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Antonio J. Cardoso
University of South Florida

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Relationship of Waste Characteristics to the Formation of Mineral Deposits in Leachate Collection Systems

by

Antonio J. Cardoso

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
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Major Professor: Audrey D. Levine, Ph.D.
Valerie J. Harwood, Ph.D.
Robert P. Carnahan, Ph.D.

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Dedication

I would like to dedicate this thesis to my family. No matter the distance, they have been one of the most important parts of this journey.

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Antonio J. Cardoso

ABSTRACT

Landfill leachate is generated as a result of reactions between water percolating through the landfill and wastes. Under normal conditions leachate is found at the bottom of landfills and from there, its movement can be controlled with collection systems to be treated, discharged, or recirculated. Landfill leachate collection systems are positioned above the liner and are designed to collect liquid under gravitational flow for the entire active, closure, and post-closure periods. Clogging of any portion of the system can lead to higher hydraulic heads and increase the potential for leakage through the liner.

To reduce the quantity of municipal solid wastes (MSW) requiring landfilling, many municipalities have adopted waste-to-energy (WTE) facilities that yield energy in the form of combustible gases and noncombustible residues. Disposal practices for WTE residuals include landfilling in monofills or co-disposal with MSW and other materials such as residues from water and wastewater treatment facilities. There has been concern about co-disposal practices, because the impacts on leachate quality and waste interactions are not well known yet.

This research was conducted to evaluate clogging of leachate collection systems due to co-disposal of MSW and combustion residues from WTE facilities. The use of laboratory lysimeters in conjunction with batch tests to predict short-term and long-term leaching characteristics of noncombustible residues from WTE facilities was also evaluated.

Laboratory lysimeters were used to simulate monofills (WTE residues and MSW) and co-disposal practices. Relationships between waste composition and leachate quality were evaluated over a seven month period. In addition, two different types of batch tests were used to analyze the leaching behavior of combustion residues from three different WTE facilities in Florida.

Data from this research produced a better understanding of the implication of co-disposal of MSW and WTE residuals in the production of precipitates in leachate collection systems. Lysimeter and batch tests proved to be useful tools for simulation of field conditions and predicting the degree to which WTE residuals contribute inorganic constituents to the leachate matrix.

Introduction

Land disposal of solid waste has been practiced for centuries. In the past, constituents leached from solid waste were considered to be attenuated by soil and groundwater. However, since the 1950's and due to increasing concerns for the environment, landfills have come under scrutiny and waste dumps have been transformed into engineered landfills (Bagchi, 1990). In addition, many municipalities have implemented the use of Waste-to-Energy (WTE) facilities with the goal of reducing the net volume and mass of wastes prior to landfilling while producing energy through mass burn or Refuse Derived Fuel (RDF) practices (FDEP, 2000).

Byproducts of thermal processing of solid waste include combustion gases, bottom and fly ash residues, and recoverable materials such as ferrous and nonferrous metals. Management approaches for ashes from WTE facilities include disposal in monofills, co-disposal with non-combusted Municipal Solid Waste (MSW) in landfills, or incorporation with other materials for various construction applications (Hjelmar, 1996). Typically, MSW landfills are permitted to receive a combination of MSW, fly and bottom ash from combustion processes, residuals from waste and wastewater treatment facilities, construction wastes, and other materials (USEPA, 2004).

In landfills, leachate is generated as a result of hydrological and biogeochemical reactions between water percolating through the landfill and wastes. Leachate is composed of the liquid that enters the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs, liquid associate with the deposited wastes, and liquid produced from waste decomposition. Leachate composition changes as wastes degrade influencing microbial activity, solubility, and partitioning of many constituents (Johnson et al., 1999; Kylefors, 2003).

Leachate collection systems play an important role in landfill management to control the build up of leachate within the landfill and limit the advective flow of leachate through the liner system. Properly functioning, leachate collection systems serve to reduce potential for groundwater contamination and control the mass loading of contaminants available to pass through the barrier system (Rowe et al., 2002). The current design concept for engineered landfills consists of constructing a low permeability liner below the landfill to restrict leachate percolation, and a perforated pipe system within a granular drainage blanket to collect leachate generated within the landfills (USEPA, 1993).

A potential difficulty in landfill leachate collection systems is that solid material may deposit and accumulate in the pore spaces of drainage materials and in the perforated collection pipes, leading to clogging (Reinhardt and Townsend, 1998; Maliva et al., 2000; Rowe et al., 2002). Factors that have been implicated in promoting clogging of leachate collection systems include sedimentation and deposition of fines, biological activity, and biogeochemical precipitation (Paksy et at., 1998).

In this thesis, a lysimeter study on the formation of biogeochemical deposits in leachate collection systems is presented. Instead of the traditional Results and Discussion section, two articles are used to illustrate some of the factors affecting the formation of precipitates in leachate collection systems. The relationship of waste composition and leachate quality is presented in the first article, in which the clogging of leachate collection systems due to co-disposal of MSW, WTE combustion residues, and byproducts from water and wastewater treatment is evaluated. The second article deals with the leaching behavior and the role of combustion residues from WTE facilities for providing calcium and other minerals, influencing the formation of precipitates that may cause malfunction of leachate collection systems.

Limited information is available on the specific mechanisms of clogging and the factors that influence reaction rates. From an engineering perspective, it is important to ensure that leachate collection systems remain operational throughout the lifespan and post-closure periods of landfills. Improved understanding of biological and mineral clogging is needed to develop strategies for preventing clogging and reducing the failure potential of the landfill barriers (Bennett et al., 2000).

Objectives

This project was conducted to investigate the impact of co-disposal of municipal solid waste (MSW), waste-to-energy (WTE) combustion residues, and residuals from water and wastewater treatment, and associated characteristics of leachate on the development of mineral precipitates that lead to clogging of leachate collection systems. The specific objectives are:

1. Use of laboratory lysimeter tests to compare leachate characteristics from monofills of MSW or WTE combustion residues to leachates generated by co-disposal of MSW, WTE combustion residues, and residuals from water and wastewater treatment.

2. Assess the use of laboratory lysimeters in conjunction with batch tests to predict short-term and long-term leaching characteristics of combustion residues from WTE facilities.

3. Identify dominant chemical and biological factors that influence the formation of deposits in leachate collection systems.

Literature Review

A major issue associated with the disposal of municipal solid wastes in landfills is the management of leachates generated from reactions between waste materials and rainfall or other sources of moisture. In this section, the composition and formation of landfill leachates are discussed and relevant State and Federal regulatory requirements for landfill leachate management are presented. An area of concern in the operation of engineered landfill is the potential for clogging of the leachate collection systems and therefore, a review of previous research on the development of biogeochemical deposits in landfill leachate drainage systems is presented. A comparison of field and laboratory studies that used lysimeters to determine the effect of different factors on leachate composition and clog development is also provided. Finally, the literature review is concluded with a discussion on waste-to-energy (WTE) combustion residuals.

Engineered Landfills

Landfilling or land disposal is the most commonly used method for disposal of municipal solid wastes around the world. The planning, design, and operation of landfills involve the application of scientific, engineering, and economic principles (Bagchi, 1990; Tchobanoglous et al., 1993). The construction and design of landfills is influenced by the topography, the hydrology, and potential environmental constraints associated with management of the landfill site.

Landfills are engineered to prevent and control risks to human health and minimize the potential for negative effects on the environment associated with solid waste disposal. Landfill practice is dynamic in that it will change with both advances in technology and changes in regulations (EPA Ireland, 2000). A summary of relevant aspects to be considered in the design of engineered landfills is presented in Table 1.

Table 1. Summary of Relevant Aspects to be Considered in Landfill Design.

Aspect	Consideration
Nature and quantity of wastes	The waste types accepted at the landfill dictates the control measures required. Quantities and rate of waste input determine the life of the site.
Water control	To reduce leachate generation, control measures are required to minimize the quantity of water contacting the landfill waste.
Protection of soil and water	A liner must be provided to prevent leachate migration to soil, groundwater, and surface water. The liner must meet prescribed requirements.
Leachate management	Leachate collection systems must be provided to ensure that leachate accumulation at the base of the landfill is kept to a minimum.
Gas control	The accumulation and migration of landfill gas must be controlled.
Environmental nuisances	Provisions must be incorporated to minimize and control nuisances such as odors, fires, noise, and dust.
Stability	The sub-grade and basal liner should be sufficiently stable to prevent excessive settlement. The method of waste emplacement should ensure stability of the waste mass against sliding and rotational failure.

Adapted from EPA publication EPA625-R-01-012, Florida Administrative Code 62-701.40000(4)(b), and EPA Ireland (2000).

MSW landfills are permitted to receive a combination of MSW, bottom and fly ash from combustion processes, residuals from water and wastewater treatment facilities, construction wastes, and other materials (USEPA, 1993). Regulatory requirements stipulate that MSW landfills must have liners and leachate collection systems to prevent the migration of leachate into groundwater systems (USEPA, 1993). To better understand the potential for clogging of leachate collection systems, it is important to evaluate the composition and formation of landfill leachate, as well as current design and operating leachate management practices.

Landfill Leachate

Leachate is generated as a result of reactions between water percolating through the landfill and wastes. It results from a complex interplay between hydrological and biogeochemical processes. Leachate is composed of the liquid that enters the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs, liquid associated with the deposited wastes, and liquid produced from waste decomposition. While hydrological processes determine the extent of leaching, biogeochemical processes of the matrix components determine the major solution variables (Bagchi, 1990; Johnson et al., 1999).

Leachate generation from landfilled wastes occurs over time spans ranging from decades to centuries, depending on the size and depth of the landfill, precipitation patterns, and leachate management practices. Waste consolidation and pressure differentials promote the migration of leachate through the landfill layers. Under normal conditions, leachate is found at the bottom of landfills and from there, although some lateral movement may also occur, its movement can be controlled with collection systems to be treated, discharged, or recirculated (Tchobanoglous and Kreith, 2002).

Leachate Characteristics

When water percolates through solid wastes, biological materials and chemical constituents are mobilized into the liquid. Dissolved and suspended materials in leachates are composed of varying concentrations of organic carbon, ammonia, chloride, iron, sodium, potassium, carbonates, and other constituents (Levine and Kroemer, 1989). The quality and quantity of leachate generated in a landfill is influenced by waste characteristics, local precipitation patterns, landfill age and location, and other site specific variables (Peeling et at., 1999; Johnson et al., 1999).

The composition of the leachate is an indication of the state of the biological processes occurring within the waste matrix and the relative solubility of the chemical constituents. Movement of liquid through the waste layers and collection systems can promote biological activity which, coupled with chemical reactions, has the potential to produce mineral precipitates. Certain compounds like sodium, potassium, and chloride are readily soluble and their concentrations do not change significantly during degradation processes, although an abundance of these ions does influence the ionic strength of the leachate (EPA Ireland, 2000; Rhea, 2004). Other ions such as calcium, iron, and magnesium are particularly important with respect to the precipitation of solids (Islam and Singhal, 2004; VanGulck et al., 2003; Rowe et al., 2002; Maliva et al., 2000).

As a landfill ages, changes in the quantity and quality of the leachate occur due to the establishment of microbial communities and the degradation and solubilization of constituents from the waste. Over the last thirty years, many factors have contributed to changes in the composition of municipal solid waste and therefore, leachate (Rowe et al., 2002; Rhea, 2004). Representative data on the characteristics of landfill leachates are reported in Table 2.

Table 2. Representative Data on the Characteristics of Landfill Leachates.

