842.517	1820.593	1772.780	59.115	1842.517	1655.23	1.224
	0.625	C46	22.966	1767.071	1776.547	1799.303	1873.599	1447.897	356.723	1873.599	22.966	1.000
	0.5	C45	34.174	1841.862	1836.731	1822.534	1861.593	1479.379	361.355	1861.593	34.174	1.022
	0.375	C44	37.936	1810.326	1639.185	1801.287	1849.738	1427.694	349.303	1849.738	37.936	0.986
	0.25	C43	37.88	1823.908	1929.415	1821.395	1851.548	1492.829	364.262	1929.415	37.88	1.031
	0.125	C42	37.946	1840.893	1406.147	1816.424	1880.97	1396.476	350.307	1880.97	37.946	0.964
	0	C41	24.228	1791.511	1611.694	1845.597	1873.099	1429.226	354.186	1873.099	24.228	0.987
Tank	0.75	To	26.19			1828.17	20.751	625.037	601.569	1828.17	20.751	1.000

Table C1.10- Leachate chemistry- Chloride

Media	Sampling point	Sample id	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L	Chloride, mg/L
			24th Aug 2011	06th Sep 2011	20th Jan 2012	30th Jan 2012	7th Feb 2012	Average	Error	Max	Min	Normalised (Average/C*6)
PLTT	0.75	C17			2683.947	2689.57	2707.699	2693.739	7.166	2707.699	2683.947	1.259
	0.625	C16	34.614	2836.317	2518.418	2643.576	2663.814	2139.348	528.615	2836.317	34.614	1.000
	0.5	C15	34.062	2949.917	2582.255	2676.757	2807.812	2210.161	547.540	2949.917	34.062	1.033
	0.375	C14	33.448	2609.54	2490.474	2634.23	2649.968	2083.532	513.286	2649.968	33.448	0.974
	0.25	C13	32.59	2883.77	2621.633	2644.823	2502.167	2136.997	529.731	2883.770	32.590	0.999
	0.125	C12	33.29	2736.77	2791.97	2671.011	2818.372	2210.283	544.834	2818.372	33.290	1.033
	0	C11	24.222	2729.163	3185.519	2685.961	2924.44	2309.861	578.182	3185.519	24.222	1.080
OTR	0.75	C27			2823.786	4537.441	2865.738	3408.988	564.356	4537.441	2823.786	1.539
	0.625	C26	33.806	2960.501	2567.493	2609.264	2903.354	2214.884	550.768	2960.501	33.806	1.000
	0.5	C25	23.236	2607.67	2433.172	2661.312	2129.972	1971.072	495.709	2661.312	23.236	0.890
	0.375	C24	38.594	2849.191	2591.467	2641.041	2824.982	2189.055	539.949	2849.191	38.594	0.988
	0.25	C23	31.304	2870.255	2555.328	2617.856	2540.129	2122.974	526.278	2870.255	31.304	0.959
	0.125	C22	29.92	2962.728	2344.978	2614.428	2913.6	2173.131	547.238	2962.728	29.920	0.981
	0	C21	31.574	2898.388	2597.594	2625.932	3036.544	2238.006	557.759	3036.544	31.574	1.010
Gravel	0.75	C37			2595.951	2709.717	2481.676	2595.781	65.830	2709.717	2481.676	1.107
	0.625	C36	48.292	2829.247	3080.28	2710.031	3059.412	2345.452	578.517	3080.280	48.292	1.000
	0.5	C35	40.524	2953.736	2445.799	2726.659	3029.044	2239.152	558.967	3029.044	40.524	0.955
	0.375	C34	41.212	2928.228	2226.511	2693.428	3018.614	2181.599	552.417	3018.614	41.212	0.930
	0.25	C33	42.108	2907.667	2697.928	2710.824	3029.422	2277.590	562.317	3029.422	42.108	0.971
	0.125	C32	40.898	2896.358	2869.597	2674.975	3058.399	2308.045	570.047	3058.399	40.898	0.984
	0	C31	40.304	3167.92	2939.376	2714.658	3047.428	2381.937	590.141	3167.920	40.304	1.016
OTR+PLTT	0.75	C47			2339.083	2698.116	2959.281	2665.493	179.777	2959.281	2339.083	1.188
	0.625	C46	22.966	2981.791	2538.043	2624.979	3049.135	2243.383	563.790	3049.135	22.966	1.000
	0.5	C45	34.174	3083.475	2621.962	2667.48	3014.196	2284.257	569.883	3083.475	34.174	1.018
	0.375	C44	37.936	3051.882	2307.627	2641.974	3005.605	2209.005	559.274	3051.882	37.936	0.985
	0.25	C43	37.88	3078.313	2759.955	2681.412	3005.456	2312.603	573.449	3078.313	37.880	1.031
	0.125	C42	37.946	3075.075	1951.936	2665.702	3060.479	2158.228	567.906	3075.075	37.946	0.962
	0	C41	24.228	2988.5	2270.895	2732.312	3049.455	2213.078	564.128	3049.455	24.228	0.986
Tank	0.75	T1	25.796	3103.909	2728.721	2689.746	20.949	1713.824	693.903	3103.909	20.949	1.000

Table C1.11- Leachate chemistry- Sulfate

Media	Sampling point	Point id	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L	Sulphate, mg/L
			06th Sep 2011	20th Jan 2012	30th Jan 2012	7th Feb 2012	Average	Error	Max	Min	Normalised (Average/C*6)
PLTT	0.75	C17	5.000	75.078	3.590	40.882	31.138	16.999	75.078	3.590	0.905
	0.625	C16	5.000	81.904	45.698	5.000	34.401	18.513	81.904	5.000	1.000
	0.5	C15	5.000	93.078	5.000	5.000	27.020	22.020	93.078	5.000	0.785
	0.375	C14	5.000	82.254	5.000	5.000	24.314	19.314	82.254	5.000	0.707
	0.25	C13	5.000	86.508	4.164	5.000	25.168	20.448	86.508	4.164	0.732
	0.125	C12	5.000	86.806	3.225	5.000	25.008	20.604	86.806	3.225	0.727
	0	C11	24.489	96.888	3.314	5.000	32.423	22.019	96.888	3.314	0.943
OTR	0.75	C27	5.000	90.324	79.123	46.331	55.195	19.159	90.324	5.000	10.897
	0.625	C26	5.000	6.752	5.000	3.509	5.065	0.663	6.752	3.509	1.000
	0.5	C25	5.000	10.000	5.000	5.000	6.250	1.250	10.000	5.000	1.234
	0.375	C24	5.000	10.000	5.000	5.000	6.250	1.250	10.000	5.000	1.234
	0.25	C23	5.000	10.504	5.000	5.000	6.376	1.376	10.504	5.000	1.259
	0.125	C22	5.000	10.000	5.000	5.000	6.250	1.250	10.000	5.000	1.234
	0	C21	5.000	10.000	5.000	5.000	6.250	1.250	10.000	5.000	1.234
Gravel	0.75	C37	5.000	75.910	45.154	36.403	40.617	14.585	75.910	5.000	1.468
	0.625	C36	5.000	102.464	2.435	0.805	27.676	24.944	102.464	0.805	1.000
	0.5	C35	5.000	79.896	5.000	5.000	23.724	18.724	79.896	5.000	0.857
	0.375	C34	5.000	77.446	5.000	5.000	23.112	18.112	77.446	5.000	0.835
	0.25	C33	5.000	136.008	5.000	156.270	75.570	40.953	156.270	5.000	2.731
	0.125	C32	5.000	100.448	3.325	5.000	28.443	24.005	100.448	3.325	1.028
	0	C31	5.000	101.770	5.000	5.000	29.193	24.193	101.770	5.000	1.055
OTR+PLTT	0.75	C47	5.000	65.470	44.810	44.764	40.011	12.648	65.470	5.000	0.340
	0.625	C46	450.008	10.670	5.000	5.000	117.670	110.788	450.008	5.000	1.000
	0.5	C45	5.000	10.116	5.829	5.000	6.486	1.226	10.116	5.000	0.055
	0.375	C44	5.000	10.000	4.091	5.000	6.023	1.343	10.000	4.091	0.051
	0.25	C43	5.000	10.000	5.000	73.364	23.341	16.716	73.364	5.000	0.198
	0.125	C42	5.000	10.000	5.000	398.851	104.713	98.053	398.851	5.000	0.890
	0	C41	5.000	10.000	5.000	5.000	6.250	1.250	10.000	5.000	0.053
Tank	0.75	T1	136.547	94.438	47.219	5.000	70.801	28.529	136.547	5.000	1.000

Appendix C2- Changes in Leachate Chemistry – Day 127-427

Table C2.1- Leachate chemistry- Temperature

Media	Level (m)	Point ID	Temp °C 20-Apr-12	Temp °C 8-May-12	Temp °C 12-Jun-12	Temp °C 26-Jun-12	Temp °C 13-Jul-12	Temp °C 31-Jul-12	Temp °C 28-Aug-12	Temp °C 11-Sep-12	Temp °C 25-Sep-12	Temp °C 10-Oct-12	Temp °C 23-Oct-12	Temp °C Mean	Temp °C SD	N	Temp °C Error	Normalised	Temp °C Max	Temp °C Min
PLTT	0.75	C17	17.1	20.9	21.3	21.9	24.9	22	21.7	22.1	21	18.5	16.7	20.7	2.4	11	0.7	1.04	24.9	16.7
	0.625	C16	17.9	19.5	20	20.8	24.3	21.7	22.3	18.1	20.7	17.7	17	20.0	2.2	11	0.7	1.00	24.3	17
	0.5	C15	18	19.6	20	20.7	24.2	21.7	22.3	18.1	20.7	17.7	16.9	20.0	2.2	11	0.7	1.00	24.2	16.9
	0.375	C14	18	19.7	20	20.7	24.1	21.4	22	18.1	20.8	17.6	17	19.9	2.2	11	0.6	1.00	24.1	17
	0.25	C13	18.2	19.7	20	20.7	24	21.3	22	18.1	20.6	17.8	17.1	20.0	2.1	11	0.6	1.00	24	17.1
	0.125	C12	18.5	19.9	20.3	20.8	24.2	21.2	22.1	18	20.6	17.7	17.3	20.1	2.1	11	0.6	1.00	24.2	17.3
	0	C11	18.7	20.8	21	20.9	24.3	21.1	22.3	18.6	21.3	18.6	17.8	20.5	1.9	11	0.6	1.02	24.3	17.8
OTR	0.75	C27	17.9	20.2	20.8	21.3	26.1	21.6	21.6	18.6	20.4	18	16.9	20.3	2.5	11	0.8	1.02	26.1	16.9
	0.625	C26	17.8	19.4	19.9	20.7	24.1	21.5	22.3	18	20.7	17.7	17	19.9	2.2	11	0.7	1.00	24.1	17
	0.5	C25	17.7	19.5	19.9	20.7	24.1	21.4	22.2	18	20.8	17.8	16.9	19.9	2.2	11	0.7	1.00	24.1	16.9
	0.375	C24	17.6	19.5	19.8	20.7	24.1	21.3	22.1	18.1	20.8	17.6	16.8	19.9	2.2	11	0.7	1.00	24.1	16.8
	0.25	C23	17.5	19.4	19.7	20.6	23.9	21.2	21.9	17.9	20.9	17.6	16.7	19.8	2.2	11	0.7	0.99	23.9	16.7
	0.125	C22	17.4	19.6	19.6	20.5	23.7	21	21.7	17.7	20.9	17.3	16.4	19.6	2.2	11	0.7	0.98	23.7	16.4
	0	C21	17	18.4	19.3	20.4	23.2	20.8	21.3	17.5	20.6	16.8	15.7	19.2	2.3	11	0.7	0.96	23.2	15.7
Gravel	0.75	C37	17.8	19.7	20.4	20.7	24.7	21.4	21.6	18.1	20.7	17.6	16.8	20.0	2.3	11	0.7	1.00	24.7	16.8
	0.625	C36	18	19.4	19.8	20.7	23.9	21.6	22.2	17.8	21.1	17.8	17	19.9	2.2	11	0.7	1.00	23.9	17
	0.5	C35	17.9	19.4	19.8	20.7	23.7	21.5	22.1	17.8	20.8	17.8	16.9	19.9	2.1	11	0.6	1.00	23.7	16.9
	0.375	C34	17.7	19.3	19.7	20.6	23.8	21.3	22	17.8	20.7	17.7	16.9	19.8	2.1	11	0.6	0.99	23.8	16.9
	0.25	C33	17.7	19.3	19.7	20.5	23.6	21.3	21.9	17.7	20.6	17.9	16.7	19.7	2.1	11	0.6	0.99	23.6	16.7
	0.125	C32	17.2	19.2	19.5	20.3	23.6	21.1	21.8	17.6	20.5	17.6	16.4	19.5	2.2	11	0.7	0.98	23.6	16.4
	0	C31	16.3	19	19.2	19.8	23.1	20.4	21.4	16.8	19.8	17.3	15.8	19.0	2.3	11	0.7	0.95	23.1	15.8
OTR+PLTT	0.75	C47	17.5	19.4	20.3	20.4	24.2	21.1	21.4	17.6	20.7	17.4	16.6	19.7	2.3	11	0.7	0.99	24.2	16.6
	0.625	C46	17.9	19.5	19.9	20.8	24.3	21.1	22.3	17.8	20.6	17.5	16.7	19.9	2.3	11	0.7	1.00	24.3	16.7
	0.5	C45	17.8	19.5	19.8	20.7	24.1	21.1	22.2	17.5	20.6	17.4	16.6	19.8	2.3	11	0.7	0.99	24.1	16.6
	0.375	C44	17.8	19.3	19.7	20.6	24.1	20.9	22	17.7	20.8	17.4	16.4	19.7	2.3	11	0.7	0.99	24.1	16.4
	0.25	C43	17.5	19.3	19.7	20.7	24	20.6	21.9	17.6	20.8	17.8	16.1	19.6	2.3	11	0.7	0.99	24	16.1
	0.125	C42	17.4	19.2	19.6	20.4	23.1	20.2	21.7	17.3	20.6	17.4	15.7	19.3	2.2	11	0.7	0.97	23.1	15.7
	0	C41	16.8	18.9	19.3	20.1	23	21.3	21.4	16.6	19.9	16.8	14.8	19.0	2.5	11	0.8	0.96	23	14.8
Tank-outlet	0	To	20.4	30.2	33	40.4	42.5	27.4	20.9	27.8	36.7	37.6	18.5	30.5	8.3	11.0	2.5	1.54	42.5	18.5

Table C2.2- Leachate chemistry- Conductivity

Media Type	Level (m)	Point ID	Conduct, mS 20-Apr-12	Conduct, mS 8-May-12	Conduct, mS 6/12/2012	Conduct, mS 26-Jun-12	Conduct, mS 13-Jul-12	Conduct, mS 14-Jul-12	Conduct, mS 28-Aug-12	Conduct, mS 11-Sep-12	Conduct, mS 25-Sep-12	Conduct, mS 10-Oct-12	Conduct, mS 23-Oct-12	Conduct, mS Mean	Conduct, mS Error	Normalised (mean/C6*)	Conduct, mS Max	Conduct, mS Min	N	SD
PLTT	0.75	C17	15.51	15.28	15.24	15.38	15.3	13.91	15.68	15.35	15.95	17.74	15.94	15.57	0.27	1.03	17.74	13.91	11	0.90
	0.625	C16	15.13	15.28	15.1	14.9	15.23	14.08	14.61	15.71	15.87	15.69	15.28	15.17	0.16	1.00	15.87	14.08	11	0.52
	0.5	C15	14.99	15.29	15.2	15.21	15.18	14.66	14.67	15.55	15.54	15.56	15.27	15.19	0.10	1.00	15.56	14.66	11	0.32
	0.375	C14	14.82	15.08	15.25	15.28	15.02	14.3	14.94	15.41	15.8	15.53	15.35	15.16	0.12	1.00	15.8	14.3	11	0.40
	0.25	C13	14.74	15	15.28	14.64	15.2	14.26	14.32	15.16	15.5	15.37	15.57	15.00	0.14	0.99	15.57	14.26	11	0.45
	0.125	C12	14.62	15.12	15.24	15.27	15.3	14.6	14.95	15.02	15.48	15.47	15.51	15.14	0.10	1.00	15.51	14.6	11	0.32
	0	C11	14.69	15.15	15.15	15.38	15.23	14.42	14.75	15.75	15.8	15.74	15.64	15.25	0.14	1.00	15.8	14.42	11	0.47
OTR	0.75	C27	15.19	15.26	15.21	15.12	14.87	13.64	16.04	16.06	15.13	15.27	15.63	15.22	0.20	1.01	16.06	13.64	11	0.65
	0.625	C26	14.54	14.04	15.37	15.28	14.75	14.43	14.94	15.74	15.73	15.6	15.36	15.07	0.17	1.00	15.74	14.04	11	0.57
	0.5	C25	15.02	15.48	15.42	15.39	14.7	14.03	14.28	15.43	15.76	15.52	15.5	15.14	0.17	1.00	15.76	14.03	11	0.56
	0.375	C24	15.33	15.46	15.27	15.35	15.46	14.83	14.82	15.71	15.86	15.37	15.36	15.35	0.09	1.02	15.86	14.82	11	0.31
	0.25	C23	14.83	15.45	15.28	15.16	15.18	14.29	14.8	15.74	15.94	15.64	15.27	15.23	0.14	1.01	15.94	14.29	11	0.47
	0.125	C22	14.84	15.46	15.4	15.51	15.35	14.28	15.07	15.64	15.62	15.83	16.16	15.38	0.15	1.02	16.16	14.28	11	0.51
	0	C21	14.84	15.13	15.47	15.45	15.45	14.44	13.86	16.04	16.07	15.67	16.11	15.32	0.21	1.02	16.11	13.86	11	0.71
Gravel	0.75	C37	15.31	14.98	14.98	14.93	15.04	13.93	15.73	15.63	15.67	15.05	15.84	15.19	0.16	1.00	15.84	13.93	11	0.54
	0.625	C36	15.27	14.92	15.13	14.91	15.22	14.2	15.16	15.4	15.87	15.72	15.92	15.25	0.15	1.00	15.92	14.2	11	0.49
	0.5	C35	15.13	15.35	15.45	15.38	15.56	14.53	15.02	15.85	15.75	15.27	15.95	15.39	0.12	1.01	15.95	14.53	11	0.41
	0.375	C34	14.55	15.4	14.97	15.37	15.66	14.39	14.94	15.51	15.43	15.17	15.94	15.21	0.14	1.00	15.94	14.39	11	0.47
	0.25	C33	15.18	15.59	15.38	15.42	15.21	14.49	14.53	15.44	15.41	15.41	15.96	15.27	0.13	1.00	15.96	14.49	11	0.43
	0.125	C32	15.24	15.58	15.66	15.7	15.55	14.62	14.64	15.77	15.75	15.28	16.03	15.44	0.14	1.01	16.03	14.62	11	0.46
	0	C31	15.51	15.13	15.08	15.71	15.73	13.03	14.97	16.04	15.77	17.7	16.1	15.52	0.34	1.02	17.7	13.03	11	1.11
OTR+PLTT	0.75	C47	15.42	14.98	14.8	14	14.2	13.93	16.18	15.44	15.67	14.98	15.21	14.98	0.21	0.99	16.18	13.93	11	0.71
	0.625	C46	15.44	15.55	15.29	14.97	15.41	14.38	14.4	15.34	15.33	15.27	15.7	15.19	0.13	1.00	15.7	14.38	11	0.43
	0.5	C45	14.39	15.51	15.3	14.97	14.97	14.43	14.5	15.48	15.38	15.83	16.03	15.16	0.17	1.00	16.03	14.39	11	0.56
	0.375	C44	14.79	14.75	15.31	15.03	15.12	14.74	14.78	15	15.62	15.41	16.04	15.14	0.13	1.00	16.04	14.74	11	0.42
	0.25	C43	15.4	15.58	15.33	14.57	14.93	14.53	14.06	15.57	15.73	15.89	16.09	15.24	0.19	1.00	16.09	14.06	11	0.64
	0.125	C42	14.79	15.54	14.99	14.57	15.19	15.26	13.87	15.39	15.85	15.85	16.14	15.22	0.20	1.00	16.14	13.87	11	0.65
	0	C41	15.35	15.45	15.29	15.16	15.23	15.05	14.64	15.24	15.58	15.91	16.23	15.38	0.13	1.01	16.23	14.64	11	0.42
Tank-outlet	0.75	T0	15.8	16.34	16.43	15.31	15.25	14.15	16	16.7	16.32	15.62	15.55	15.77	0.22	1.00	16.7	14.15	11	0.72

Table C2.3- Leachate chemistry- pH

Media Type	Level (m)	Point ID	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	
			4/20/2012	5/8/2012	6/12/2012	6/26/2012	7/13/2012	7/31/2012	8/28/2012	9/11/2012	10/10/2012	10/23/2012	N	Min	Max	Mean	SD	error	Normalised mean
PLTT	0.75	C17	7.91	8.24	8.48	8.5	8.4	8.86	8.02	8.23	8.56	8.76	10	7.91	8.86	8.40	0.30	0.10	1.02
	0.625	C16	8.16	7.84	8.2	8.27	8.23	8.61	8.29	7.97	8.23	8.52	10	7.84	8.61	8.23	0.23	0.07	1.00
	0.5	C15	8.15	7.85	8.2	8.27	8.21	8.62	8.29	7.98	8.23	8.52	10	7.85	8.62	8.23	0.23	0.07	1.00
	0.375	C14	8.16	7.83	8.15	8.26	8.2	8.58	8.27	7.97	8.24	8.49	10	7.83	8.58	8.22	0.22	0.07	1.00
	0.25	C13	8.18	7.81	8.06	8.21	8.17	8.55	8.33	7.98	8.21	8.37	10	7.81	8.55	8.19	0.21	0.07	0.99
	0.125	C12	8.21	7.81	8.03	8.15	8.13	8.33	8.33	7.92	8.19	8.31	10	7.81	8.33	8.14	0.18	0.06	0.99
	0	C11	8.13	7.8	7.91	8.02	8.09	8.28	8.33	7.82	8.09	8.26	10	7.8	8.33	8.07	0.19	0.06	0.98
OTR	0.75	C27	7.9	8.25	8.5	8.51	8.42	8.86	8.02	8.23	8.57	8.77	10	7.9	8.86	8.40	0.31	0.10	1.03
	0.625	C26	8.13	7.8	8.17	8.23	8.2	8.65	7.94	7.92	8.24	8.56	10	7.8	8.65	8.18	0.27	0.08	1.00
	0.5	C25	8.15	7.79	8.15	8.22	8.2	8.64	7.91	7.9	8.24	8.57	10	7.79	8.64	8.18	0.27	0.09	1.00
	0.375	C24	8.17	7.79	8.13	8.21	8.19	8.6	7.94	7.93	8.24	8.54	10	7.79	8.6	8.17	0.25	0.08	1.00
	0.25	C23	8.17	7.76	8.11	8.16	8.14	8.59	7.94	7.9	8.23	8.51	10	7.76	8.59	8.15	0.26	0.08	1.00
	0.125	C22	8.19	7.75	8.04	8.12	8.1	8.56	7.99	7.91	8.22	8.51	10	7.75	8.56	8.14	0.25	0.08	0.99
	0	C21	8.19	7.78	8	8.1	8.09	8.34	8	7.93	8.24	8.49	10	7.78	8.49	8.12	0.21	0.07	0.99
Gravel	0.75	C36	7.94	8.28	8.52	8.52	8.44	8.88	8.02	8.23	8.58	8.78	10	7.94	8.88	8.42	0.30	0.10	1.03
	0.625	C36	8.04	7.91	8.14	8.15	8.1	8.63	7.85	7.89	8.28	8.62	10	7.85	8.63	8.16	0.28	0.09	1.00
	0.5	C35	8.09	7.89	8.08	8.1	8.02	8.62	7.88	7.89	8.28	8.63	10	7.88	8.63	8.15	0.28	0.09	1.00
	0.375	C34	8.13	7.87	8	8.04	7.97	8.62	7.9	7.87	8.26	8.62	10	7.87	8.62	8.13	0.29	0.09	1.00
	0.25	C33	8.12	7.82	7.92	8.02	7.93	8.46	7.93	7.86	8.26	8.62	10	7.82	8.62	8.09	0.27	0.09	0.99
	0.125	C32	8.13	7.79	7.88	7.99	7.95	8.1	8.04	7.89	8.24	8.54	10	7.79	8.54	8.06	0.22	0.07	0.99
	0	C31	8.17	7.79	7.83	7.95	7.93	8.09	8.12	7.87	8.13	8.48	10	7.79	8.48	8.04	0.21	0.07	0.98
OTR+PLTT	0.75	C47	7.93	8.28	8.51	8.53	8.46	8.87	8.02	8.24	8.59	8.75	10	7.93	8.87	8.42	0.30	0.10	1.02
	0.625	C46	8.02	7.9	8.24	8.26	8.2	8.72	8.25	8.11	8.4	8.72	10	7.9	8.72	8.28	0.27	0.09	1.00
	0.5	C45	8.04	7.88	8.18	8.26	8.18	8.7	8.2	8.11	8.4	8.57	10	7.88	8.7	8.25	0.25	0.08	1.00
	0.375	C44	8.04	7.86	8.12	8.18	8.09	8.61	8.17	8.09	8.39	8.56	10	7.86	8.61	8.21	0.24	0.07	0.99
	0.25	C43	8.02	7.79	8.06	8.13	8.04	8.54	8.17	8.1	8.39	8.56	10	7.79	8.56	8.18	0.24	0.08	0.99
	0.125	C42	8.04	7.75	8	8.09	8.03	8.33	8.19	8.09	8.4	8.56	10	7.75	8.56	8.15	0.23	0.07	0.98
	0	C41	8.05	7.75	7.85	7.91	8.01	8.15	8.43	8.1	8.28	8.37	10	7.75	8.43	8.09	0.22	0.07	0.98
Tank-outlet	0.75		7.8	8.03	8.16	8.15	8.12	8.74	7.95	7.96	8.26	8.73	10	7.8	8.74	8.19	0.32	0.10	0.99