Parameter	Units	Bagchi (1990)	Owen and Manning (1997)	Kjeldsen et al. (2002)	Levine et al. (2005)
General					
pH	pH units	3.7 – 8.9	6.3 – 8.1	4.5 – 9.0	5.8 – 7.8
Conductivity	mS/cm	n/a	1.1 – 29.3	2.5 – 35.0	5.0 – 20.7
Phosphorus, Total	mg/L PO_4	BDL – 250	n/a	0.1 – 23.0	0.2 – 98.0
Solids, Total Dissolved	mg/L TDS	584 – 55,000	1,558 – 91,057	n/a	3,202 – 14,975
Solids, Total Suspended	mg/L TSS	2 – 140,900	n/a	n/a	n/a
Biological Activity Indicators					
Alkalinity, Total	mg/L as $CaCO_3$	BDL – 15,000	n/a	n/a	350 – 9,500
Organic Carbon, Total	mg/L TOC	BDL – 195,000	n/a	30 – 29,000	15 – 12,300
Volatile Acids	mg/L as acetic acid	n/a	n/a	n/a	8.3 – 1,950
Anions					
Chloride	mg/L Cl	2 – 11,400	24 – 9,710	150 – 4,500	300 – 45,000
Sulphate	mg/L SO_4	BDL – 1,900	5 – 1,720	8 – 7,750	BDL – 1,000
Cations					
Calcium	mg/L Ca	3 – 2,500	82 – 1,592	10 – 7,200	210 – 11,000
Iron	mg/L Fe	BDL – 4,000	BDL – 118.5	3.0 – 5,500	6.8 – 1,400
Magnesium	mg/L Mg	4 – 780	41 – 1,290	30 – 15,000	0.01 – 377.5
Manganese	mg/L Mn	BDL – 400	BDL – 23.1	0.03 – 1,400	46 – 9,000
Potassium	mg/L K	BDL – 3,200	11 – 1,450	50 – 3,700	66 – 67,000
Sodium	mg/L Na	12 – 6,010	10 – 4,790	70 – 7,700	60 – 2,869

BDL = Below Detection Limits
n/a = Not Available

Factors Affecting Leachate Composition

The variability of leachate characteristics complicates design and operation practices for leachate management and treatment (Kjeldsen et al., 2002; Tchobanoglous et al., 1993). The quality and quantity of leachate generated in a landfill is influenced by waste characteristics, local precipitation patterns, landfill age and location, and other site specific variables (Peeling et at. 1999; Johnson et al., 1999). A summary of the factors affecting leachate composition is presented in Table 3.

Table 3. Summary of Factors Affecting Leachate Composition.

Factor	Effect	Comments
Waste characteristics	Determines the types of compounds that leach into solution. Controls the type and extent of biological activity within the landfill.	Amount of water that can be absorbed depends on the type of waste and physical characteristics (size, surface area, porosity, etc.). WTE residues and water and wastewater treatment processes have different properties than MSW.
Local precipitation patterns	Determines frequency and the amount of water available for leachate generation. Impacts the dilution, concentration, solubilization, and/or precipitation of leachate components.	Biogeochemical processes are moisture limited. Changes between seasons (dry – wet) also play a role in dissolution/precipitation reactions.
Landfill age and location	Determines the degradation stage of the waste and the availability of certain compounds. Climatic factors and precipitation patterns are related to the location of the site.	Location also determines the type of community served by the facility and therefore, the kinds of activities producing waste.
Landfill operation	Rate of waste input and practices such as co-disposal of residues and leachate recirculation affect leachate quality and quantity.	Maintenance practices for collection system and gas control management are important too.

Knowledge about leachate generation characteristics of a landfill is a prerequisite to the planning of a leachate management strategy. The potential for the formation of leachate can be assessed by preparing a water balance that involves the amounts of water entering the landfill, the amounts of water consumed in biochemical reactions, and the quantity leaving as water vapor. The potential leachate quantity is the quantity of water in excess of the field capacity of the waste (Tchobanoglous and Kreith, 2002).

There are four successive stages in the degradation of waste which lead directly to leachate and gas production: (1) aerobic stage; (2) hydrolysis and fermentation stage; (3) anaerobic acetogenic stage; and (4) anaerobic methanogenic stage (USEPA, 2000; Kjeldsen et al., 2002). These processes are dynamic, each stage being dependent on the creation of a suitable environment by the preceding stage. In each stage a number of biologically mediated reactions take place, depending on the competing ability of the microbiological community to function within a changing chemical environment (Bagchi, 1990; Owen and Manning, 1997; EPA Ireland, 2000). Biological activity influences redox potential, pH, and temperature, which can impact the rate and extent of biological degradation and chemical equilibrium solubility affecting leachate composition.

Landfill management approaches also affect leachate characteristics. Typically, MSW landfills are permitted to receive a combination of MSW, fly and bottom ash from combustion processes, residuals from waste and wastewater treatment facilities, construction wastes, and other materials (USEPA, 2004). All these residues have very different compositions, leaching potentials, and properties that have an impact in the leachate (Hjelmar, 1996).

Interest in leachate recirculation and bioreactor landfills is intensifying around the world, because waste decomposition and the time to stabilization are accelerated through these kinds of practices (Reinhart, 1996; Morris et al., 2003; USEPA, 2000). Leachate recirculation can enhance the degradation of MSW, as it provides an aqueous environment that facilitates the provision of nutrients and microbes within the landfill affecting leachate quality (Chan et al., 2002). Leachate quality changes occur as a result of a uniform distribution of moisture, higher quantities of inoculum, possible flushing and dilution of inhibitory products, and concentration of metals due to biological activity.

Regulatory Requirements for Landfill Leachate Management

The safe and reliable long-term disposal of solid waste residues is an important component of integrated waste management. There are many potential environmental problems associated with landfilling of solid wastes. In the past, many problems occurred as a result of non engineered facilities, poor management, and weak regulatory oversight.

Regulations for waste management and landfill design have been established to protect public health and prevent environmental contamination. Design, operation, and closure practices for MSW landfills are based on 40 CFR Part 258 of the Resource Conservation and Recovery Act (RCRA) Subtitle D requirements for control of leachates and gases generated during the life of the landfill (USEPA, 2000). In this section, regulatory requirements for landfill design, landfill operation, and landfill leachate management are summarized. The Federal regulations establish minimum standards and allow the States to make the necessary adjustment to compensate for local variations.

Leachate Collection Systems

The main purpose of leachate collection systems is to allow the removal of leachate from the landfill and to control the depth of the leachate above the liner (USEPA, 2000; Tchobanoglous and Kreith, 2002). Typically, landfill leachate collection systems are positioned above the liner and are designed to collect liquid under gravitational flow for the entire active, closure, and post-closure periods. Clogging of any portion of the system can lead to higher hydraulic heads within the waste zone and increase the potential for leakage through the liner.

A schematic of a leachate collection system is shown in Figure 1 and design requirements specified by the USEPA are summarized in Table 4. As shown, the composite liner serves as the landfill base and consists of an impermeable layer with a hydraulic conductivity of less than 10^{-7} cm/sec (USEPA, 1993). Typically, clay is used to construct this relatively impermeable layer. The clay layer is overlain by a flexible membrane liner that provides an additional barrier protection in case cracking occurs in the underlying clay due to shifts in the soil.

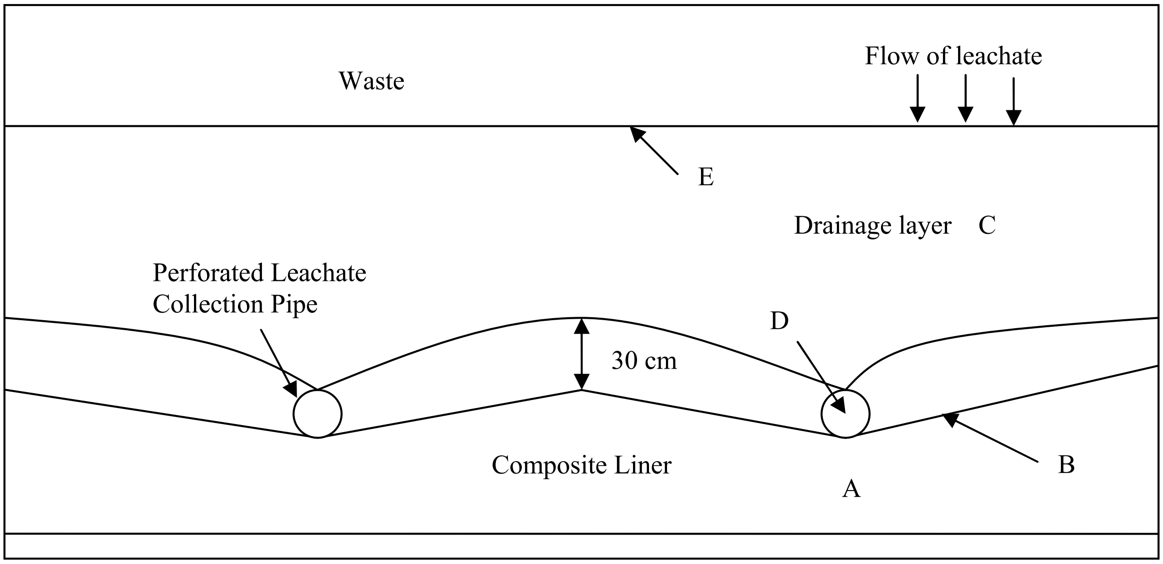


Figure 1. Diagram of the Leachate Collection System of Engineered Landfills. Adapted from Rhea (2004).

Table 4. Landfill Leachate Collection System Components Shown in Figure 1.

Parameter	Section	Material and Specifications	Label in Figure 1
Composite liner	Base	Soil with hydraulic conductivity less than 1 x 10^{-7} cm/sec. Slope > 2%.	A
	Liner	Flexible membrane.	B
Leachate collection system	Drainage layer	Placed directly over liner; material based on availability of granular material or geosynthetic net. Conductivity greater than 1 x 10^{-2} cm/sec. Slope > 2%	C
	Collection pipes	Perforated; minimum 6 inch diameter; embedded within the drainage layer; strong enough to support waste and drainage layer.	D
	Filter layer	Geotextile and/or sand. Protects drainage layer from physical clogging.	E

Adapted from Rhea (2004), EPA publication EPA530-R-93-017, and Florida Administrative Code 62-701.40000(4)(b).

If the leachate develops sufficient head (depth), it has potential to penetrate the composite liner. The leachate head is a function of leachate generation, bottom slope, pipe spacing, and the hydraulic conductivity of the drainage layer. To prevent accumulation of leachate above the composite liner, leachate collection systems are designed to maintain the leachate depth below 30 cm (Bagchi 1990; USEPA, 1993; EPA Ireland, 2000). However, during times of peak flow it is acceptable to exceed this value.

The transport of leachate from waste matrices occurs through a series of perforated pipes embedded in a drainage layer. Regulatory requirements stipulate minimum requirements for perforated pipes to be at least 6-inch diameter plastic pipe capable of supporting the combined weight of the drainage layer and the waste at design capacity. If the pipes are not able to support this weight, the leachate collection system will fail. The conductivity of the drainage layer material must be at least 10^{-2} cm/sec, with a minimum slope of 2% so that the leachate will flow towards the collection pipes (USEPA, 1993).