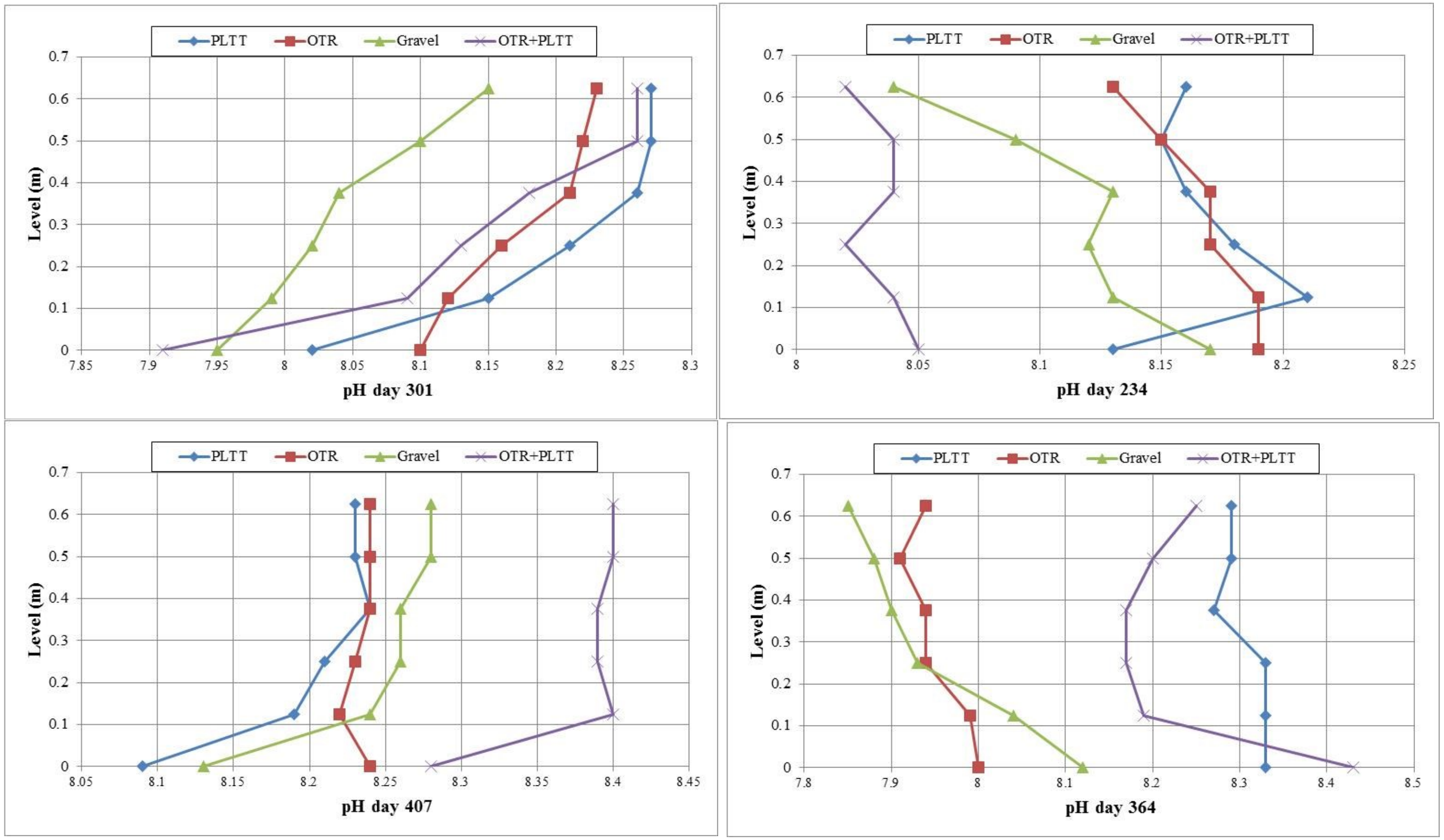


Figure C2.3-. Temporal variations in pH as leachate permeated through PLTT, OTR, gravel and OTR+PLTT columns, for days 234, 301, 364 407

Table C2.4- Leachate chemistry- TSS

Media Type	Level (m)	Point ID	TSS-mg/L 20-Apr-12	TSS-mg/L 9-May-12	TSS-mg/L 12-Jun-12	TSS-mg/L 26-Jun-12	TSS-mg/L 17-Jul-12	TSS-mg/L 31-Jul-12	TSS-mg/L 16-Aug-12	TSS-mg/L 11-Sep-12	TSS-mg/L 26-Sep-12	TSS-mg/L 10-Oct-12	TSS-mg/L Mean	N	SD	Error	Normalised mean
PLTT	0.75	C17	2472	445	405	470	470	240	162	905	1156	1545	827	10	723	229	
	0.625	C16	82	86	96	104	90	55	62	132	140	28	88	10	34	11	1.00
	0.5	C15	92	104	108	100	75	45	92	114	128	30	89	10	31	10	1.01
	0.375	C14	94	114	104	134	70	20	80	134	122	153	103	10	39	12	1.17
	0.25	C13	76	172	80	98	55	25	86	100	56	42	79	10	41	13	0.90
	0.125	C12	68	160	66	74	25	17.5	54	78	44	34	62	10	40	13	0.71
	0	C11	90	160	56	60	20	10	50	70	16	26	56	10	45	14	0.64
OTR	0.75	C27	228	370	360	400	400	270	148	965	1108	1760	601	10	514	163	
	0.625	C26	82	84	88	108	70	85	58	70	72	38	75	10	19	6	1.00
	0.5	C25	88	68	70	70	60	65	32	76	94	42	66	10	19	6	0.88
	0.375	C24	82	52	54	80	40	45	52	56	66	18	54	10	19	6	0.72
	0.25	C23	66	38	38	52	25	40	46	64	68	26	46	10	16	5	0.61
	0.125	C22	56	36	34	32	35	15	44	66	50	40	41	10	14	4	0.54
	0	C21	76	10	28	22	35	10	60	48	40	46	37	10	21	7	0.50
Gravel	0.75	C37	336	280	260	330	330	255	118	1085	4284	2200	948	10	1331	421	
	0.625	C36	106	166	106	104	55	80	48	108	104	54	93	10	35	11	1.00
	0.5	C35	90	158	80	74	35	70	36	98	78	28	75	10	38	12	0.80
	0.375	C34	66	194	50	52	20	75	50	74	50	34	67	10	48	15	0.71
	0.25	C33	62	198	40	38	25	40	40	70	38	27	58	10	51	16	0.62
	0.125	C32	54	122	24	36	25	30	34	74	34	22	46	10	31	10	0.49
	0	C31	50	52	22	30	15	15	36	62	20	16	32	10	17	5	0.34
OTR+PLTT	0.75	C47	500	130	140	330	330	200	130	570	956	3010	630	10	875	277	
	0.625	C46	72	110	94	112	70	95	56	96	60	52	82	10	22	7	1.00
	0.5	C45	80	138	88	132	45	100	54	84	66	40	83	10	34	11	1.01
	0.375	C44	96	184	90	94	55	80	64	112	56	60	89	10	39	12	1.09
	0.25	C43	86	166	74	84	55	55	60	118	74	60	83	10	35	11	1.02
	0.125	C42	52	166	58	60	40	35	64	86	55	112	73	10	40	13	0.89
	0	C41	30	90	30	34	15	25	34	128	36	80	50	10	36	12	0.61
Tank-Outlet	0.5	T1	1912	696	1865	1850	10925	5440	140	1245	4125	3600	3180	10	3170	1002	38.92

Table C2-5- Leachate chemistry- COD

Media Type	Level (m)	Point ID	COD mg/L 20-Apr-12	COD mg/L 2-Jun-12	COD mg/L 26-Jun-12	COD mg/L 30-Jul-12	COD mg/L 28-Aug-12	COD mg/L 16-Sep-12	COD mg/L 26-Sep-12	COD mg/L 10-Oct-12	COD mg/L 23-Oct-12	COD mg/L N	COD mg/L Min	COD mg/L Max	COD mg/L Mean	COD mg/L SD	COD mg/L Error	Normalised mean
PLTT	0.75	C17	3939	2435	1495	2294	3469	3234	2787	1965	1800.265	9	2602	3939	2602	819	273	1.40
	0.625	C16	2294	1730	1753	2270	1777	2317	1636	1518	1424.265	9	1858	2317	1858	346	115	1.00
	0.5	C15	2670	1495	931	1542	2059	2364	1753	1424	1424.265	9	1740	2670	1740	537	179	0.94
	0.375	C14	2999	2200	1965	1542	1941	2599	1659	1213	1330.265	9	1939	2999	1939	588	196	1.04
	0.25	C13	2364	1730	1471	3046	1659	2153	1659	1119	1024.765	9	1803	3046	1803	634	211	0.97
	0.125	C12	2082	1072	1847	1894	1119	2294	1471	1495	1541.765	9	1646	2294	1646	416	139	0.89
	0	C11	2646	1683	837	1706	1777	3046	1236	1377	1424.265	9	1748	3046	1748	692	231	0.94
OTR	0.75	C27	4761	3069	3093	2435	4691	3563	2999	1941	1847.265	9	3155	4761	3155	1051	350	1.57
	0.625	C26	2623	1753	2270	1918	2787	2247	1636	1471	1424	9	2014	2787	2014	494	165	1.00
	0.5	C25	2576	1965	2012	1401	2388	2270	1918	1659	1706	9	1988	2576	1988	375	125	0.99
	0.375	C24	2082	1777	1753	2364	2317	2035	1518	1800	1847	9	1944	2364	1944	278	93	0.97
	0.25	C23	2223	1495	1495	1589	2388	2247	1307	1565	1636	9	1772	2388	1772	399	133	0.88
	0.125	C22	1824	1095	1095	1307	2176	2811	1283	1471	1354	9	1602	2811	1602	572	191	0.80
	0	C21	1894	1001	1236	1213	2106	2552	1166	1260	1166	9	1510	2552	1510	537	179	0.75
Gravel	0.75	C37	4785	2200	3210	2764	4808	2693	3187	1518	1683	9	2983	4808	2983	1186	395	1.94
	0.625	C36	2858	1518	625	1495	2458	1283	743	1401	1448	9	1537	2858	1537	720	240	1.00
	0.5	C35	2693	1495	837	1495	2458	1730	1330	1354	1260	9	1628	2693	1628	591	197	1.06
	0.375	C34	2411	1236	931	1354	2482	1448	1636	1330	1401	9	1581	2482	1581	526	175	1.03
	0.25	C33	2670	1236	1213	1377	2411	1612	1001	1377	1471	9	1597	2670	1597	566	189	1.04
	0.125	C32	2482	907	1025	1189	2059	1659	602	1471	1377	9	1419	2482	1419	585	195	0.92
	0	C31	1988	1001	1189	1495	2012	1213	1189	1260	1307	9	1406	2012	1406	361	120	0.92
OTR+PLTT	0.75	C47	4526	2223	2552	2646	4761	2341	2341	1589	1518	9	2722	4761	2722	1158	386	1.47
	0.625	C46	2811	1800	1683	1636	2529	2059	1424	1377	1401	9	1858	2811	1858	514	171	1.00
	0.5	C45	2928	1166	1847	2200	2576	1847	696	1495	1495	9	1805	2928	1805	693	231	0.97
	0.375	C44	2505	978	1518	1119	2388	1941	672	1283	1401	9	1534	2505	1534	627	209	0.83
	0.25	C43	2223	1166	1189	1777	2505	1847	602	1401	1448	9	1573	2505	1573	582	194	0.85
	0.125	C42	1988	1166	719	1589	2012	1777	625	1354	1307	9	1393	2012	1393	503	168	0.75
	0	C41	1636	1025	555	1448	1401	1565	602	1612	1542	9	1265	1636	1265	430	143	0.68
Tank-outlet	0.75	T1	4973	3821	3539	2270	4855	3798	1471	1753	1824	9	3145	4973	3145	1349	450	1.69

Table C2-6- Leachate chemistry- BOD_5

Media Type	Level (m)	Point ID	9-May-12	12-Jun-12	26-Jun-12	12-Jul-12	28-Aug-12	11-Sep-12	10-Oct-12	N	Min	Max	Mean	SD	error	Normalised mean
			BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)		BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	BOD5 (mg/L)	
PLTT	0.75	C17	468.51	716.91	715.91	518.91	725.91	667.91	90.91	7	90.91	725.91	557.85	230.28	87.04	1.07
	0.625	C16	460.71	709.91	708.91	157.91	728.91	675.91	198.91	7	157.91	728.91	520.17	250.81	94.80	1.00
	0.5	C15	472.71	713.91	709.91	230.91	732.91	673.91	150.91	7	150.91	732.91	526.45	246.45	93.15	1.01
	0.375	C14	466.11	708.91	694.91	273.91	727.91	669.91	186.91	7	186.91	727.91	532.65	225.56	85.25	1.02
	0.25	C13	476.31	708.91	654.91	270.91	700.91	669.91	198.91	7	198.91	708.91	525.82	214.44	81.05	1.01
	0.125	C12	472.71	649.91	573.91	198.91	724.91	670.91	207.91	7	198.91	724.91	499.88	217.73	82.30	0.96
	0	C11	473.31	385.91	226.91	316.91	612.91	670.91	93.91	7	93.91	670.91	397.25	206.07	77.89	0.76
OTR	0.75	C27	413.91	713.91	712.91	696.91	726.91	667.91	713.91	7	413.91	726.91	663.77	111.78	42.25	1.25
	0.625	C26	413.91	708.91	610.91	443.91	721.91	676.91	140.91	7	140.91	721.91	531.05	211.83	80.07	1.00
	0.5	C25	470.31	706.91	537.91	277.91	731.91	677.91	75.91	7	75.91	731.91	496.97	244.84	92.54	0.94
	0.375	C24	469.71	567.91	617.91	283.91	729.91	679.91	126.91	7	126.91	729.91	496.60	220.03	83.16	0.94
	0.25	C23	469.71	499.91	389.91	195.91	729.91	679.91	118.91	7	118.91	729.91	440.60	227.77	86.09	0.83
	0.125	C22	469.11	290.91	165.91	144.91	729.91	678.91	119.91	7	119.91	729.91	371.37	256.87	97.09	0.70
	0	C21	463.71	261.91	226.91	77.91	726.91	676.91	70.91	7	70.91	726.91	357.88	269.65	101.92	0.67
Gravel	0.75	C37	453.51	710.91	712.91	694.91	728.91	659.91	111.91	7	111.91	728.91	581.85	227.91	86.14	1.26
	0.625	C36	453.51	645.91	389.91	470.91	728.91	304.91	239.91	7	239.91	728.91	462.00	175.32	66.26	1.00
	0.5	C35	451.11	384.91	254.91	92.91	727.91	284.91	84.91	7	84.91	727.91	325.94	223.55	84.49	0.71
	0.375	C34	453.51	190.91	169.91	68.91	725.91	257.91	67.91	7	67.91	725.91	276.42	237.68	89.83	0.60
	0.25	C33	452.31	76.91	162.91	229.91	726.91	220.91	64.91	7	64.91	726.91	276.40	236.84	89.52	0.60
	0.125	C32	445.71	45.91	69.91	122.91	603.91	185.91	41.91	7	41.91	603.91	216.60	221.13	83.58	0.47
	0	C31	456.51	119.91	80.91	129.91	498.91	150.91	74.91	7	74.91	498.91	216.00	181.16	68.47	0.47
OTR+PLTT	0.75	C47	451.71	714.91	709.91	602.91	724.91	664.91	121.91	7	121.91	724.91	570.17	219.64	83.01	1.22
	0.625	C46	450.51	707.91	519.91	182.91	727.91	490.91	181.91	7	181.91	727.91	466.00	220.50	83.34	1.00
	0.5	C45	451.71	706.91	590.91	648.91	724.91	674.91	631.91	7	451.71	724.91	632.88	91.80	34.70	1.36
	0.375	C44	452.91	571.91	460.91	626.91	728.91	673.91	153.91	7	153.91	728.91	524.20	192.94	72.92	1.12
	0.25	C43	451.71	388.91	333.91	176.91	728.91	672.91	47.91	7	47.91	728.91	400.17	246.16	93.04	0.86
	0.125	C42	452.31	299.91	237.91	695.91	725.91	670.91	58.91	7	58.91	725.91	448.82	260.08	98.30	0.96
	0	C41	455.31	73.91	125.91	693.91	719.91	672.91	61.91	7	61.91	719.91	400.54	306.06	115.68	0.86
Tank-outlet	0.75	T1	449.31	710.91	669.91	647.91	715.91	665.91	65.91	7	65.91	715.91	560.82	236.11	89.24	1.08
Blank	0	Bo	0.09	1.18	0.12	0.44	0.75	0.33	0.24	7	0.09	1.18	0.45	0.39	0.15	0.00

Table C2-7- Leachate chemistry- Total Solids

Media Type	Level (m)	Point ID	TS (mg/L) 24-Apr-12	TS (mg/L) 10-May-12	TS (mg/L) 12-Jun-12	TS (mg/L) 26-Jun-12	TS (mg/L) 31-Jul-12	TS (mg/L) 16/8/2012	TS (mg/L) 11-Sep-12	TS (mg/L) 23-Oct-12	N	TS (mg/L) Min	TS (mg/L) Max	TS (mg/L) Mean	TS (mg/L) SD	TS (mg/L) Error	Normalised mean
PLTT	0.75	C17	10380	9970	9565	11315	9145	8470	11850	8725	8	8470	11850	9928	1204	426	1.09
	0.625	C16	9245	9340	9025	10025	8825	8085	9895	8560	8	8085	10025	9125	651	230	1.00
	0.5	C15	9225	9380	9060	9960	8740	8055	9920	8630	8	8055	9960	9121	649	229	1.00
	0.375	C14	9255	9415	8930	10300	8700	8140	10105	8635	8	8140	10300	9185	741	262	1.01
	0.25	C13	9180	9610	8915	9605	8620	8130	10065	8775	8	8130	10065	9113	628	222	1.00
	0.125	C12	9155	9405	8850	9625	8175	8130	9955	8655	8	8130	9955	8994	662	234	0.99
	0	C11	9050	9390	8770	9095	8445	8195	9910	8595	8	8195	9910	8931	551	195	0.98
OTR	0.75	C27	10195	9920	9570	11150	9285	8160	11665	8960	8	8160	11665	9863	1143	404	1.09
	0.625	C26	9280	9460	8955	9855	8635	8085	9820	8625	8	8085	9855	9089	626	221	1.00
	0.5	C25	9250	9420	8925	9870	9015	8150	9810	8685	8	8150	9870	9141	576	204	1.01
	0.375	C24	9205	9380	8820	9625	8730	8120	9820	8640	8	8120	9820	9042	566	200	0.99
	0.25	C23	9185	9330	8555	9300	8605	8110	9810	8595	8	8110	9810	8936	556	197	0.98
	0.125	C22	9155	9335	8730	9030	8815	8045	9875	8610	8	8045	9875	8949	542	191	0.98
	0	C21	9140	9195	8600	8930	8700	8145	9710	8705	8	8145	9710	8891	469	166	0.98
Gravel	0.75	C37	10280	9810	9460	11010	8995	8400	12445	8535	8	8400	12445	9867	1362	481	1.11
	0.625	C36	9270	9265	8870	9165	8410	8080	9285	8715	8	8080	9285	8882	453	160	1.00
	0.5	C35	9445	9285	8685	8910	8400	8085	9375	8850	8	8085	9445	8879	483	171	1.00
	0.375	C34	9335	9235	8630	8825	8575	8010	9235	8635	8	8010	9335	8810	446	158	0.99
	0.25	C33	9295	9230	8485	8745	8490	8060	9140	8720	8	8060	9295	8771	429	152	0.99
	0.125	C32	9250	8930	8445	8640	8390	8110	7970	8765	8	7970	9250	8563	423	150	0.96
	0	C31	9195	8850	8530	8720	8450	8035	9015	8640	8	8035	9195	8679	359	127	0.98
OTR+PLTT	0.75	C47	13310	9670	9495	10715	8855	8460	10875	8490	8	8460	13310	9984	1628	576	1.09
	0.625	C46	9470	9395	9145	9565	8745	8250	9860	8750	8	8250	9860	9148	531	188	1.00
	0.5	C45	9465	9505	8075	9570	8745	8250	9965	8800	8	8075	9965	9047	680	240	0.99
	0.375	C44	9390	9060	8875	9200	8820	8235	10050	8825	8	8235	10050	9057	526	186	0.99
	0.25	C43	8980	9220	8780	9020	8785	8260	10065	8805	8	8260	10065	8989	516	182	0.98
	0.125	C42	9220	9180	8620	8810	8690	8290	9790	8720	8	8290	9790	8915	464	164	0.97
	0	C41	9210	9010	8430	8710	8575	8215	9995	8715	8	8215	9995	8858	555	196	0.97
Tank-outlet	0.75	T1	9260	9385	9005	9730	15860	8820	15840	8840	8	8820	15860	10843	3105	1098	1.19

Table C2-9- Leachate chemistry- Calcium

Media Type	Level (m)	Point id	Calcium, mg/L 26-Jun-12	Calcium, mg/L 31-Jul-12	Calcium, mg/L 28-Aug-12	Calcium, mg/L 11-Sep-12	Calcium, mg/L 10-Oct-12	Calcium, mg/L Mean	Calcium, mg/L Error	Calcium, mg/L Max	Calcium, mg/L Min	Normalised mean	SD	N
PLTT	0.75	C17	6.935	3.650	83.999	21.583	7.071	24.647	15.158	83.999	3.650	0.94	33.895	5
	0.625	C16	7.259	6.252	6.273	31.588	80.340	26.342	14.342	80.340	6.252	1.00	32.069	5
	0.5	C15	8.209	6.941	8.214	33.369	7.029	12.752	5.161	33.369	6.941	0.48	11.541	5
	0.375	C14	7.163	4.038	5.363	32.687	7.404	11.331	5.374	32.687	4.038	0.43	12.018	5
	0.25	C13	7.186	3.264	5.744	34.401	81.198	26.359	14.829	81.198	3.264	1.00	33.159	5
	0.125	C12	7.641	5.743	4.478	37.861	7.634	12.671	6.326	37.861	4.478	0.48	14.145	5
	0	C11	8.114	4.438	5.502	31.843	7.668	11.513	5.128	31.843	4.438	0.44	11.466	5
OTR	0.75	C27	7.840	3.737	62.547	20.141	4.538	19.760	11.094	62.547	3.737	1.52	24.806	5
	0.625	C26	7.665	4.154	8.273	39.904	4.932	12.985	6.775	39.904	4.154	1.00	15.149	5
	0.5	C25	7.430	3.861	8.203	37.697	6.740	12.786	6.271	37.697	3.861	0.98	14.022	5
	0.375	C24	7.542	4.007	8.651	37.159	8.464	13.164	6.057	37.159	4.007	1.01	13.543	5
	0.25	C23	8.279	4.859	8.831	43.470	4.454	13.978	7.425	43.470	4.454	1.08	16.603	5
	0.125	C22	8.295	3.787	8.854	36.389	5.564	12.578	6.024	36.389	3.787	0.97	13.469	5
	0	C21	6.798	4.304	8.139	37.903	5.884	12.606	6.355	37.903	4.304	0.97	14.210	5
Gravel	0.75	C37	10.455	3.482	59.934	13.247	3.468	18.117	10.630	59.934	3.468	1.76	23.769	5
	0.625	C36	9.784	2.804	9.092	24.245	5.577	10.300	3.706	24.245	2.804	1.00	8.287	5
	0.5	C35	9.148	2.975	10.939	22.526	7.412	10.600	3.262	22.526	2.975	1.03	7.293	5
	0.375	C34	8.793	17.345	7.374	28.647	4.593	13.350	4.377	28.647	4.593	1.30	9.787	5
	0.25	C33	8.700	5.570	6.962	38.049	6.400	13.136	6.249	38.049	5.570	1.28	13.974	5
	0.125	C32	8.232	6.965	7.609	34.905	4.277	12.398	5.667	34.905	4.277	1.20	12.672	5
	0	C31	8.526	6.639	8.099	36.854	5.423	13.108	5.962	36.854	5.423	1.27	13.331	5
OTR+PLTT	0.75	C47	12.046	2.451	57.315	12.598	4.193	17.720	10.105	57.315	2.451	1.96	22.596	5
	0.625	C46	9.569	1.943	5.545	24.232	3.972	9.052	3.996	24.232	1.943	1.00	8.935	5
	0.5	C45	8.322	1.588	6.869	22.668	3.850	8.659	3.693	22.668	1.588	0.96	8.257	5
	0.375	C44	8.522	1.234	5.784	22.870	6.139	8.910	3.684	22.870	1.234	0.98	8.237	5
	0.25	C43	7.727	1.394	5.340	23.366	3.819	8.329	3.898	23.366	1.394	0.92	8.715	5
	0.125	C42	10.276	1.619	9.909	22.380	3.463	9.529	3.642	22.380	1.619	1.05	8.143	5
	0	C41	6.820	1.844	5.460	21.984	5.744	8.370	3.505	21.984	1.844	0.92	7.837	5
Tank-outlet	0.75	T1	9.734	1.271	81.666	12.780	5.486	22.187	14.996	81.666	1.271	1.00	33.532	5

Table C2-10- Leachate chemistry- Magnesium

Media	Level (m)	Point id	Magnesium (mg/L) 26-Jun-12	Magnesium (mg/L) 28-Aug-12	Magnesium (mg/L) 11-Sep-12	Magnesium (mg/L) 10-Oct-12	Magnesium (mg/L) Mean	Magnesium (mg/L) Error	Magnesium (mg/L) Max	Magnesium (mg/L) Min	Normalised mean	SD	N
PLTT	0.75	C17	146.283	213.127	251.883	24.557	158.962	49.828	251.883	24.557	1.013	99.655	4
	0.625	C16	138.117	206.647	262.847	20.006	156.904	52.275	262.847	20.006	1.000	104.550	4
	0.5	C15	130.452	195.180	244.068	20.111	147.452	48.406	244.068	20.111	0.940	96.811	4
	0.375	C14	128.234	235.621	226.927	23.025	153.451	49.831	235.621	23.025	0.978	99.662	4
	0.25	C13	124.769	229.703	235.157	21.598	152.807	50.577	235.157	21.598	0.974	101.154	4
	0.125	C12	123.812	241.126	227.542	23.279	153.940	50.825	241.126	23.279	0.981	101.651	4
	0	C11	127.289	275.925	232.455	23.587	164.814	56.476	275.925	23.587	1.050	112.952	4
OTR	0.75	C27	126.205	246.584	230.157	354.328	239.318	46.689	354.328	126.205	0.978	93.378	4
	0.625	C26	123.113	260.670	222.771	372.468	244.755	51.514	372.468	123.113	1.000	103.027	4
	0.5	C25	125.247	274.756	228.491	360.360	247.214	48.979	360.360	125.247	1.010	97.958	4
	0.375	C24	126.098	276.812	226.802	0.000	157.428	61.122	276.812	0.000	0.643	122.244	4
	0.25	C23	127.232	278.868	229.406	0.000	158.876	61.655	278.868	0.000	0.649	123.309	4
	0.125	C22	127.472	276.818	234.840	16.413	163.885	58.354	276.818	16.413	0.670	116.708	4
	0	C21	126.702	319.128	228.080	24.123	174.508	63.696	319.128	24.123	0.713	127.392	4
Gravel	0.75	C37	134.280	282.413	245.384	329.551	247.907	41.607	329.551	134.280	0.998	83.214	4
	0.625	C36	138.986	268.192	247.421	338.886	248.371	41.384	338.886	138.986	1.000	82.768	4
	0.5	C35	137.378	253.971	245.470	356.486	248.326	44.766	356.486	137.378	1.000	89.532	4
	0.375	C34	129.965	252.657	247.136	372.462	250.555	49.514	372.462	129.965	1.009	99.028	4
	0.25	C33	136.412	292.193	180.659	357.906	241.792	50.716	357.906	136.412	0.974	101.431	4
	0.125	C32	138.595	300.629	179.181	390.491	252.224	57.524	390.491	138.595	1.016	115.047	4
	0	C31	145.177	329.955	181.040	405.332	265.376	61.454	405.332	145.177	1.068	122.907	4
OTR+PLTT	0.75	C47	150.882	292.532	186.386	312.279	235.520	39.497	312.279	150.882	0.994	78.994	4
	0.625	C46	151.954	314.478	183.504	297.676	236.903	40.599	314.478	151.954	1.000	81.198	4
	0.5	C45	149.529	276.810	198.000	296.650	230.247	34.318	296.650	149.529	0.972	68.636	4
	0.375	C44	147.929	276.707	189.360	343.356	239.338	43.846	343.356	147.929	1.010	87.692	4
	0.25	C43	148.363	279.193	186.928	366.311	245.199	48.816	366.311	148.363	1.035	97.633	4
	0.125	C42	147.500	288.470	189.940	357.277	245.797	47.461	357.277	147.500	1.038	94.923	4
	0	C41	157.478	332.661	183.698	336.210	252.512	47.606	336.210	157.478	1.066	95.212	4
Tank	0.75	T1	151.645	330.237	184.311	344.553	252.686	49.445	344.553	151.645	1.067	98.891	4