To prevent physical clogging of the collection pipes, the size of the drainage material must be larger than the perforations in the pipe. Another measure used to prevent physical clogging is the filter layer. This layer of geotextile and sand is placed above the drainage blanket and prevents waste from traveling into the drainage layer and the collection pipes creating physical blockages in the flow (USEPA, 1993). Leachate monitoring points and leachate collection sumps or a header pipe system may also be required for leachate control and removal.

Biological and chemical clogs can occur in the leachate collection system pipes (Fleming et al., 1999; Jefferies and Bath, 1999; Maliva et al., 2000; Missmer International, 2000; Paksy et al., 1998; Reinhardt and Townsend, 1998; Rittman et al., 1996; Rowe and Fleming, 1998; Rowe et al., 2000a, b, c; Rowe et al., 2002; USEPA, 1983). Within pipes, accumulation of deposits may be induced because of inadequate localized flows caused by areas of hydraulic perturbation (EPA Ireland, 2000). To help control the formation of mineral precipitates and biofilms, clean-out access ports are required in leachate collection systems. These ports must be placed at locations that allow cleaning equipment and chemicals to access the whole system (USEPA, 1993).

The suggested method for removal of mineral deposits is to flush the system with a liquid that contains biocides and cleaning agents. The cleaning is intended to remove mineral precipitates and biofilm buildup in the pipes, but does not prevent the formation of future clogs (USEPA, 1993). The cleaning frequency is determined by local regulations and landfill operating protocols.

Clogging of Leachate Collection Systems

Typically, the design life of landfills spans several decades, depending on the available space and the quantity of waste received (Fleming et al., 1999). A common reason for failure of leachate collection systems is clogging as a result of the growth of biofilms, accumulation of inorganic solids, and attachment of suspended particles in pipes, drainage layers, and/or the filter layer (VanGulck et al., 2003; Islam and Singhal, 2004; Manning and Robinson, 1999; Rowe et al., 2002). The leachate characteristics which have an impact in the potential mechanisms related to the formation of deposits in leachate drainage systems are summarized in Table 5.

Table 5. Potential Clogging Mechanisms and Leachate Characteristics of Concern.

Potential Clogging Mechanism	Leachate Characteristics of Concern
Particulate	pH and solids (TS, TDS, TSS).
Biological	pH, oxygen, organic content (COD, BOD, TOC), nutrients (total phosphorus and total nitrogen), oxidation-reduction potential (ORP), temperature, and inhibitory metals (Zn, Cu, Fe, etc).
Chemical Precipitate Formation	pH, conductivity, alkalinity (CO_3), calcium, chloride, magnesium, manganese, sodium, sulfate, and phosphorus.
Biochemical	pH, iron, manganese, partial pressure of CO_2, redox potential, electron acceptors (sulfate, nitrate, oxygen), inhibitory metals (Zn, Cu, Fe, etc).

Adapted from EPA Ireland (2000).

In some cases, evidence of clogging has been observed to occur within 4 years of landfill initiation (Rowe et al. 2002). Drainage media have been implicated in the formation of clogs in landfill leachate collection systems (Rowe et al. 2000c; USEPA, 1991). While the initial hydraulic conductivity and porosity of different media may be similar, there are differences in the size of the pores and the available surface area for different types of media. For a given volume, smaller media provides a greater surface area, allowing for increased biofilm development that may influence the clogging rate (Koerner and Koerner, 1990; Rohde and Gribb, 1990; Rowe et al. 2000a).

Regardless of the medium, the flow of the leachate also affects the rate at which clogs form. Clogging has been found in both saturated and unsaturated zones of leachate collection systems. In anaerobic environments, unsaturated regions tend to have less clogging than saturated regions due to differences in available substrate for microbial activity. Microbial activity can influence environmental conditions like redox potential and pH, which impact the rate and extent of biological degradation and chemical solubility (Kylefors et al. 2003).

During times of high leachate flow rates, the increased activity of the microorganisms can lead to biofilm production and the precipitation of insoluble minerals. In reality, the environment in the leachate collection system of a landfill cycles between saturated and unsaturated conditions depending on precipitation patterns. Unfortunately, deposition of precipitates is most pronounced in regions that experience changing flows, cycling between saturated and unsaturated conditions (Paksy et al., 1998; Rowe et al., 2000b).

The clogging process appears to pass through a number of microbial mediated stages which include, but may not necessarily be limited to, formation of surface biofilms, generation of slimes, and growth on interconnected mineral bio-concretions that gradually become denser and less pervious. Entrapment within these formations of recalcitrant particles (silt and sand particles or fines derived from the waste) may also accelerate clogging. The structural integrity of the clog may be developed by precipitation of low-solubility sulfide and carbonate minerals (Fleming et al. 1999).

Landfill leachates have been reported to contain significant numbers of microorganisms which are delivered to the drainage system, attach to surfaces, and form biofilms (Huang et al., 2003; 2004). It is hypothesized that bacteria growing within the decomposing waste detach from the developing biofilms, flow with the leachate into the leachate collection system, and colonize the granular drainage material (Rowe et al. 2000a).

The accumulation of clog material can be represented as being composed of a volatile and inorganic solid film (Cooke et al., 2001; Rowe et al., 2002). The volatile film contains an active component where microorganisms grow and substrate is utilized and an inactive component which consists of precipitate material, inorganic solids, and entrapped inorganic suspended particles (VanGulck and Rowe, 2004b). Unlike the active biofilm, the inactive film does not approach a steady state but continues to increase over time.

Leachates have abundant potential to precipitate minerals (Owen and Manning, 1997). The most common precipitate is of calcium carbonate, but others are manganese carbonate, manganese sulfides, and silicates (EPA Ireland, 2000). Geochemical modeling studies have reported calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) to be supersaturated in landfill leachates (Owen and Manning, 1997; Bennett et al., 2000; Johnson et al., 1999). Typically, leachates are also saturated with respect to $FeCO_3$, $MgCO_3$, and $Ca_5(PO_4)_3OH$ (Rowe et al., 2002). As leachate passes through the drainage material, depletion of calcium can be correlated with the loss of COD due to the fermentation of acetic acid and the consequent generation of carbon dioxide and formation of carbonic acid (Rittmann et al., 1996). The results are an increase in pH and carbonate concentration, both of which allow, or accelerate, the chemical precipitation of calcium carbonate and other compounds.

It has also been suggested that the amount of calcium carbonate in the precipitate can be estimated from the mass ratio of calcium to carbonate in leachates (Rowe and Booker, 1998). If precipitation were the only mechanism for calcium accumulation within the clog material, and all calcium within the clog material were bound to carbonate, a mass balance consideration of calcium carbonate precipitation (equation 1) requires the theoretical calcium to carbonate ratio to be 0.667 (40 g Ca^{2+}/60 g CO_3^{2-}).

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_{3\,(s)} \qquad \text{(equation 1)}$$

Calcium to carbonate mass ratios larger than 0.667 suggest that calcium may precipitate as compounds other than calcium carbonate, while ratios less than 0.667 suggest metals other than calcium may precipitate with carbonate (VanGulck et al., 2003; VanGulck and Rowe, 2004a, b). From this approach, it was determined that the availability of calcium rather than the carbonate limits the formation of the calcite in leachate drainage and collection systems (Rowe et al. 2002).

Several field studies have reported the composition of the clog material found in landfill leachate collection systems. Brune et al. (1991) conducted studies in German landfills, while Fleming et al. (1999) reported organic and inorganic materials in a Toronto landfill. Maliva et al. (2000) detected a low magnesium form of calcite in clog scale obtained from a leachate collection pipe in a Florida landfill that received combustion residues from a WTE facility. Levine et al. (2005) also reported the composition of clog materials collected at different locations of the leachate collection system in the same Florida landfill. The results of these studies are presented in Table 6.

Table 6. Comparison of Composition of Material Precipitated in Landfill Leachate Collection Systems (Values Reported in Percentages).

Material	Brune et al. (1991)	Fleming et al. (1999)	Levine et al. (2005)
Ca	21	20	75 – 85
CO_3	34	30	n/a
Si	16	21	1 – 5
Mg	1	5	<1
Fe	8	2	<1

n/a = Not Available

Samples removed in these studies ranged from soft clog material containing solid sand-size particles, to hard solid material with the appearance and consistency of a weak concrete or rock. The precipitate is generally mixed with a biological slime, which is quite adherent and can block flow through the drainage system. Precipitates produced as a result of biochemical activity are generally quite different in form and structure from those resulting in chemical processes alone and may show a greater tendency to clogging. This clogging tendency is apparent in the case of adherence to plastic piping (EPA Ireland, 2000).

Lysimeter Studies

In addition to observations from active landfills, laboratory studies have been used to assess different aspects of landfilling practices. Various tests have been developed to determine the leaching behaviors of materials (Hage and Mulder, 2003). Tests used to establish the leaching characteristics of wastes include field tests, simulator (lysimeter) tests, and batch tests. A comparison of these tests is given in Table 7.

Table 7. Comparison of Types of Tests Used to Evaluate Waste Leaching Potentials.

Category	Description	Advantages	Disadvantages
Field	Monitors leachate characteristics produced by wastes in an established landfill.	Establishment of microbial communities; heterogeneity of waste constituents.	Can take several years; limited access to the reacting materials; inability to determine the contribution of waste constituents to leachate quality.
Simulator	Waste is placed in a column, commonly called a lysimeter, and allowed to react over several months.	Establishment of microbial populations; mimics a landfill; controlled flow of leachant; access to the reacting materials in select locations.	Can take months to complete; inability to determine the contribution of the individual waste constituents to the characteristics of the leachate.
Batch	Select wastes are placed in non-reactive containers with leachant for a specific length of time.	Can be completed in weeks; identification of the contribution of waste constituents to leachate quality.	Missing microbial activity; limited interaction among different types of waste.

Adapted from Rhea (2004).

Simulators or lysimeters tests require less time than field tests but can still take several months to be completed. Lysimeters can be used to simulate specific landfill conditions under a controlled environment, evaluated the relationships between waste composition and leachate quality, and provide an opportunity to observe the establishment of microbial communities in relation to leachate flow patterns. In these tests, wastes are placed in parallel reactors where temperature, moisture content, and the degree of leachate recirculation can be controlled and gas production and leachate composition can be monitored. In addition, the composition of the wastes can be characterized more completely than in a landfill setting.

In many ways lysimeters are black boxes, since the ability to determine a direct relationship between individual materials and leachate characteristics is unknown (Rhea, 2004). The design, placement, and operation of the reactors depend on the purpose of the study and can influence the results. In a laboratory, the results may not correlate with field tests due to differences in temperature, time, and liquid to solid contact frequency (van der Sloot, 1998). Lysimeter design parameters from published studies are compared in Table 8, while different lysimeter operation aspects are summarized in Table 9.

Table 8. Design Parameters Used in Lysimeter Studies.