Table C2-11- Leachate chemistry- Sodium

Media	Level (m)	Point ID	Sodium, mg/L 26-Jun-12	Sodium, mg/L 28-Aug-12	Sodium, mg/L 11-Sep-12	Sodium, mg/L 10-Oct-12	Sodium, mg/L Mean	Sodium, mg/L Error	Sodium, mg/L Max	Sodium, mg/L Min	Normalised	SD	N
PLTT	0.75	C17	171.099	1728.966	1622.541	1804.019	1331.656	388.639	1804.019	171.099	1.060	777.279	4
	0.625	C16	171.740	1588.443	1502.034	1764.285	1256.625	365.721	1764.285	171.740	1.000	731.442	4
	0.5	C15	171.408	1548.947	1559.900	1684.536	1241.197	357.920	1684.536	171.408	0.988	715.839	4
	0.375	C14	172.009	1561.472	1527.623	1809.427	1267.633	370.570	1809.427	172.009	1.009	741.141	4
	0.25	C13	169.913	1424.470	1558.715	1770.151	1230.812	360.719	1770.151	169.913	0.979	721.438	4
	0.125	C12	172.424	1511.490	1543.396	1733.040	1240.087	359.231	1733.040	172.424	0.987	718.462	4
	0	C11	168.911	1451.161	1546.496	1736.629	1225.799	357.257	1736.629	168.911	0.975	714.515	4
OTR	0.75	C27	171.033	1932.673	1599.383	1758.379	1365.367	403.886	1932.673	171.033	1.060	807.773	4
	0.625	C26	172.541	1712.764	1552.394	1715.290	1288.247	373.849	1715.290	172.541	1.000	747.697	4
	0.5	C25	172.045	1706.010	1535.369	1735.992	1287.354	374.386	1735.992	172.045	0.999	748.771	4
	0.375	C24	169.992	1673.613	1529.910	1767.444	1285.240	374.944	1767.444	169.992	0.998	749.888	4
	0.25	C23	170.368	1755.450	1545.603	1724.884	1299.076	379.072	1755.450	170.368	1.008	758.144	4
	0.125	C22	172.675	1723.800	1511.603	1749.650	1289.432	376.052	1749.650	172.675	1.001	752.104	4
	0	C21	171.339	1556.373	1519.586	1764.503	1252.950	364.546	1764.503	171.339	0.973	729.093	4
Gravel	0.75	C37	172.980	1862.070	1448.264	1716.456	1299.942	385.304	1862.070	172.980	1.048	770.609	4
	0.625	C36	173.673	1743.627	1388.078	1657.283	1240.665	363.632	1743.627	173.673	1.000	727.265	4
	0.5	C35	172.650	1727.933	1404.449	1706.375	1252.852	367.560	1727.933	172.650	1.010	735.120	4
	0.375	C34	171.738	1683.738	1560.310	1721.121	1284.227	372.418	1721.121	171.738	1.035	744.835	4
	0.25	C33	172.934	1663.341	1547.040	1716.206	1274.880	369.011	1716.206	172.934	1.028	738.021	4
	0.125	C32	173.124	1715.997	1550.321	1737.599	1294.260	376.046	1737.599	173.124	1.043	752.092	4
	0	C31	172.731	1734.343	1509.708	1704.173	1280.239	372.510	1734.343	172.731	1.032	745.019	4
OTR+PLTT	0.75	C47	171.641	1864.801	1444.791	1625.141	1276.594	378.229	1864.801	171.641	1.027	756.458	4
	0.625	C46	170.320	1704.863	1410.709	1688.161	1243.513	364.035	1704.863	170.320	1.000	728.069	4
	0.5	C45	171.106	1620.692	1417.809	1673.403	1220.753	354.193	1673.403	171.106	0.982	708.386	4
	0.375	C44	170.975	1651.750	1435.634	1639.259	1224.404	354.619	1651.750	170.975	0.985	709.239	4
	0.25	C43	172.207	1659.552	1438.090	1751.551	1255.350	366.991	1751.551	172.207	1.010	733.982	4
	0.125	C42	171.706	1733.486	1392.681	1618.678	1229.138	359.515	1733.486	171.706	0.988	719.031	4
	0	C41	175.089	1748.231	1421.950	1749.713	1273.745	374.243	1749.713	175.089	1.024	748.486	4
Tank	0.75	To	169.415	1837.759	1433.953	1701.114	1285.560	381.380	1837.759	169.415	1.034	762.760	4

Appendix C3- Mass Balance Analysis

1. COD

Table C3-1. Mass balance analysis of COD- PLTT Column

influent	C	mean C	Flux (g)
0	3457		
25	5161	4309	1034.16
50	3000	4080.5	979.32
75	3400	3200	768
100	3700	3550	852
125	3800	3750	900
150	6000	4900	1176
175	1600	3800	912
200	2000	1800	432
225	2200	2100	504
250	2200	2200	528
275	1800	2000	480
300	1700	1750	420
325	2000	1850	444
350	2100	2050	492
375	2000	2050	492
400	1600	1800	432
425	1500	1550	372
	Total		11,217.48

	effluent	mean C	Flux (g)
0	3800		
25	4300	4050	972
50	2500	3400	816
75	2600	2550	612
100	3500	3050	732
125	4400	3950	948
150	4000	4200	1008
175	1600	2800	672
200	2000	1800	432
225	2400	2200	528
250	2400	2400	576
275	1700	2050	492
300	1000	1350	324
325	1300	1150	276
350	1700	1500	360
375	2000	1850	444
400	1300	1650	396
425	1500	1400	336
			9,924.00

Balance	1,293.48	
% retained	0.1153093	11.53093208

Table C3-2. Mass balance analysis of COD- OTR Column

influent	C	mean C	Flux (g)
0	3700		
25	4300	4000	960
50	3100	3700	888
75	3300	3200	768
100	3400	3350	804
125	3500	3450	828
150	2500	3000	720
175	1700	2100	504
200	2000	1850	444
225	2400	2200	528
250	2400	2400	576
275	1700	2050	492
300	2100	1900	456
325	2100	2100	504
350	2200	2150	516
375	2600	2400	576
400	1600	2100	504
425	1400	1500	360
	Total		10,428.00

	effluent	mean C	Flux (g)
0	3600		
25	4000	3800	912
50	2200	3100	744
75	3000	2600	624
100	3400	3200	768
125	3250	3325	798
150	1800	2525	606
175	1550	1675	402
200	1700	1625	390
225	1800	1750	420
250	1600	1700	408
275	1000	1300	312
300	1200	1100	264
325	1200	1200	288
350	1200	1200	288
375	2200	1700	408
400	1166	1683	403.92
425	1166	1166	279.84
			8,315.76

Balance	2,112.24	
% retained	0.2025547	20.25546605

Table C3-3. Mass balance analysis of COD- Gravel Column

influent	C	mean C	Flux (g)
0	3704		
25	3500	3602	864.48
50	2000	2750	660
75	3940	2970	712.8
100	3940	3940	945.6
125	3940	3940	945.6
150	3500	3720	892.8
175	1700	2600	624
200	2200	1950	468
225	2600	2400	576
250	2500	2550	612
275	1800	2150	516
300	1200	1500	360
325	1300	1250	300
350	1700	1500	360
375	2200	1950	468
400	1189	1694.5	406.68
425	1448	1318.5	316.44
	Total		10,028.40

	effluent	mean C	Flux (g)
0	3704		
25	3606	3655	877.2
50	1725	2665.5	639.72
75	1400	1562.5	375
100	2000	1700	408
125	3250	2625	630
150	2000	2625	630
175	1250	1625	390
200	1500	1375	330
225	1700	1600	384
250	1700	1700	408
275	1200	1450	348
300	1200	1200	288
325	1400	1300	312
350	1600	1500	360
375	1700	1650	396
400	1189	1444.5	346.68
425	1307	1248	299.52
			7,422.12

Balance	2,606.28	
% retained	0.2598899	25.98899126

Table C3-4. Mass balance analysis of COD- OTR+PLTT Column

influent	C	mean C	Flux (g)
0	4248		
25	4000	4124	989.76
50	2600	3300	792
75	3500	3050	732
100	3700	3600	864
125	3400	3550	852
150	2500	2950	708
175	1600	2050	492
200	2100	1850	444
225	2500	2300	552
250	2500	2500	600
275	2000	2250	540
300	1700	1850	444
325	1700	1700	408
350	1900	1800	432
375	2500	2200	528
400	1424	1962	470.88
425	1401	1412.5	339
	Total		10,187.64

	effluent	mean C	Flux (g)
0	4544		
25	3383	3963.5	951.24
50	2000	2691.5	645.96
75	2000	2000	480
100	2100	2050	492
125	2100	2100	504
150	1500	1800	432
175	1300	1400	336
200	1400	1350	324
225	1550	1475	354
250	1500	1525	366
275	1200	1350	324
300	600	900	216
325	1000	800	192
350	1400	1200	288
375	1500	1450	348
400	1600	1550	372
425	1542	1571	377.04
			7,002.24

Balance	3,185.40	
% retained	0.312673	31.26730038

2. Calcium

Table C3-5. Mass balance analysis of Calcium- PLTT Column

influent	C	mean C	Flux (g)
0	35		
25	32	33.5	8.04
50	32	32	7.68
75	35	33.5	8.04
100	35	35	8.4
125	37	36	8.64
150	40	38.5	9.24
175	25	32.5	7.8
200	22	23.5	5.64
225	18	20	4.8
250	15	16.5	3.96
275	12	13.5	3.24
300	8	10	2.4
325	7	7.5	1.8
350	7	7	1.68
375	15	11	2.64
400	60	37.5	9
	Total		93.00

	effluent	mean C	Flux (g)
0	25		
25	26	25.5	6.12
50	27	26.5	6.36
75	28	27.5	6.6
100	30	29	6.96
125	32	31	7.44
150	27	29.5	7.08
175	26	26.5	6.36
200	24	25	6
225	20	22	5.28
250	16	18	4.32
275	17	16.5	3.96
300	9	13	3.12
325	6	7.5	1.8
350	6	6	1.44
375	20	13	3.12
400	19	19.5	4.68
			80.64

Balance	12.36	
% retained	0.1329032	13.290323

Table C3-6. Mass balance analysis of Calcium- OTR Column

influent	C	mean C	Flux (g)
0	33.8		
25	32	32.9	7.896
50	30	31	7.44
75	27	28.5	6.84
100	26	26.5	6.36
125	24	25	6
150	22	23	5.52
175	23	22.5	5.4
200	20	21.5	5.16
225	16.5	18.25	4.38
250	14	15.25	3.66
275	8	11	2.64
300	7	7.5	1.8
325	6	6.5	1.56
350	5	5.5	1.32
375	15	10	2.4
400	20	17.5	4.2
	Total		72.58

	effluent	mean C	Flux (g)
0	31.5		
25	26	28.75	6.9
50	26	26	6.24
75	26	26	6.24
100	26	26	6.24
125	26	26	6.24
150	25.3	25.65	6.156
175	23	24.15	5.796
200	20	21.5	5.16
225	16	18	4.32
250	14	15	3.6
275	10	12	2.88
300	7	8.5	2.04
325	5	6	1.44
350	5	5	1.2
375	15	10	2.4
400	20	17.5	4.2
			71.05

Balance	1.52	
% retained	0.0209987	2.0998677

Table C3-7. Mass balance analysis of Calcium- Gravel Column

influent	C	mean C	Flux (g)
0	48		
25	30	39	9.36
50	33	31.5	7.56
75	33	33	7.92
100	32	32.5	7.8
125	31	31.5	7.56
150	30	30.5	7.32
175	25	27.5	6.6
200	23	24	5.76
225	20	21.5	5.16
250	16	18	4.32
275	14	15	3.6
300	11	12.5	3
325	6	8.5	2.04
350	5	5.5	1.32
375	15	10	2.4
400	14	14.5	3.48
	Total		85.20

	effluent	mean C	Flux (g)
0	40		
25	30	35	8.4
50	30	30	7.2
75	30	30	7.2
100	29	29.5	7.08
125	28	28.5	6.84
150	28	28	6.72
175	25	26.5	6.36
200	22	23.5	5.64
225	18	20	4.8
250	15	16.5	3.96
275	17	16	3.84
300	9	13	3.12
325	7	8	1.92
350	7	7	1.68
375	15	11	2.64
400	20	17.5	4.2
			81.60