Reference	Aspect	Column Material	Packing Material
Blight et al. (1999)	$3.12\ m^2$ X 1.06 m deep	Brick and concrete	Liner: HDPE Drainage layer: 100 mm gravel MSW
Chan et al. (2002)	150 mm diameter; 150 cm length	Stainless steel	MSW, sewage sludge, marine dredging
Cooke et al. (2001)	51 mm diameter; 760 cm length	PVC	6-mm diameter glass beads
Fleming et al. (1999)	0.25 X 0.6 X 0.70 m	PVC	Drainage blanket: clear stone MSW: 5 – 10 yr old waste Geotextile
Islam and Singhal (2004)	50 mm diameter; 500 mm length	n/a	Clean sand: 0.21 – 0.61 mm in size
Karnchanawong et al. (1995)	1.9 m diameter; 6.14 m length	Steel coated with coal tar resin	Drainage layer: gravel Cover layer: soil MSW
Paksy et al. (1998)	350 mm diameter; 900 mm length	MDPE/HDPE	Drainage layer: limestone and Thames gravel MSW: 4 – 5 yr old waste
Peeling et al. (1999)	220 mm diameter; 910 mm length	MDPE/HDPE	Drainage layer: limestone and Thames gravel MSW: 4 – 5 yr old waste
Rowe et al. (2000)	50 mm diameter; 700 mm length	PVC Schedule 40	4, 6, 15 mm diameter glass beads.
Sallam, M. (2002)	150 mm diameter; 122 cm length	PVC	Drainage layer: silica gravel MSW Geotextile
San and Onay (2001)	35 cm diameter; 100 cm length	PVC	Drainage layer: gravel MSW: shredded and compacted synthetic solid waste.
VanGulck and Rowe (2004)	51 mm diameter; 700 mm length	PVC Schedule 40	6 mm diameter glass beads.

n/a = Not Available

Table 9. Operational Aspects of Lysimeter Studies.

Reference	Liquid source and flow rate	Time span and temperature	Gas and leachate collection
Blight et al. (1999)	Rainfall	865 days 17 – 20 °C	Leachate: single base drainage orifice
Chan et al. (2002)	Distilled water (500 ml) added weekly; leachate recirculation	69 – 78 days 38 °C	Gas: gas-venting valve on the lid, connected to water-filled glass column Leachate: weekly samples from valve at the bottom
Cooke et al. (2001)	Liquid: landfill and synthetic leachate Flow rate: continuous, upward (1.12 L/d)	280 days 22 °C	Allowed escape of gas
Islam and Singhal (2004)	Liquid: landfill leachate Flow rate: continuous, upward (0.33 – 7.2 L/d)	58 – 126 days 18 – 30 °C	n/a
Karnchanawong et al. (1995)	Rainfall	853 days n/a	Leachate samples collected weekly
Paksy et at. (1998)	Liquid: landfill and synthetic leachate Flow rate: continuous, vertically down (0.6 – 10 L/d)	800 days 18 – 37 °C	Gas outlet port in the lid
Peeling et at. (1999)	Liquid: synthetic leachate with recirculation Flow rate: continuous, vertically down (0.62, 1.30, 2.59 L/d)	350 – 500 days n/a	Gas: flow meters; headspace gases sampled with syringes
Rowe et al. (2000)	Liquid: landfill and synthetic leachate Flow rate: continuous, upward (1, 2, 4 L/d)	121 – 422 days 26 – 37 °C	Gas: Tedlar gas collection bag; piezometer connection Leachate: valve above the top of the beads
Sallam, M. (2002)	Liquid: landfill and synthetic leachate with recirculation Flow rate: continuous, vertically down (0.04 L/d)	180 days 17 – 28 °C	Gas valve at the top
San and Onay (2001)	Liquid: tap water; leachate recirculation Flow rate: continuous, vertically down	275 days 34 °C	Gas: measured using the inverted cylinder technique Leachate: screen and tubing
VanGulck and Rowe (2004)	Liquid: landfill leachate Flow rate: continuous, upward (1.02 L/d)	245 days 21 °C	Gas: Tedlar gas collection bag; piezometer connection Leachate: valve above the top of the beads

n/a = Not Available

Lysimeter studies have been used for leachate characterization and modeling of MSW co-disposed with incinerated residuals. Based on reported results from tests on leachate quality, co-disposal of MSW and incinerated residuals provides an efficient method of waste disposal, since the organic content of the leachate is lower than for leachates produced during the traditional disposal method (Gau and Chow, 1998). It was also found that a shallower waste layer produces lower concentrations of pollutants in the leachate, although higher amounts of leachate volume and extracted substances per dry weight of waste may be produced (Karnchanawong et al., 1995).

Identification of the effects of leachate recirculation on biogas production and leachate quality has been subject of several lysimeter studies (Blight et al., 1999; Chan et al., 2002; San and Onay, 2001). The conclusions of these studies suggests that leachate recirculation could maximize the efficiency and waste volume reduction rate of landfill sites, with the additional benefit of overall leachate loading reduction for treatment. Waste decomposition can be improved by an increase in the moisture flow, as a result of increased flushing and dilution of the inhibitory products, maintenance of favorable environmental conditions by uniform distribution of moisture, and addition of higher quantities of inoculums and nutrients (USEPA, 2000).

Laboratory lysimeter studies have been used to assess the clogging process. Paksy et al. (1998) demonstrated that the clogging rates in anaerobic drainage systems are highly sensitive to the particle size of the drainage material, and that drains subjected to alternating periods of saturation and unsaturation may become more uniformly and more extensively clogged. These studies recommended that drainage material consisting of sand or gravel with a nominal particle size less than 10 mm should be avoided, and that it is preferable to keep the whole system fully saturated.

Cooke et al. (2001) used lysimeter tests to compare calcium removal and COD consumption in landfill leachate drainage systems. They found that calcium removal goes through three stages: a lag period, a period of rapidly increasing removal, and a steady-state period. Calcium removal paralleled changes in the COD. This correspondence underscores the importance of microbial reactions in stimulating the precipitation of calcium carbonate. In addition, VanGulck and Rowe (2004a) and VanGulck et al. (2003) demonstrated through the use of column experiments, that the anaerobic fermentation of volatile fatty acids (mainly acetate) is the primary driver of calcium carbonate precipitation in leachate drainage collection systems.

Several physical, geochemical, and biological interactions have been reported from column studies (Peeling et al., 1999; Rowe et al., 2002; VanGulck and Rowe, 2004b). Leachate transport in soils resulted in a reduction of its permeability, possibly due to impermeable barriers formed through stimulation of anaerobic activity at the base of landfills (Islam and Singhal, 2004). Experimental observations suggested simultaneous reduction of manganese and iron accompanied by sulfate degradation and methane production.

From lysimeter studies, Rowe at al. (2000b) concluded that mass loading has a significant impact on the rate and extent of clogging in a granular medium. The increased mass of inorganic material available for precipitation on the granular medium, coupled with the higher mass loading near the collection pipes tends to accelerate clogging. Reducing the distance between the leachate collection pipes can decrease the total volume of leachate collected by each pipe and reduce the mass loading and the rate of clogging around the pipe.

The placement of a geotextile filter/separator between the unsaturated stone layer and the overlying waste was studied by McIsaac et al. (2000). In this study, the presence of a separator minimized the occlusion of the voids with waste material at the top of the unsaturated stone layer. The presence of a geotextile decreased the amount of fines and sand sized particles, resulted in less clog material present in the drain material. Visually more clog material was observed in the drainage system in lysimeters with no geotextile separator.

The information obtained from lysimeter studies provides a means to understand the factors and identify environmental conditions that influence the clogging process. From an engineering perspective, it is important to ensure that landfill leachate collection systems remain operational throughout the lifespan and post-closure periods of landfills (Bennett et al. 2000). Therefore, improved understanding of biological and mineral clogging is needed.

Waste-To-Energy Residuals

WTE combustion is an important technology that can be a significant factor in an overall fully integrated solid waste management strategy. These technologies offer great opportunities for reducing the volume and mass of waste to be landfilled up to 90% and 75% respectively, as well as for generating heat and power (USEPA, 2004). The major constraints on WTE combustion facilities are their cost, the level of sophistication needed to operate them safely, control of air emissions, and the fact that the public lacks confidence in their safety (Tchobanoglous and Kreith, 2002).

Byproducts of thermal processing of solid waste include combustion gases, ash residues, and recoverable materials such as ferrous and nonferrous metals. Ash residues are produced and discharged at various locations in a WTE facility. Combustion residues vary in composition depending on the source of the combusted material, degree of pre-processing (mass-burn, RDF, material recovery), the efficiency of the combustion process, the ash management practices, emission control systems, and the methods of residue collection (Berenyi, 1996; Brereton, 1996; USEPA, 2004). Different types of ash and their characteristics are summarized in Table 10.

Table 10. Summary of Different Types of Ash Residues from a WTE Facility.

Residue	Location	Characteristics
Bottom ash	Discharged from the bottom of the furnace, primarily the grate, after the waste has progressed down the stoker.	Consists of inert residues, glass and metallic objects, and 2 to 10 percent carbon. It is usually quenched with water, although it can also be collected in a dry state.
Stoker grate siftings	Fall through clearances in the grates and are collected with bottom ash.	May include unburned organic matter.
Boiler ash	Carried by combustion gases. It may fall onto the stoker into the bottom ash, or it may be collected in hoppers.	Consists of flying particles and condensable metal vapor which may attach to refractory and water-cooled walls.
Fly ash	Carried by combustion gases through the furnace, boiler, and scrubber. It is collected by the particulate control device.	Reaction products of primarily calcium chlorides and un-reacted lime. Includes volatiles condensed during flue gas cooling.
Scrubber reaction products	Collected at the bottom of spray-dry or dry lime-injection acid gas scrubbers.	Include fly ash and reacted or partially reacted alkaline reagent (such as lime) and some carbon.
Mixed ash	Various locations from the combustion and emission control equipment.	May contain siftings, bottom ash, boiler deposits, scrubber residues, fly ash, and scrubber products.

Adapted from Hasselriis (2002) and Wiles (1996).

Disposal of ash residues imposes a substantial increment to the total cost of operation of a WTE facility. Since 1994, when the Supreme Court ruled that ash from MSW combustion must be treated as other hazardous wastes in *City of Chicago vs. Environmental Defense Fund*, all WTE facilities have been required to test the ash using the Federal Resource Conservation and Recovery Act testing requirements for hazardous waste, prior to disposal in lined landfills (FDEP, 2000). There are over 150 WTE plants in operation today in the United States and since they have become an integral part of waste management around the country, more are either planned or under construction (Tchobanoglous and Kreith, 2002).

Ash Management and Disposal

Over the past several years there has been significant controversy concerning the proper management of the residues from WTE facilities and their regulatory classification as hazardous or non-hazardous waste. This controversy and other factors, such as the lack of Federal guidance and heavy metal content, have resulted in inconsistent management requirements among several States and uncertainty about beneficial utilization of the residues (Wiles, 1996).

Ash residues can be processed at the WTE facility to reduce the rate of release of contaminants into the environment, facilitate disposal, improve the quality of the residues, remove valuable and useful materials, and to prepare portions of the ash for beneficial use (Hasselriis, 2002). Treatment options include processing to recover ferrous and nonferrous metals, compaction aging during storage, solidification/stabilization, vitrification, and chemical extraction. Major utilization options include aggregate for road base, embankments, asphalt pavements, and aggregate in Portland cement for construction (Wiles, 1996). Utilization, however, must follow sound scientific and engineering principles and be conducted with appropriate measures to assure that it is acceptable to the environment and to human health.

Although there are options for using ash residues and for treating them prior to use or as a requirement for disposal, most of the WTE combustion residues generated in the United States are disposed either in monofills, or co-disposed with MSW and/or residuals from water and wastewater treatment facilities (Hjelmar, 1996; Wiles, 1996; Levine et al., 2005). Placing ash residues in monofills has the advantage that a solid, relatively impervious mass is created, over which trucks can drive as soon as it is placed. Ash monofills can be so impervious to water that 90% or more of rainfall runs off, without leaching much of the soluble material in the ash (Hasselriis, 2002). There has been concern about co-disposal practices because the impacts on leachate quality and waste interactions are not well known yet.

Due to the potential leaching of contaminants, landfilling of WTE combustion residues may have long-term consequences for the environment. It has been suggested that monofill or co-disposal of WTE combustion residues and MSW may lead to sub-optimal management solutions in terms of resource conservation and environmental safety (Hjelmar, 1996). Co-disposal of combustion residues with MSW has the potential to introduce metals, minerals and other non-biodegradable materials to the leachate matrix; the acids generated by decomposing MSW could increase concentrations of soluble toxic metals in the collected leachate (Hasselriis, 2002). WTE ash would provide minerals while MSW would provide biomass, carbonate species, and alternative electron acceptors, resulting in clogging of leachate collection systems due to mineral precipitation (Levine et al., 2005).

Leachate from WTE Combustion Residues

From a technical perspective, the development of strategies for disposal of WTE combustion residues and management of the leachate should be based on extensive knowledge of leaching behaviors. The degree to which combustion residues contribute to landfill leachate characteristics is influenced by the type of combustion residue, the disposal practices, the net volume of liquid that percolates through the landfill, biological activity, the age of the landfill, and site-specific factors (Johnson et al., 1999).

The potential for leaching of minerals from combustion residues has been evaluated by several researchers (Abbas et al., 2003; Bruder-Hubscher et al., 2002; Hage and Mulder, 2003; Kim et al., 2003; Kim and Batchelor, 2001; Kylefors et al., 2003; Song et al., 2004; van der Sloot, 1998). In addition, differences in the properties of combustion residues from different types of processing have been identified (Brereton, 1996; Dijkstra et al., 2002; Song et al., 2004). WTE combustion residues show systematic leaching patterns, and the leaching behaviors are controlled by such factors as pH, redox potential, ionic strength, complexing inorganic ions and organics, and L/S ratios.

The leachate from WTE residues usually contains roughly 50% of soluble salts resulting from the removal of acid gases by emission controls, and low organic contents. The major elements include Ca, Cl, Fe, K, Na, O, and SO_4, while minor elements are Cr, Cu, Mg, Mn, Pb, and Zn (Wiles, 1996). A comparison of leachate characteristics from ash monofills is given in Table 11.

Table 11. Comparison of Leachate Quality from Ash Monofills.

Parameter	Bagchi (1990)	Cambotti and Roffman (1993)	Hjelmar (1996)	Lundtorp et al. (2003)
pH (pH units)	8.47 – 9.94	5.7 – 7.5	8.7 – 10.5	11.19 – 11.20
Conductivity (mS/cm)	2.5 – 18.7	n/a	1,400 – 3,900	2.4 – 310
Aluminum (mg/L)	2.3 – 88.8	n/a	n/a	0.230 – 0.420
Arsenic (mg/L)	< 0.187	BDL – 0.40	0.005 – 0.025	n/a
Cadmium (mg/L)	0.004 – 0.300	BDL – 0.60	BDL – 0.001	BDL – 3.50
Calcium (mg/L)	n/a	1,300 – 16,000	32 – 1,000	450 – 4,500
Chloride (mg/L)	32.6 – 305.0	n/a	2,400 – 11,400	25 – 390,000
Chromium (mg/L)	< 0.010 – 0.044	BDL – 0.03	BDL – 0.080	0.220 – 0.460
Copper (mg/L)	0.026 – 0.103	BDL – 0.60	BDL – 0.210	BDL – 0.035
Iron (mg/L)	< 0.01 – 0.10	BDL – 32.0	< 0.010 – 0.760	0.020 – 0.054
Lead (mg/L)	0.15 – 0.60	BDL – 0.14	BDL – 0.040	0.008 – 1,600
Magnesium (mg/L)	0.006 – 0.057	n/a	n/a	n/a
Mercury (mg/L)	< 0.0002	BDL	BDL – 0.003	BDL – 0.003
Nickel (mg/L)	0.01 – 0.03	n/a	n/a	0.001 – 0.017
Potassium (mg/L)	3.66 – 79.80	520 – 6,900	600 – 4,300	98 – 85,000
Sodium (mg/L)	11.5 – 48.5	3,000 – 9,300	2,800 – 7,300	800 – 70,000
Sulfate (mg/L)	105 – 1,400	n/a	2,000 – 7,200	n/a
Zinc (mg/L)	0.002 – 0.012	BDL – 1.60	< 0.010 – 0.590	0.016 – 0.068

BDL = Below Detection Limits
n/a = Not Available

The concentrations of trace elements in the leachate are low due to the reducing environment (redox potential is low due to microbiological degradation of the residual organic material) and the favorable pH regime. Aging or weathering of ash normally results in a decrease of leachate pH towards neutral. One aging reaction results from uptake of CO_2 and self-neutralization of the ash. Other aging reactions that promote metal immobilization include hydrolysis of oxides to hydroxides, and the oxidation of elemental metals to form oxyhydroxide surface deposits. These changes result in decreased solubility of many elements and consequently decreased release (Wiles, 1996; Hjelmar, 1996).

Landfill practices have evolved from very basic beginnings to become a sophisticated activity, with careful planning to ensure containment of gases and leachate, and to ensure achievement of waste and landfill site stabilization. Knowledge about the relationship between waste composition and leachate quality, from the point of view of environmental protection, is needed to improve landfill management practices. As new waste treatment technologies are developed and society consumption habits are modified, the production and composition of the waste, as well as the products of waste degradation, are also in constant change. Understanding leaching behaviors of the different types of wastes could result in better landfill design, landfill operation, and improved leachate management practices.

LYSIMETER COMPARISON OF THE ROLE OF WASTE CHARACTERISTICS IN THE FORMATION OF MINERAL DEPOSITS IN LEACHATE DRAINAGE SYSTEMS

Antonio Cardoso[1]; Audrey Levine[1]; Bina Nayak[2]; Valerie Harwood[2]
University of South Florida
[1]Department of Civil and Environmental Engineering
[2]Department of Biology
4202 East Fowler Ave.; Tampa, FL 33620
ajcardos@eng.usf.edu; levine@eng.usf.edu; bnayak@mail.usf.edu;
vharwood@cas.usf.edu

Lisa R. Rhea
Jones, Edmunds and Assoc., Inc.
324 S. Hyde Park Ave., Suite 250; Tampa, FL 33606
lrhea@jea.net

Abstract: A common operational problem in leachate collection systems is clogging due to deposits formation within pore spaces and collection pipes. This study was conducted to evaluate clogging of leachate collection systems due to co-disposal of Municipal Solid Waste (MSW) and combustion residues from Waste-to-Energy (WTE) facilities. Five parallel lysimeters were filled (monofills or mixtures) with combinations of MSW, WTE combustion residues, and water/wastewater treatment byproducts. Each lysimeter received a regular application of leachate to simulate flooding and drying conditions; chemical tests of the leachates were conducted over a seven month period. Waste composition and the presence/absence of biological activity influenced leachate properties such as redox potential, pH, and alkalinity, which impacted the rate and extent of biological degradation and chemical solubility. Calcium carbonate was identified as one of the most abundant chemical precipitates. Leachates from ash monofills had high levels of pH, calcium and other minerals such as potassium and sodium, while carbonate levels were limited due to the lack of biological activity. The MSW monofill generated leachates with high levels of biological activity, lower concentrations of calcium, and a rich carbonate system. The co-disposal of MSW, combustion and treatment process residues generated leachates not limited in either calcium or carbonate, creating ideal conditions for precipitates formation.

Keywords: Clogging; Co-disposal; Leachate collection systems; Lysimeter; Municipal Solid Waste; WTE combustion residues

1. INTRODUCTION

One of the principal considerations in the planning, design, and operation of engineered landfills is the management of leachate. Leachate collection systems consist of a series of perforated pipes within a granular drainage blanket to collect the leachate. Low permeability liners are installed below the leachate collection system to restrict leachate percolation. These systems are managed to prevent build-up of leachate within the landfill and to reduce the mass loading of contaminants available to pass through the liner (Rowe et al. 2002). A common operational problem in leachate collection systems is clogging due to the formation of deposits in the pore spaces and collection pipes. In general, clogging of leachate management systems has been attributed to several factors including sedimentation and deposition of fines, biological activity, and biogeochemical precipitation (Paksy et at. 1998).

From an engineering perspective, it is important to ensure that leachate collection systems remain operational throughout the lifespan and post-closure periods of landfills; therefore, improved understanding of biological and mineral clogging is needed. The objective of this paper is to evaluate the clogging of leachate collection systems due to co-disposal of Municipal Solid Waste (MSW) and combustion residues from Waste-to-Energy (WTE) facilities.

2. BACKGROUND

Safe and reliable long-term disposal of solid wastes in engineered landfills is widely practiced (Tchobanoglous et al. 1993), however due to limited availability of sites for new landfills, particularly in highly populated urbanized regions, municipalities are under increasing pressure to reduce the quantity of landfilled waste. WTE facilities provide a means to reduce waste volumes in landfills and to recover energy through mass burn or Refuse Derived Fuel (RDF) practices. Byproducts of thermal processing of solid waste include combustion gases, bottom and fly ash residues, and recoverable materials such as ferrous and nonferrous metals. Management approaches for ashes from WTE facilities include disposal in monofills, co-disposal with non-combusted MSW in landfills, or incorporation with other materials for various construction applications. Typically, MSW landfills are permitted to receive a combination of MSW, fly and bottom ash from combustion processes, residuals from waste and wastewater treatment facilities, construction wastes, and other materials (USEPA, 2004).

2.1. Leachate characteristics

Leachate is generated as a result of reactions between water percolating through the landfill and wastes. Waste consolidation and pressure differentials promote the migration of leachate through the landfill layers. Dissolved and suspended materials in leachates are composed of varying concentrations of organic carbon, ammonia, chloride, iron, sodium, potassium, carbonates, and other constituents (Levine and Kroemer, 1989; Tchobanoglous et al. 1993). The quality and quantity of leachate generated in a landfill is influenced by waste characteristics, local precipitation patterns, landfill age and location, and other site specific variables (Peeling et at. 1999). Movement of liquid through the waste layers and collection systems can promote microbial activity which, coupled with chemical reactions, has the potential to produce mineral precipitates. Representative data on the characteristics of landfill leachates are reported in Table 12.

Table 12. Representative Data on the Characteristics of Landfill Leachate.