Balance	3.60	
% retained	0.0422535	4.2253521

Table C3-8. Mass balance analysis of Calcium- OTR+PLTT Column

influent	C	mean C	Flux (g)
0	24		
25	42	33	7.92
50	41	41.5	9.96
75	36	38.5	9.24
100	32	34	8.16
125	26	29	6.96
150	22	24	5.76
175	20	21	5.04
200	18	19	4.56
225	16	17	4.08
250	14	15	3.6
275	13	13.5	3.24
300	10	11.5	2.76
325	5	7.5	1.8
350	3	4	0.96
375	5	4	0.96
400	13	9	2.16
	Total		77.16

	effluent	mean C	Flux (g)
0	25		
25	35	30	7.2
50	34	34.5	8.28
75	32	33	7.92
100	30	31	7.44
125	26	28	6.72
150	25	25.5	6.12
175	24	24.5	5.88
200	20	22	5.28
225	18	19	4.56
250	14	16	3.84
275	12	13	3.12
300	7	9.5	2.28
325	5	6	1.44
350	3	4	0.96
375	10	6.5	1.56
400	13	11.5	2.76
			75.36

Balance	1.80	
% retained	0.0233281	2.3328149

3. TSS

Table C3-9. Mass balance analysis of TSS- PLTT Column

influent	C	mean C	Flux (g)	
0	31			
25	38	34.5	8.28	
50	24	31	7.44	
75	40	32	7.68	
100	70	55	13.2	
125	140	105	25.2	
150	80	110	26.4	
175	100	90	21.6	
200	97	98.5	23.64	
225	95	96	23.04	
250	100	97.5	23.4	
275	105	102.5	24.6	
300	105	105	25.2	
325	80	92.5	22.2	
350	70	75	18	
375	107	88.5	21.24	
400	130	118.5	28.44	
	Total		319.56	
		Balance	107.76	
		% retained	0.3372137	33.721367

	effluent	mean C	Flux (g)
0	63		
25	10	36.5	8.76
50	20	15	3.6
75	10	15	3.6
100	20	15	3.6
125	100	60	14.4
150	10	55	13.2
175	83	46.5	11.16
200	86	84.5	20.28
225	90	88	21.12
250	130	110	26.4
275	110	120	28.8
300	60	85	20.4
325	20	40	9.6
350	30	25	6
375	62	46	11.04
400	20	41	9.84
			211.80

Table C3-10. Mass balance analysis of TSS- OTR Column

influent	C	mean C	Flux (g)
0	34		
25	20	27	6.48
50	14	17	4.08
75	60	37	8.88
100	90	75	18
125	108	99	23.76
150	118	113	27.12
175	280	199	47.76
200	200	240	57.6
225	120	160	38.4
250	83	101.5	24.36
275	86	84.5	20.28
300	100	93	22.32
325	80	90	21.6
350	70	75	18
375	66	68	16.32
400	72	69	16.56
	Total		371.52

	effluent	mean C	Flux (g)
0	20		
25	22	21	5.04
50	10	16	3.84
75	40	25	6
100	90	65	15.6
125	130	110	26.4
150	120	125	30
175	25	72.5	17.4
200	40	32.5	7.8
225	60	50	12
250	40	50	12
275	20	30	7.2
300	25	22.5	5.4
325	38	31.5	7.56
350	30	34	8.16
375	50	40	9.6
400	40	45	10.8
			184.80

Balance	186.72	
% retained	0.502584	50.258398

Table C3-11. Mass balance analysis of TSS- Gravel Column

influent	C	mean C	Flux (g)
0	20		
25	0	10	2.4
50	30	15	3.6
75	50	40	9.6
100	40	45	10.8
125	100	70	16.8
150	50	75	18
175	60	55	13.2
200	80	70	16.8
225	95	87.5	21
250	140	117.5	28.2
275	140	140	33.6
300	105	122.5	29.4
325	60	82.5	19.8
350	60	60	14.4
375	90	75	18
400	105	97.5	23.4
	Total		279.00

	effluent	mean C	Flux (g)
0	25		
25	26	25.5	6.12
50	14	20	4.8
75	18	16	3.84
100	22	20	4.8
125	100	61	14.64
150	10	55	13.2
175	22	16	3.84
200	33	27.5	6.6
225	42	37.5	9
250	50	46	11.04
275	40	45	10.8
300	23	31.5	7.56
325	15	19	4.56
350	25	20	4.8
375	55	40	9.6
400	20	37.5	9
			124.20

Balance	154.80	
% retained	0.5548387	55.48387097

Table C3-12. Mass balance analysis of TSS- OTR+PLTT Column

influent	C	mean C	Flux (g)
0	20		
25	16	18	4.32
50	30	23	5.52
75	38	34	8.16
100	74	56	13.44
125	40	57	13.68
150	80	60	14.4
175	95	87.5	21
200	90	92.5	22.2
225	75	82.5	19.8
250	90	82.5	19.8
275	105	97.5	23.4
300	100	102.5	24.6
325	70	85	20.4
350	75	72.5	17.4
375	80	77.5	18.6
400	60	70	16.8
	Total		263.52

	effluent	mean C	Flux (g)
0	44		
25	30	37	8.88
50	14	22	5.28
75	10	12	2.88
100	16	13	3.12
125	16	16	3.84
150	16	16	3.84
175	28	22	5.28
200	30	29	6.96
225	30	30	7.2
250	60	45	10.8
275	60	60	14.4
300	30	45	10.8
325	15	22.5	5.4
350	30	22.5	5.4
375	100	65	15.6
400	36	68	16.32
			126.00

Balance	137.52	
% retained	0.5218579	52.185792

Appendix C4: Drainable porosity

Table C4-1- Drainable Porosity

	Sample level	Sample point (m)	Height (m)		Vol-total (m3)	Vol-fluid mass	Vol-fluid Volume	New Porosity	Initial porosity	% loss	normalised porosity	lost porosity
PLTT		0.625										
	C16-C15	0.5	0.125	0.031875	0.032		0.010	0.352	0.447		0.788	
	C15-C14	0.375	0.122	0.03111	0.031	10.965	0.011	0.352	0.447	-21.15%	0.788	0.212
	C14-C13	0.25	0.132	0.03366	0.034	12.335	0.012	0.366	0.447	-18.02%	0.820	0.180
	C13-C12	0.125	0.128	0.03264	0.033	11.530	0.012	0.353	0.447	-20.97%	0.790	0.210
	C12-C11	0	0.135	0.034425	0.034	14.855	0.015	0.432	0.447	-3.46%	0.965	0.035
								0.371	Average loss	-20.05%		

	Sample level	Sample point (m)	Height (m)		Vol-total (m3)		Vol-fluid (m3)	New Porosity	Initial porosity	% loss	normalised porosity	lost porosity
OTR		0.625										
	C26-C25	0.5	0.128	0.03264	0.033	12.845	0.013	0.394	0.41	-4.02%	0.960	0.040
	C25-C24	0.375	0.125	0.031875	0.032	11.940	0.012	0.375	0.41	-8.64%	0.914	0.086
	C24-C23	0.25	0.129	0.032895	0.033	11.655	0.012	0.354	0.41	-13.58%	0.864	0.136
	C23-C22	0.125	0.13	0.03315	0.033	12.450	0.012	0.376	0.41	-8.40%	0.916	0.084
	C22-C21	0	0.136	0.03468	0.035	14.020	0.014	0.404	0.41	-1.40%	0.986	0.014
								0.380	Average loss	-7.21%		

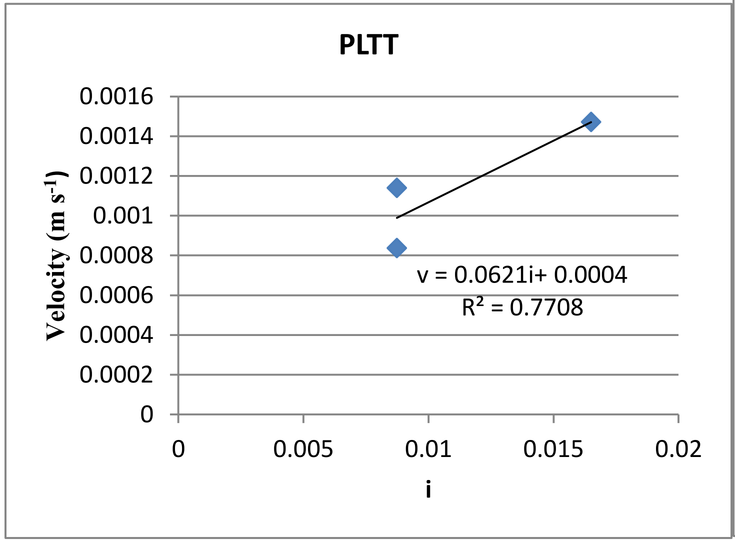
	Sample level	Sample point (m)	Height (m)		Vol-total (m3)		Vol-fluid (m3)	New Porosity	Initial porosity	% loss	normalised porosity	lost porosity
Gravel		0.625										
	C36-C35	0.5	0.127	0.032385	0.032	11.610	0.012	0.358	0.393	-8.78%	0.912	0.088
	C35-C34	0.375	0.126	0.03213	0.032	11.760	0.012	0.366	0.393	-6.87%	0.931	0.069
	C34-C33	0.25	0.13	0.03315	0.033	12.315	0.012	0.371	0.393	-5.47%	0.945	0.055
	C33-C32	0.125	0.13	0.03315	0.033	12.155	0.012	0.367	0.393	-6.70%	0.933	0.067
	C32-C31	0	0.135	0.034425	0.034	12.630	0.013	0.367	0.393	-6.65%	0.934	0.066
									Average loss	-6.89%		

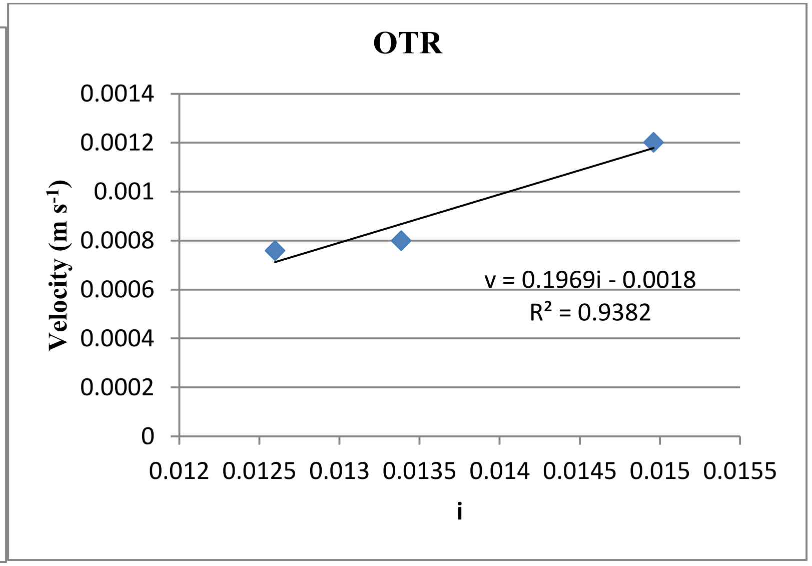
	Sample level	Sample point (m)	Height (m)		Vol-total (m3)		Vol-fluid (m3)	New Porosity	Initial porosity	% loss	normalised porosity	lost porosity
PLTT+OTR		0.625										
	C46-C45	0.5	0.1	0.0255	0.026	9.840	0.010	0.386	0.435	-11.29%	0.887	0.113
	C45-C44	0.375	0.125	0.031875	0.032	10.500	0.011	0.329	0.435	-24.27%	0.757	0.243
	C44-C43	0.25	0.131	0.033405	0.033	11.810	0.012	0.354	0.435	-18.73%	0.813	0.187
	C43-C42	0.125	0.131	0.033405	0.033	11.465	0.011	0.343	0.435	-21.10%	0.789	0.211
	C42-C41	0	0.13	0.03315	0.033	12.705	0.013	0.383	0.435	-11.89%	0.881	0.119
									Average loss	-17.46%		

Table C4-2. Drainable porosities for the clogged TDA media

Media	Mass of pail (kg)	Water +Bucket (kg)	Volume of water (m^3)	Media height (m)	Media volume (m^3)	Porosity	3rd drainable porosity	3rd/ current	Original Porosity	difference	% difference
PLTT	4.1	53.37	0.049	0.50	0.128	0.386	0.371	1.042	0.447	-0.041594	-4.2
ORT	4.1	62.42	0.058	0.59	0.151	0.387	0.38	1.018	0.41	-0.0183715	-1.8
Gravel	4.07	74.33	0.070	0.75	0.191	0.367	0.366	1.004	0.393	-0.0037501	-0.4
OTR+PLTT	4.125	64.69	0.061	0.64	0.164	0.370	0.359	1.031	0.435	-0.0305097	-3.1

Appendix C5: Hydraulic conductivities of clogged media


PLTT
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Velocity (m s-1)
v = 0.0621i+ 0.0004
R² = 0.7708
0
0.005
0.01
0.015
0.02
i


OTR
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Velocity (m s-1)
v = 0.1969i - 0.0018
R² = 0.9382
0.012
0.0125
0.013
0.0135
0.014
0.0145
0.015
0.0155
i