Parameter	Units	Bagchi (1990)	Tchobanoglous et al. (1993)	Kjeldsen et al. (2002)	Levine et al. (2005)
General					
pH	pH units	3.7 – 8.9	4.5 – 7.5	4.5 – 9.0	5.8 – 7.8
Phosphorus, Total	mg/L PO_4	BDL – 234	5 – 100	0.1 – 23.0	n/a
Solids, Total	mg/L	586 – 195,900	n/a	2,000 – 60,000	1,200 – 88,000
Biological related					
Alkalinity, Total	mg/L as $CaCO_3$	BDL – 15,050	1,000 – 10,000	n/a	350 – 9,500
Organic Carbon, Total	mg/L TOC	BDL – 195,000	1,500 – 20,000	30 – 29,000	n/a
Anions					
Chloride	mg/L Cl	2 – 11,375	200 – 3,000	150 – 4,500	300 – 45,000
Sulfate	mg/L SO_4	BDL – 1,850	50 – 1,000	8 – 7,750	BDL – 1,000
Cations					
Calcium	mg/L Ca	3 – 2,500	200 – 3,000	10 – 7,200	210 – 11,000
Copper	mg/L Cu	BDL – 9.0	n/a	0.005 – 10.0	n/a
Iron	mg/L Fe	BDL – 4,000	50 – 1,200	3.0 – 5,500	1 - 900
Magnesium	mg/L Mg	4 – 780	50 – 1,500	30 – 15,000	6.8 – 1,400
Manganese	mg/L Mn	BDL – 400	n/a	0.03 – 1,400	n/a
Potassium	mg/L K	BDL – 3,200	200 – 1,000	50 – 3,700	46 – 9,000
Sodium	mg/L Na	12 – 6,010	200 – 2,500	70 – 7,700	66 – 67,000
Zinc	mg/L Zn	BDL - 731	n/a	0.03 – 1,000	n/a

BDL = Below Detection Limit; n/a = not available

Laboratory and field studies on clogging of leachate collection systems have identified calcium carbonate to be the dominant component of the clog material (Rowe at al. 2000b; Cooke et al. 2001). It has been postulated that a mixed community of facultative anaerobes, iron-related bacteria, sulfate-reducing bacteria, slime formers, and enterics may act as catalysts for calcite nucleation and precipitate formation (Rowe et al. 2000a; Maliva et al. 2000; Kylefors et al. 2003). The structural integrity of the clog material is influenced by precipitation of low solubility carbonate and sulfate minerals (Fleming et al. 1999). Biological activity influence redox potential, pH, and temperature, which can impact the rate and extent of biological degradation and chemical equilibrium solubility.

2.2. Lysimeter studies

In addition to observations from active landfills, laboratory lysimeter studies have been used to assess the clogging process. Lysimeters are reactors that can be used to simulate landfill reactions and to assess the variability of leachate composition under different controlled conditions. In these tests, wastes are placed in column reactors for an extended period of time allowing for direct comparison of leachate properties. Lysimeter design parameters from published studies are compared in Table 13.

Lysimeter studies have reported that clogging rates under anaerobic conditions are highly sensitive to the particle size of the drainage material, and that drains subjected to alternating periods of saturation and unsaturation tend to be clogged more extensively (Paksy et al. 1998). Based on these studies, it has been suggested to avoid drainage material consisting of sand or gravel with a nominal particle size less than 10 mm.

Table 13. Design Parameters Used in Lysimeters Studies.

Lysimeter Geometry and Size	Lysimeter Structure	Packing Material	Reference
Column: Diameter: 50 mm Height: 700 mm	PVC: Schedule 40	6-mm diameter glass beads	Rowe et al. (2002)
Box: Width: 250 mm Length: 600 mm Height: 700 mm	PVC	Drainage blanket: clear stone MSW: 5-10 yr old waste Geotextile: separating MSW from drainage blanket	Fleming et al. (1999)
Box: Width: 1760 mm Length: 1060 mm Height: 1760 mm	Brick and Concrete	Liner: HDPE Drainage layer: 100-mm gravel MSW	Blight et al. (1999)
Column: Diameter: 230 mm Height: 900 mm	MDPE/HDPE	Drainage layer: limestone/Thames gravel MSW: 4-5 yr old waste	Paksy et al. (1998)

Lysimeter tests have also been used to compare calcium removal and COD consumption in landfill leachate drainage systems (Cooke et al. 2001). They found that calcium levels paralleled COD removal, suggesting that microbial reactions may be involved in precipitation of calcium carbonate. The rate and extent of clogging in drainage layers has also been correlated to mass loading rates (Rowe et al. 2000b). The placement of a geotextile filter/separator between the drainage layer and the overlying waste was reported to decrease the amount of fines and sand sized particles and resulted in less clog material present in the drainage layer as compared to parallel lysimeters without geotextile separation (McIsaac et al. 2000).

3. MATERIALS AND METHODS

In this project, laboratory lysimeters were used to assess the potential for development of mineral deposits in relation to waste composition and flow patterns. The lysimeter design, operation and monitoring methods are summarized in this section.

3.1. Lysimeter design

The lysimeters were designed as cylindrical reactors with a volume of 0.42 m^3 and a surface area of 0.30 m^2. Each of the five lysimeters was constructed using 1.4 m long, 30.5 cm diameter, schedule 40 PVC pipes. Leachate generated in the lysimeters was collected in 32 mm diameter PVC pipe with 9.5 mm diameter perforations, which were spaced at intervals of 15 cm with two staggered rows separated by 120°. The materials surrounding the collection pipes were combinations of gravel, sand, geotextiles, geonet, and liners. Peristaltic pumps and leachate reservoirs were attached to the lysimeters as shown in Figure 2.

The leachate application system consisted of an inverted funnel and a perforated plate as shown in Figure 3. This system helped to limit excessive channeling of the water, and promoted exposure of the entire lysimeter contents to liquid on a regular basis.

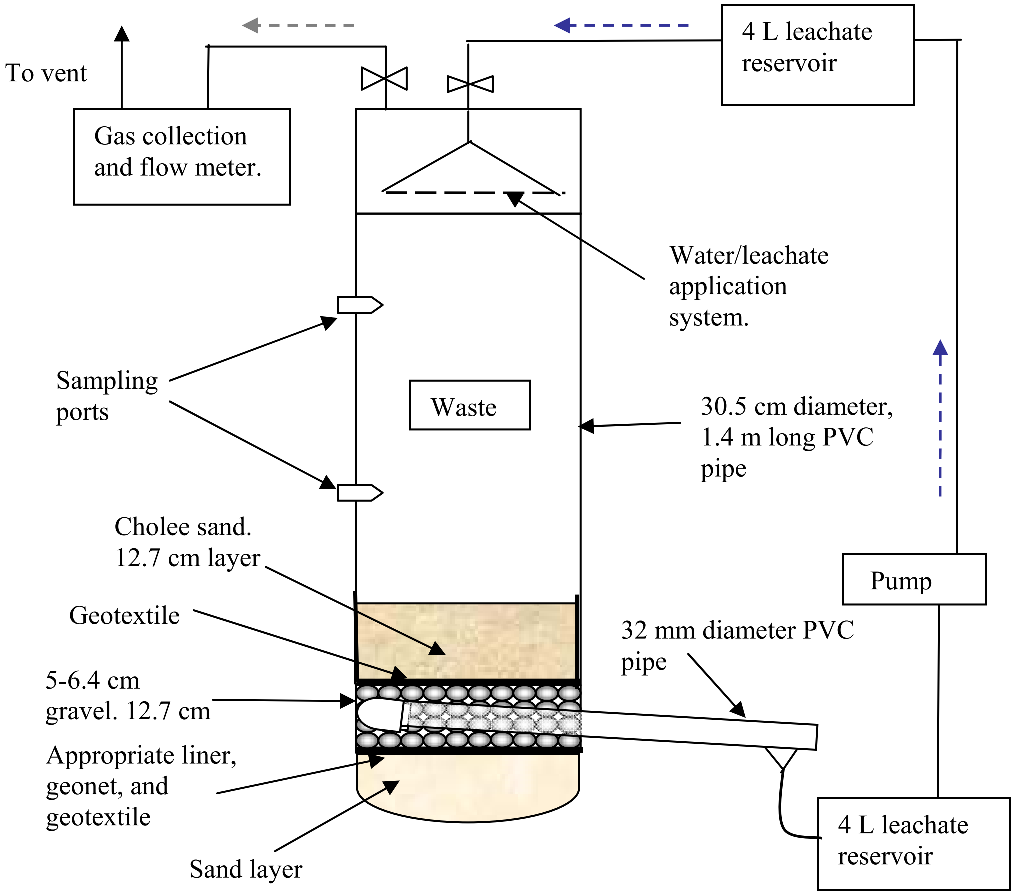


Figure 2. Schematic of Lysimeter Design Used in this Study.

Figure 3. Leachate Application System Consisting of Inverted Funnel and Perforated Plate.

3.2. Composition and distribution of waste in the reactors

The lysimeters included two ash monofills, one MSW monofill (RDF process rejects), and 2 reactors to simulate co-disposal of RDF process rejects, combustion residues, and water and wastewater treatment plant byproducts (chemical sludge and biosolids). The co-disposal reactors (Mixture 1 and Mixture 2) were started up by combining the materials in a 60 L container and manually mixing the contents prior to introduction into the lysimeters. The distribution of waste materials in each lysimeter is shown in Table 14.

Table 14. Composition and Distribution of Waste Sources in the Lysimeters (by Mass).

Lysimeter	MSW	WTE ash		Treatment plant residues	
		Fly ash	Bottom ash	Water treatment	Wastewater treatment
Monofills					
Ash	0%	20%	80%	0%	0%
MSW	100%	0%	0%	0%	0%
Co-disposal	60%	6%	24%	5%	5%

All materials used for this study were obtained in April 2004 from the North County Resource Recovery Facility in Palm Beach County, FL. This facility started accepting wastes in 1989 and it was designed with a footprint of 1.35 km^2 (334 acres). The landfill accepts ash and residues from a WTE Plant that burns RDF, unprocessed MSW, wastewater and water treatment residuals, dead animals, and other non-hazardous wastes as defined by their by Solid Waste Authority’s Household Hazardous Waste Facility.

After emplacement of the wastes, distilled water was applied to each lysimeter to saturate the wastes to field capacity. A measured quantity of water was slowly added to the top of each lysimeter until the wastes were completely submerged. The lysimeters were then covered and allowed to absorb the water for a 72 hour period. Following the absorption period, excess water was drained and the volume recovered was measured. The difference between the amount of distilled water added and the amount of water recovered was considered to be the net field capacity of each lysimeter, equal to the water absorbed by the wastes to reach saturation. The estimated liquid to solid ratios needed to reach field capacity for each type of lysimeter are shown in Table 15.

Table 15. Field Capacity of Each Type of Lysimeter.

Lysimeter	Volume added (L)	Volume recovered (L)	Volume absorbed (L)	Liquid/Solid ratio (g/g)
Monofills				
Ash	40	24	16	0.09
MSW	70	52	18	0.13
Co-disposal	50	33	17	0.11

3.3. Lysimeter operation and monitoring

After reaching field capacity, an additional four liters of distilled water were applied to each lysimeter to generate leachate and initiate waste degradation. Every 24 hours, three liters of leachate was pumped from the lower to the upper reservoir and applied to each lysimeter through the leachate application system, simulating a rain event of 15 to 20 minutes. This mode of operation was intended to provide alternating cycles of flooding and draining within each lysimeter in an effort to accelerate the leaching reactions and provide adequate moisture for biological activity.

Leachate characteristics were monitored to identify dominant electron acceptors, redox conditions, dissolved mineral contents, and buffer capacities. Samples were collected routinely over a seven month period and analyzed for the parameters listed in Table 16. The volume of leachate that was withdrawn for each sampling event was replaced with an equal amount of distilled water to maintain a constant volume of liquid within the lysimeter.

3.4. Microbiological testing

Microbiological testing involved monitoring the concentration of bacteria once per week using a staining technique. 10 mL of sample was obtained from each lysimeter and filtered. The filters were stained using the 4, 6-diamidino-2-phenylindole (DAPI) stain, which binds to the DNA of cells and makes them appear blue under a fluorescence microscope. This technique measures the total number of bacteria per unit volume, but does not indicate viability.

Table 16. Summary of the Chemical Test Performed on the Leachate Samples.