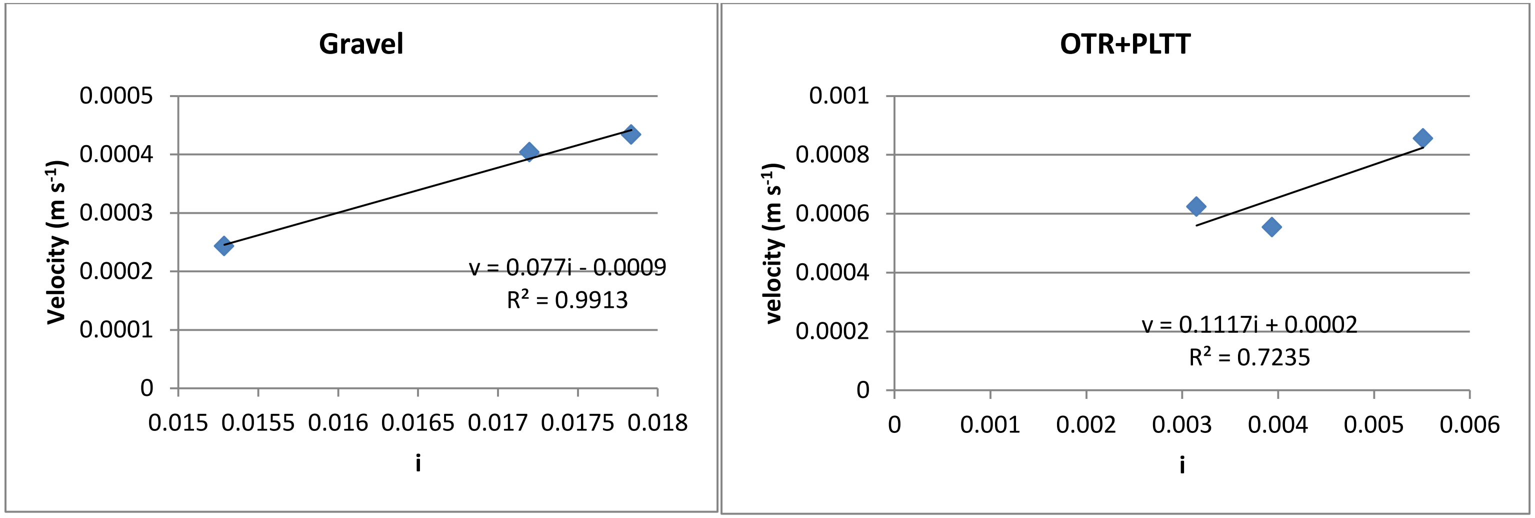
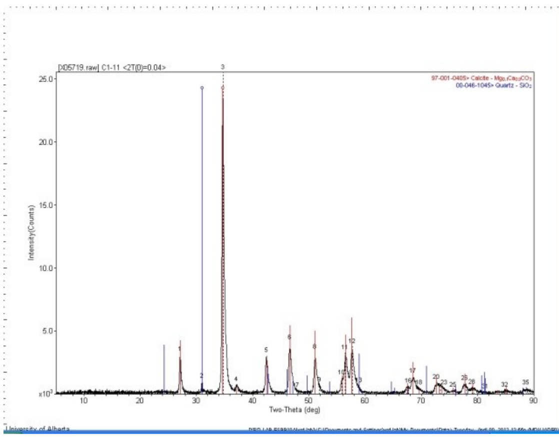
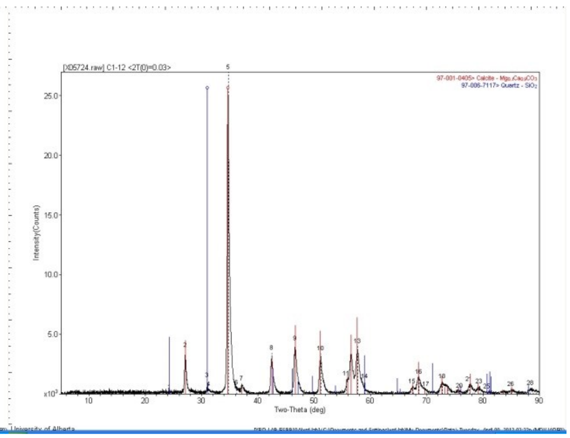


Figure C5-1. Hydraulic conductivities of TDA and gravel prior to column diassembly

Appendix C6: Mineral Phases

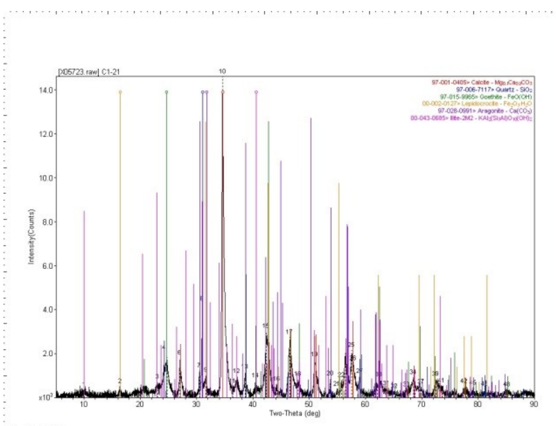
Column 1-PLTT



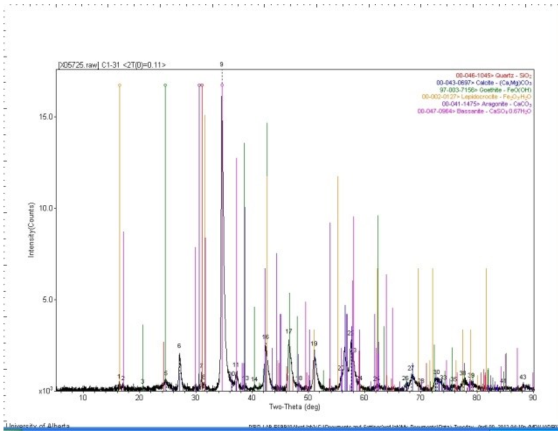


C1-11 – bottom1

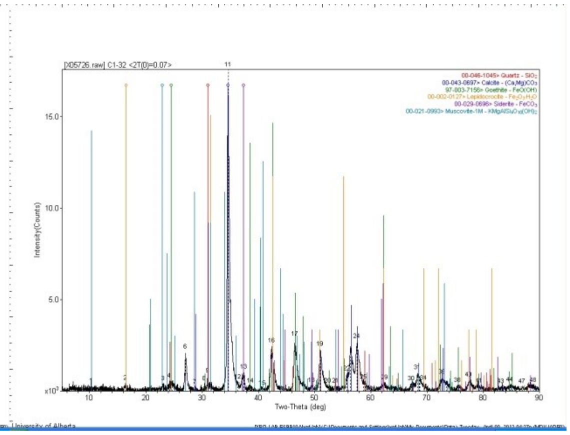
C1-12-bottom 2



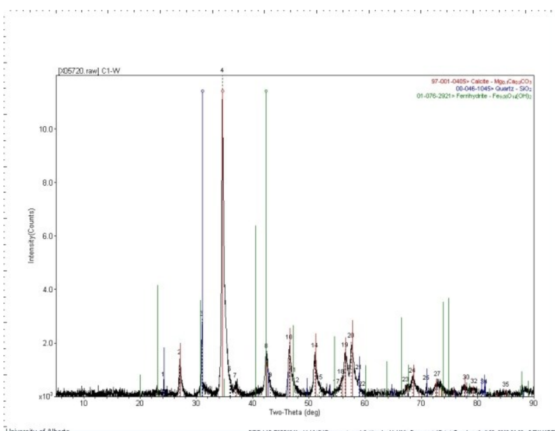
C1-21-middle



C1-31-top1

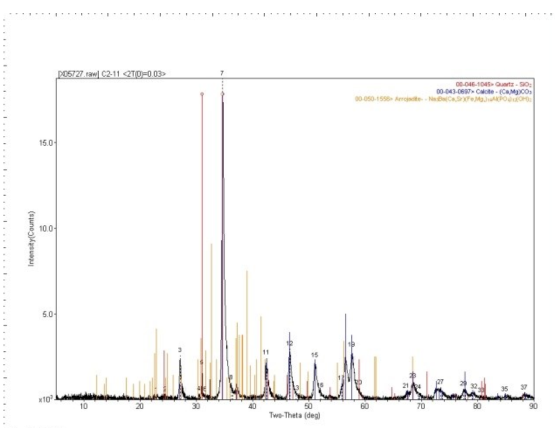


C1-32-top2

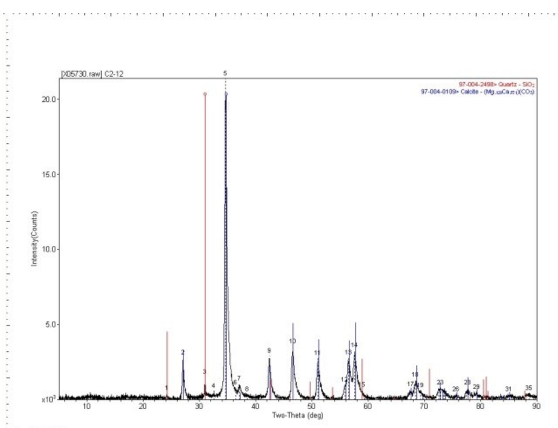


C1- Suspended solids after flushing

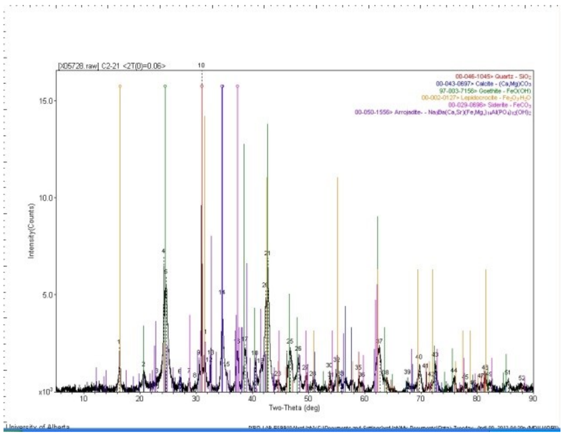
Column 2- OTR



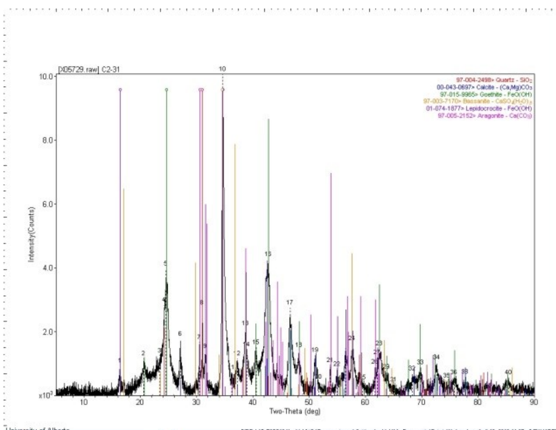
C2-11 -bottom 1



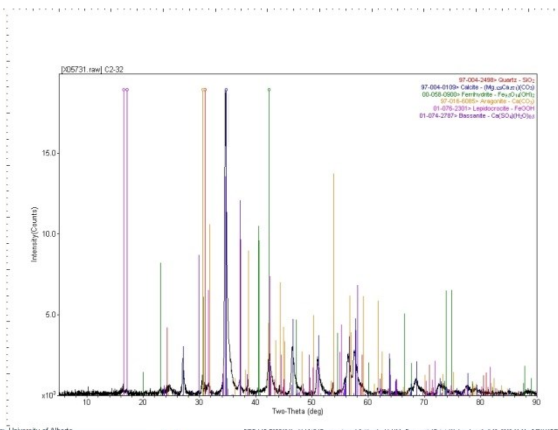
C2-12-bottom 2



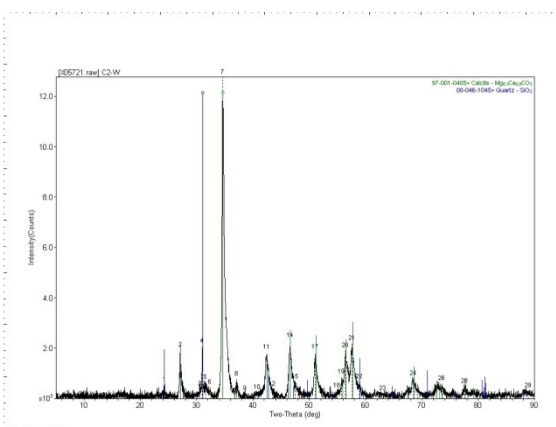
C2-21- middle



C2-31 -top 1

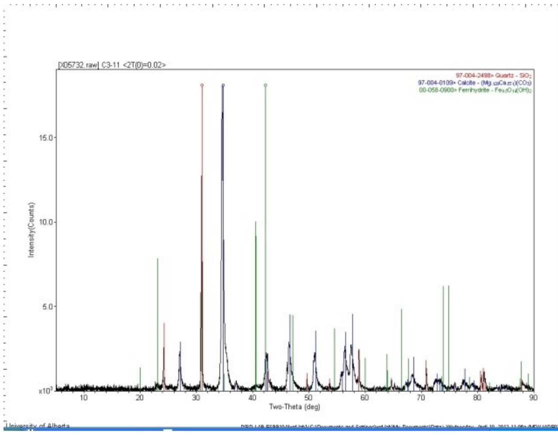


C2-32-top2

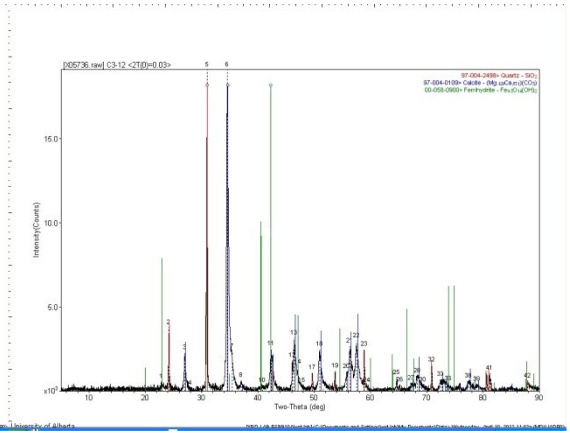


C2-Suspended solids after flushing

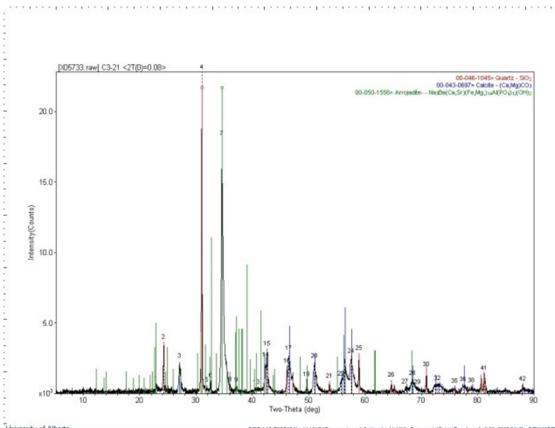
Column 3- Gravel



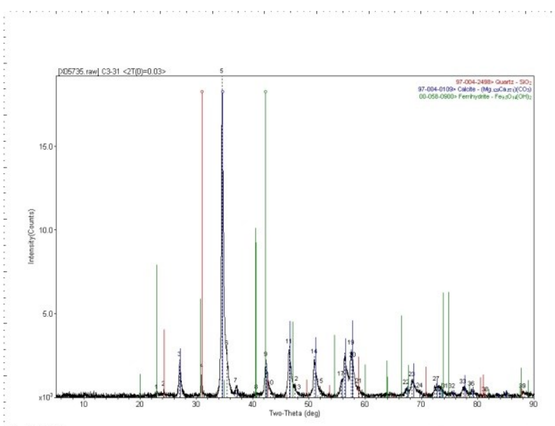
C3-11 -bottom 1



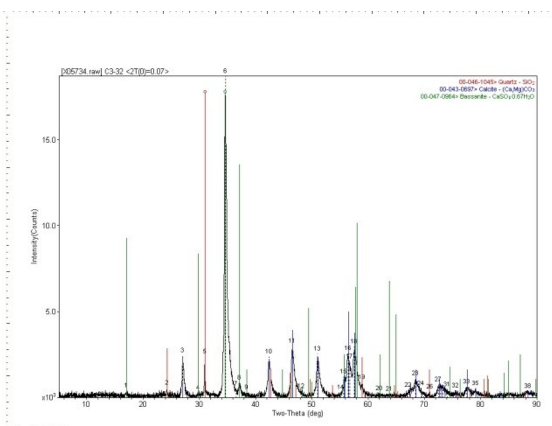
C3-12- bottom 2



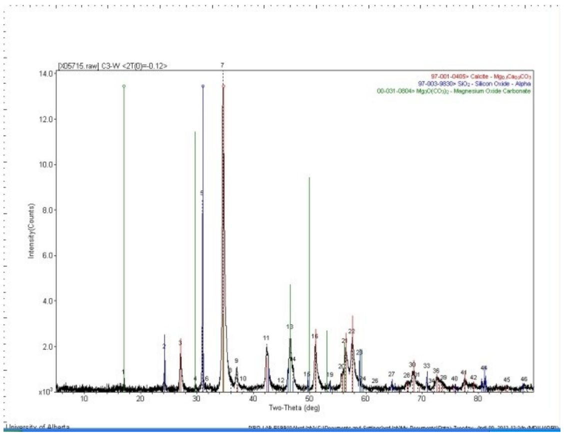
C3-21-middle level



C3-31-top 1

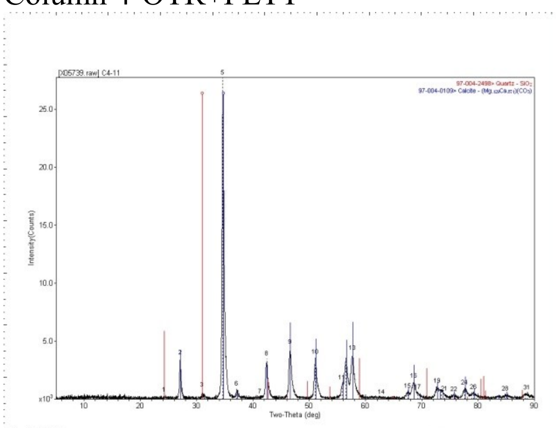


C3-32- top 2

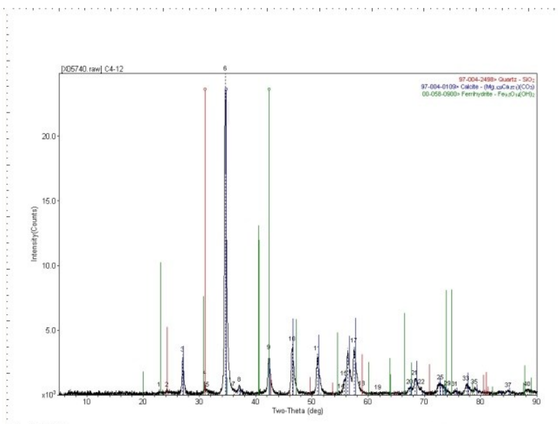


C3-Suspended Solids after flushing

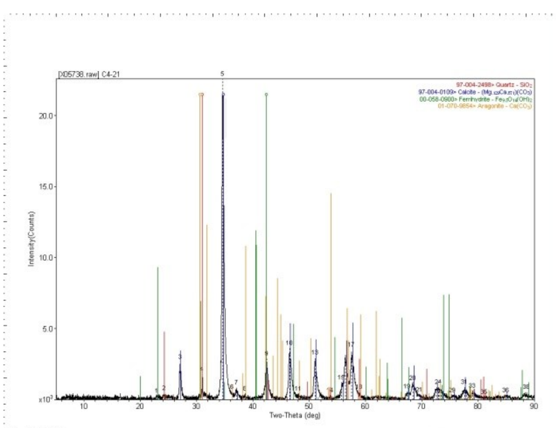
Column 4-OTR+PLTT



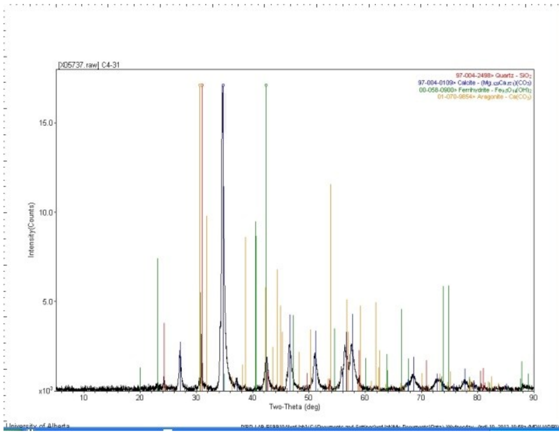
C4-11-bottom 1



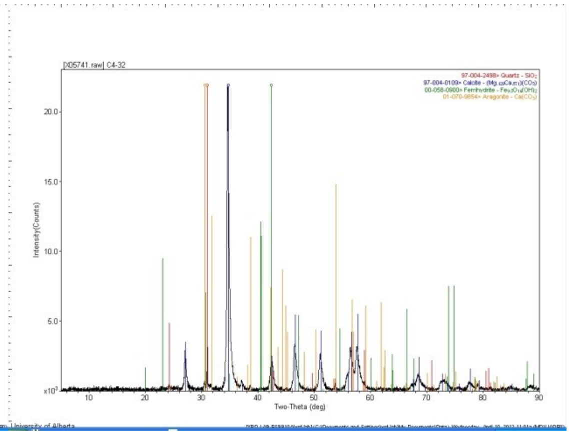
C4-12- bottom 2



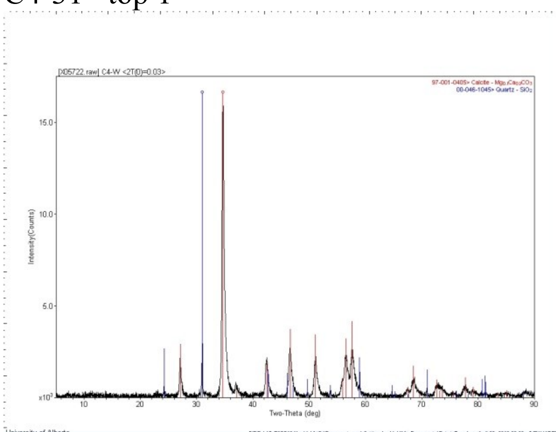
C4-21- middle level



C4-31 –top 1



C4-32-top2



C4-Suspended Solids after flushing

Figure C6-4. XRD profiles taken at the bottom, middle and top levels of the PLTT, OTR, gravel and OTR+PLTT columns. Code C1-11 refers to the bottom 1 of column 1 (PLTT) and code C1-12 refers to bottom 2 of column 1 (PLTT).

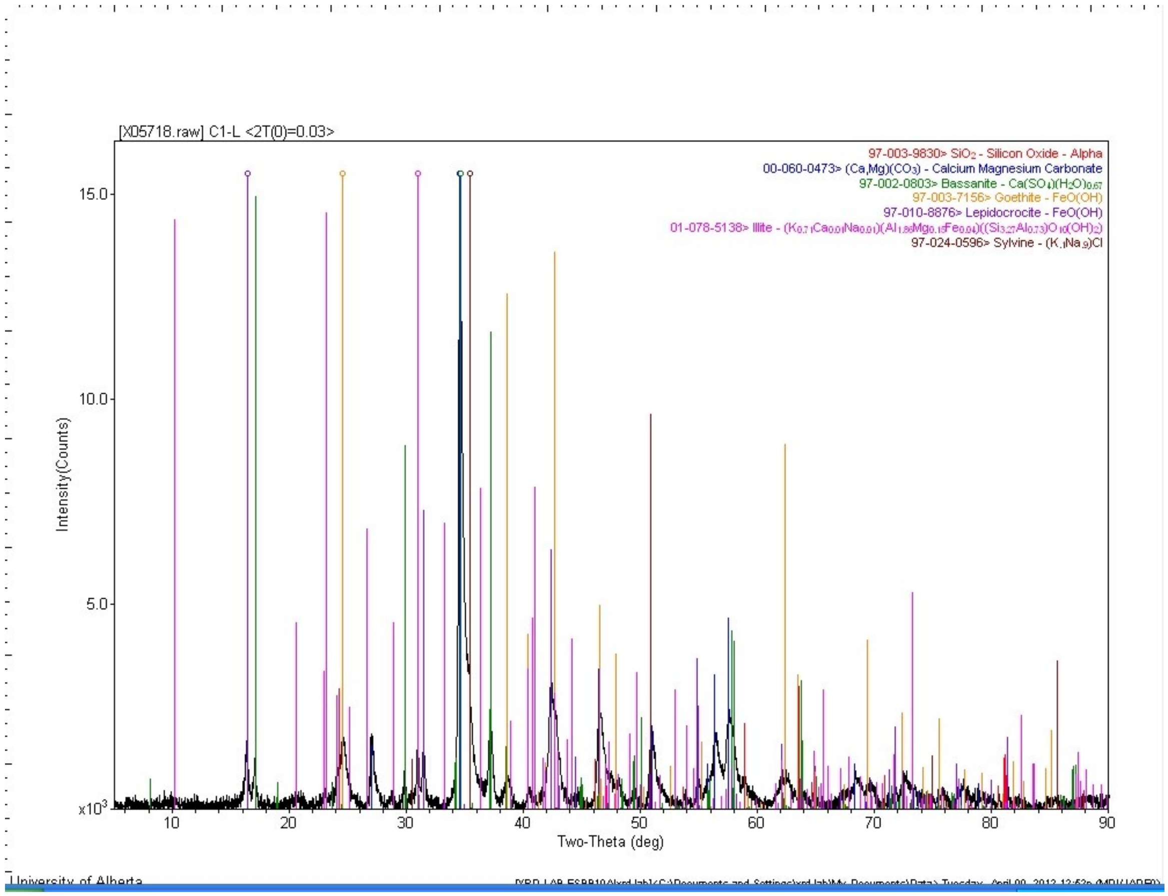


Figure C6-4b. XRD profiles for leachate input into column 1

Appendix C7: Photographic Records

Column1- PLTT

C7-5-1. Column 1- PLTT top level

C7-5-2. Column 1- PLTT Middle level

C7-5-3. Column 1- PLTT Bottom level

Column 2- OTR

C7-5-4. Column 2- OTR top level

C7-5-5. Column 2- OTR middle level

C7-5-6. Column 2- OTR bottom level

Column 3- Gravel

C7-5-7. Column 3- Gravel top level

C7-5-8. Column 3- Gravel middle level

C7-5-9. Column 3- Gravel bottom level

Column 4- OTR+PLTT

C7-5-10. Column 4- OTR+PLTT top level

C7-5-11. Column 4- OTR+PLTT middle level

Figure C7-5-12. Column 4- OTR+PLTT bottom level

Figure C7-5. Photographic records showing sampling of the clog particles at the top, middle and bottom levels of PLTT, OTR, gravel and OTR+PLTT columns