Test	Method^{A}	Instrument	Detection Limits
General			
Conductivity^{T}	2510 B. Laboratory Method	inoLab conductivity meter	1 µS/cm
ORP^{T}	2580 B. Electrometric Method	Hach ORP probe	1 mV
pH^{T}	4500-H+ B. Electrometric Method	Fisher Scientific AR50 pH meter	0.01
Solids (TS, TVS)^{O}	2540 B. Total Solids and 2540 E. Total Volatile Solids	AG245 Mettler Toledo and Fisher Scientific Isotemp® Muffle	6.0 mg/L
Temperature^{T}	2550 B. Laboratory Method	inoLab temperature probe	0.1 °C
Nutrients^{O}			
Nitrogen, Total	4500-N C. Persulfate Method	Hach DR/4000U Spectrophotometer	0.2 mg/L
Phosphorus, Total	4500-P C. Vanadomolybdophosphoric Acid Colorimetric Method	Hach DR/4000U Spectrophotometer	0.2 mg/L
Biological related			
Alkalinity, Total^{T}	2320 B. Titration Method	Burette	20 mg/L as $CaCO_3$
Organic Carbon, Total^{O}	5310 C. Persulfate - Ultraviolet Method	Sievers 800 Portable TOC Analyzer	0.1 mg/L
Volatile Acids^{T}	DiLallo and Albertson (1961). Dual Titration Method	Burette	10 mg/L as acetic acid
Anions^{O}			
Chloride	4140 B. Capillary Ion Electrophoresis with indirect UV Detection	Beckman P/ACE System 5500 Capillary Electrophoresis	0.1 mg/L
Sulfate			
Cations^{O}			
Calcium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer AAnalyst 100 Atomic Absorption Spectrometer	0.01 mg/L
Iron			
Magnesium			
Potassium			
Sodium			

^{A} All methods from Standard Methods 20th edition (1998).
^{T} Twice per week sampling frequency.
^{O} Once per week sampling frequency

4. RESULTS AND DISCUSSION

To facilitate comparison of all data, the lysimeters were categorized either as monofills or mixtures as defined in Table 13. The monofills include the ash monofills

(Ash 1 and Ash 2) and the MSW monofill (MSW); the mixtures include the lysimeters simulating co-disposal of MSW, ash, and treatment plant residues (Mixture 1 and Mixture 2). The focus of this paper is to compare factors that influence precipitate formation including pH, alkalinity, the concentrations of dissolved minerals, carbonate, and the presence/absence of biological activity.

4.1. pH and Alkalinity

The leachates generated from the ash monofill lysimeters were relatively clear and free of particles, biomass and were significantly different from the other leachates in terms of pH and alkalinity. As shown in Figure 4, the pH associated with the ash lysimeters was significantly higher (t-test p value of 0.62) than the pH of leachates from the MSW or the co-disposal lysimeters; the high pH levels may have inhibited biological activity in the lysimeters containing WTE combustion residues.

Alkalinity levels in leachates from ash dominated lysimeters were fairly consistent, whereas alkalinity levels decreased with time in leachates from MSW dominated lysimeters at a rate of about 9 to 18 mg/L-day for the MSW monofill and 4 to 9 mg/L-day for leachates from lysimeters containing mixtures. All alkalinity levels converged at approximately 2000 mg/L as $CaCO_3$ under steady-state conditions, but the composition of the alkalinity varied for each group of reactors. The carbonate alkalinity of the leachates from ash lysimeters was only 10% of the total alkalinity, whereas the carbonate fraction of the total alkalinity for the MSW monofill and mixtures leachates ranged from 75 to 95%.

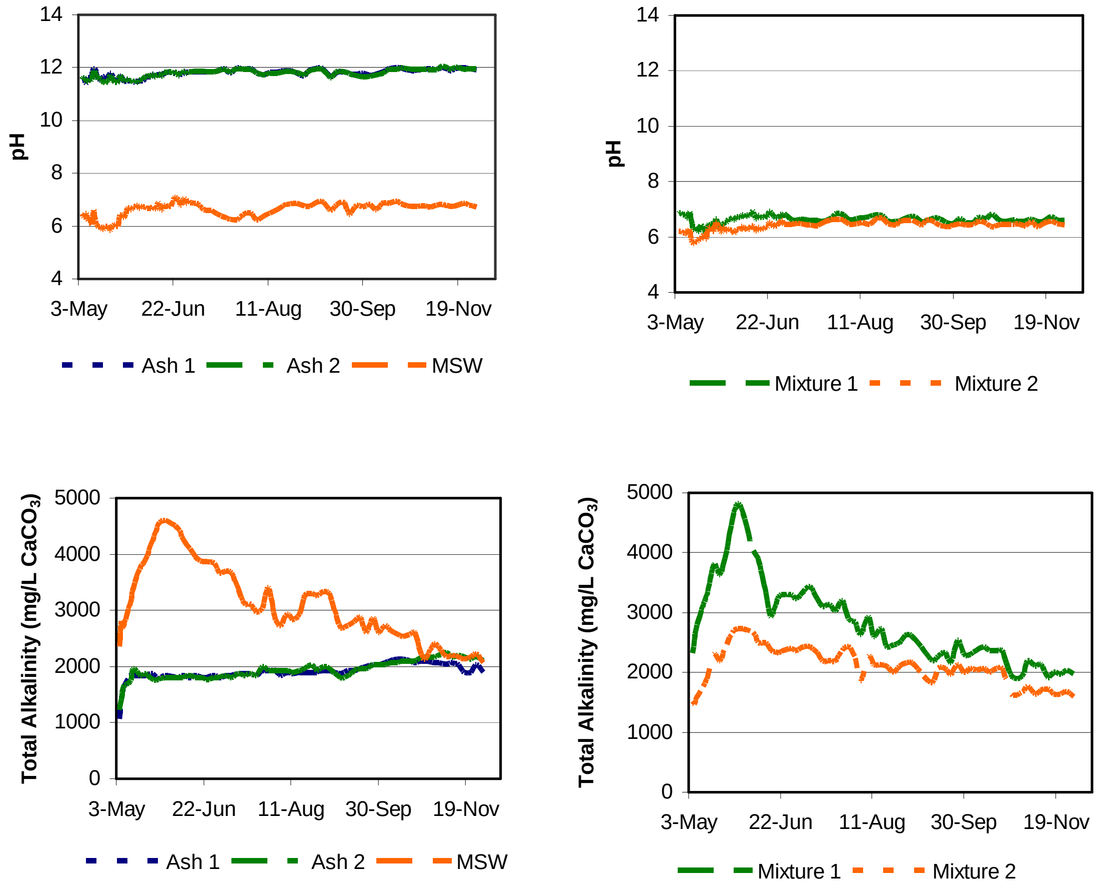


Figure 4. Comparison of the pH and Alkalinity in Leachates from Lysimeters Containing Monofills or Co-disposal.

4.2. Total Volatile Solids and Total Dissolved Solids

The Total Volatile Solids (TVS) can be used as an estimate of the organic content of the leachates, while the concentration of Total Dissolved Solids (TDS) provides an estimate of the amount of minerals available for formation of precipitates and the ionic strength of the leachate. A comparison of the concentrations of total volatile and dissolved solids in leachates from the lysimeters is shown in Figure 5. As shown, the TVS content of the MSW monofill leachate was four to six times higher than the TVS content of the leachate from ash monofills, particularly during the first few months of operation. The volatile fraction of the co-disposal leachates tended to be higher than the MSW monofill fraction most likely due to contributions of the wastewater treatment byproducts.

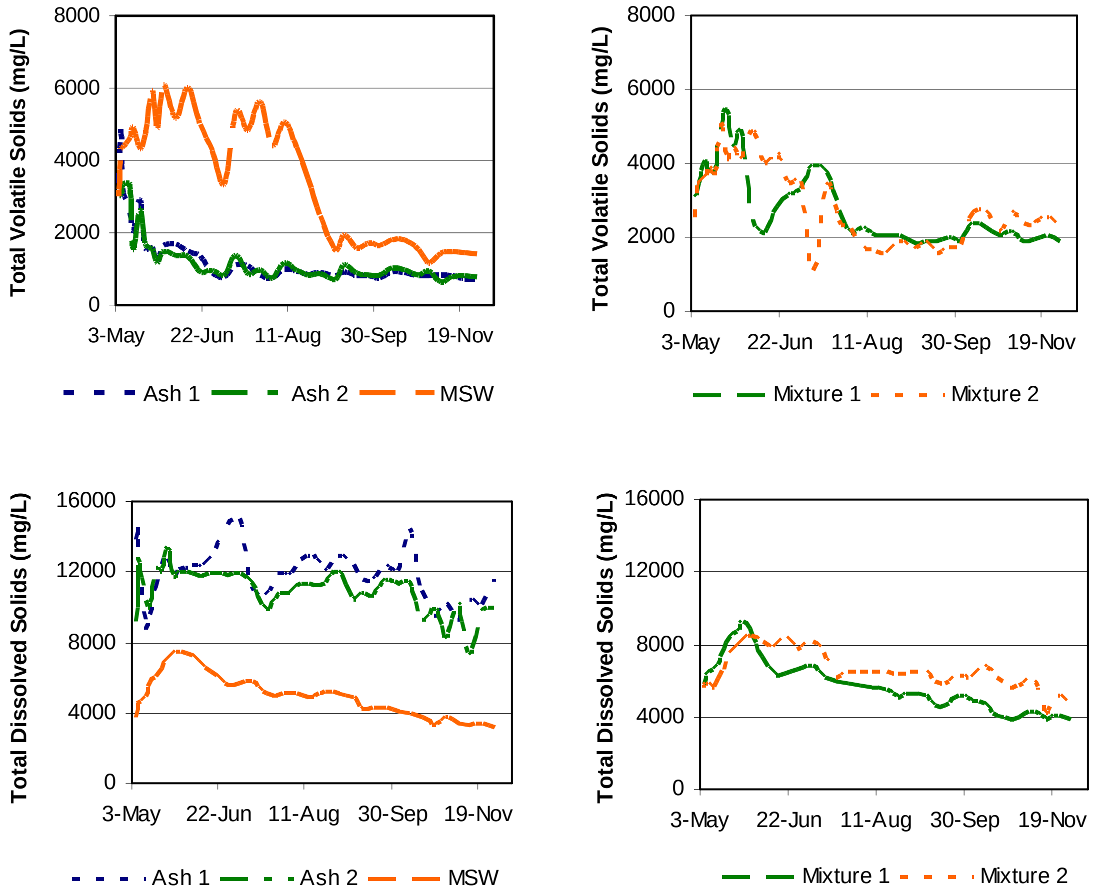


Figure 5. Comparison of the Concentration of Total Volatile and Dissolved Solids in Leachates from Lysimeters Containing Monofills or Co-disposal.

Conversely, the TDS content of leachates derived from the ash monofills was two to three times higher than the TDS from the MSW monofill leachate, due to the higher mineral content of the ashes. Typically, the solids concentrations in the co-disposal leachates reflected the relative quantity of ash (30%) and MSW (60%) within each lysimeter.

4.3. Volatile Acids and Microbial Concentrations

The degradation of organic matter in landfills is a sequential process initiated by hydrolysis of complex organic matter into simple carbohydrates, amino acids, and fatty acids. The simple carbohydrates and acids provide energy for growth by fermenting bacteria, producing volatile acids and hydrogen. The volatile acids are then partially oxidized to produce additional hydrogen and acetic acid, which are the main substrates used by methanogens to produce methane (Tchobanoglous et al. 1993). The volatile acids concentration therefore can be used as a key indicator of microbial activity. Volatile acids and microbial concentrations are shown in Figure 6.

The concentrations of volatile acids in leachates from the MSW monofill lysimeter were significant higher than the concentrations associated with leachates from the co-disposal lysimeters, especially during the first few months of operation, when concentrations up to 1,000 mg/L as acetic acid were observed. The accumulation of volatile acids suggested that it took longer for the methanogenic population to develop in the MSW monofill than in the co-disposal lysimeters, which contained biosolids that may have provided a more diverse microbial population. The volatile acids levels within leachates from the ash monofill lysimeters were almost negligible and constant during the entire experimental period, suggesting the lack of microbial populations in that environment.

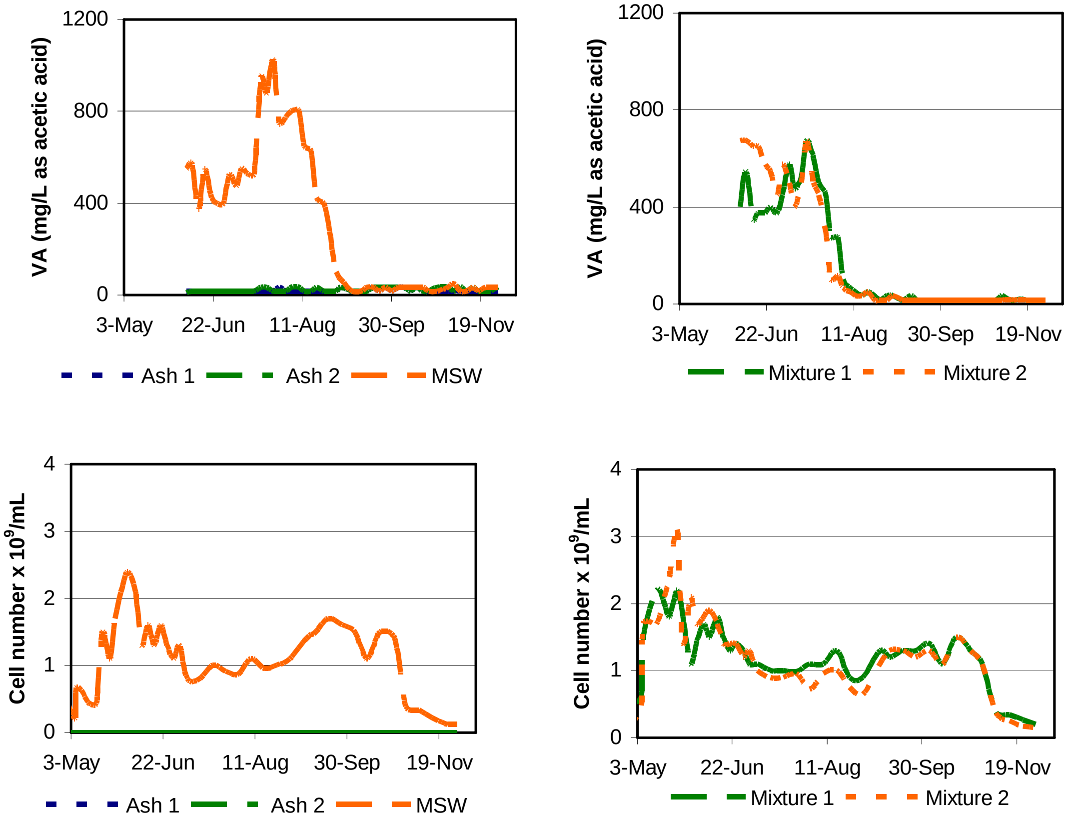


Figure 6. Comparison of Volatile Acids and Microbial Concentrations in Leachates from Lysimeter Containing Monofills or Co-disposal.

The highest microbial concentrations in the lysimeter leachates were associated with the co-disposal of MSW, ash and treatment plant byproducts. Microbial concentrations in the leachates from the ash monofill lysimeters (Ash 1 and Ash 2) were below detection limits as determined by DAPI staining. During the first month of operation, the DAPI cell count in the leachates obtained from the other lysimeters increased consistently. After about a month, the cell numbers in these leachates started decreasing and then the counts appeared to stabilize suggesting the emergence of a stable population of microorganisms as the readily degradable material was consumed.

4.3. Calcium, Calcium/Alkalinity Ratio, and Calcium/TDS Ratio.

Because calcium carbonate has been reported to be the most common precipitate to form in leachate collection systems (Jefferies and Bath, 1999; Manning and Robinson, 1999; Reinhart and Townsend, 1998), examination of the ratio of calcium to alkalinity can provide some insight into the overall stability of the leachate. A relatively high ratio of calcium to alkalinity suggests that the formation of precipitates is limited by the availability of carbonate. Leachates with these characteristics may be susceptible to forming precipitates under conditions that favor biological activity or promote exposure of the leachate to atmospheric carbon dioxide (Bagchi, 1990).

A comparison of calcium concentrations of the leachates from the lysimeters is shown in Figure 7. Calcium levels ranged from about 350 to over 4,000 mg/L. There was a trend of decreasing calcium concentrations over time in each lysimeter at a rate ranging from 7 to 10 mg/L-day for the monofills (correlation coefficient, R^2, 0.8 to 0.9) and 3 to 5 mg/L-d for the co-disposal.

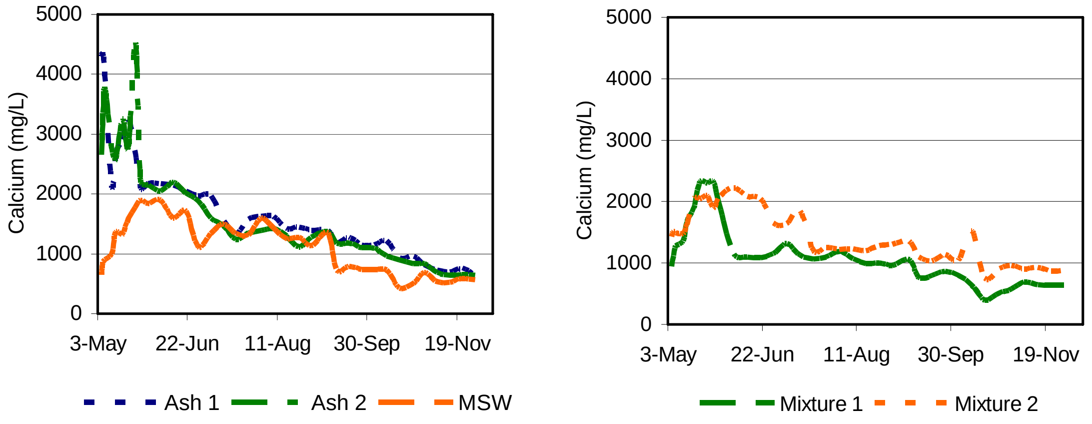


Figure 7. Comparison of the Calcium Concentrations in Leachates from Lysimeters Containing Monofills or Co-disposal.

A comparison of the relationship of calcium to total dissolved solids and calcium to alkalinity is shown in Figure 8. Calcium to TDS ratios tended to be higher for the leachates from lysimeters containing MSW (either monofill or co-disposal), whereas calcium to alkalinity ratios tended to be higher for the ash monofills than for lysimeters containing MSW. These ratios reflect the relative sources of carbonate in the ash dominated lysimeters as compared to the MSW dominated lysimeters. Also, the ratios of calcium to TDS tended to exhibit a more pronounced decrease over time in the ash dominated leachates as compared to the MSW dominated leachates from the co-disposal with the rate of decrease about 0.05% per day (correlation coefficient, R^2, 0.9). Similar trends were observed for the calcium to alkalinity ratios with the rate of decrease about 0.004 mg calcium per mg alkalinity per day.

4.4. Development of solid deposits.

After about 4 months of lysimeter operation, operational problems developed within the leachate management system due to the development of deposits within the leachate collection tubing of MSW dominated lysimeters (monofill and mixtures). No deposits developed in the ash dominated lysimeters. The tubing was replaced and the elemental composition of the deposits was analyzed. Deposits in the MSW monofill tubing tended to contain more biomass and less granular material than did the deposits from the lysimeters containing mixtures of MSW, ash, and treatment plant residuals as shown in Figure 9.

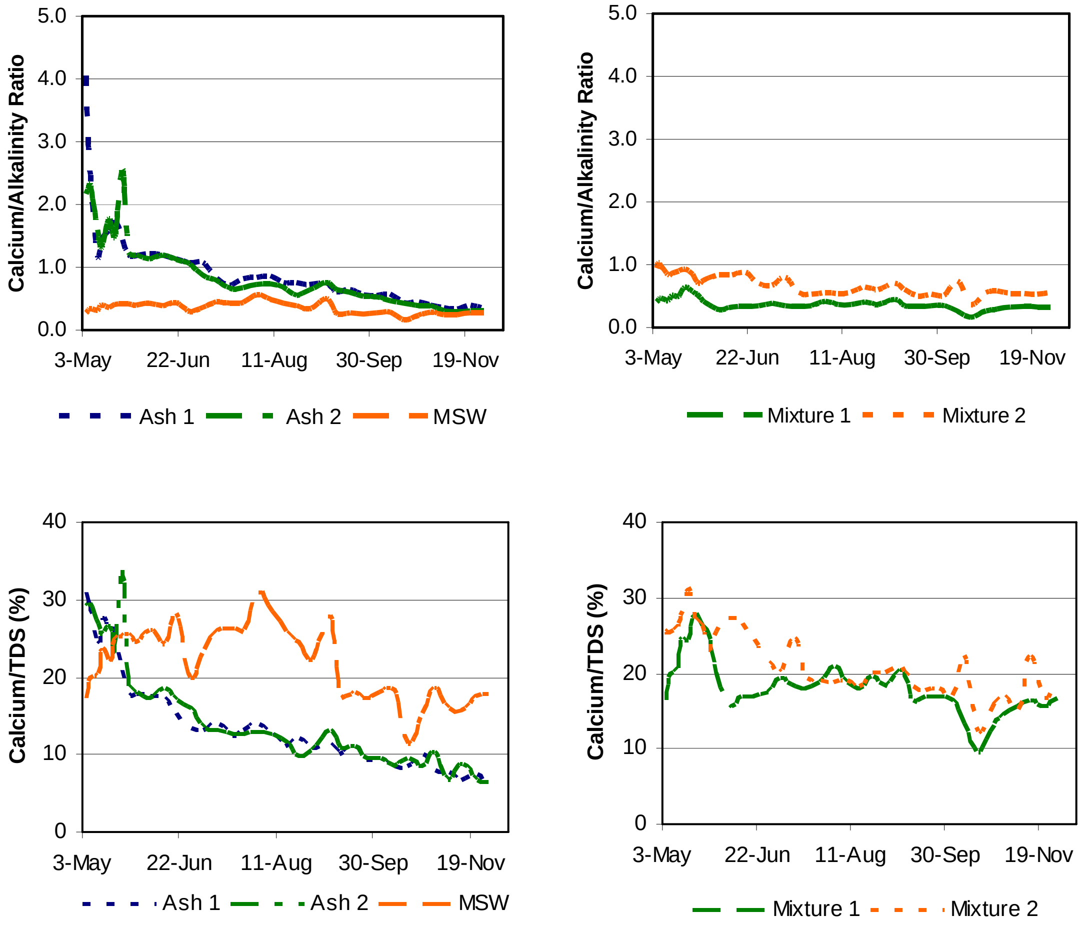
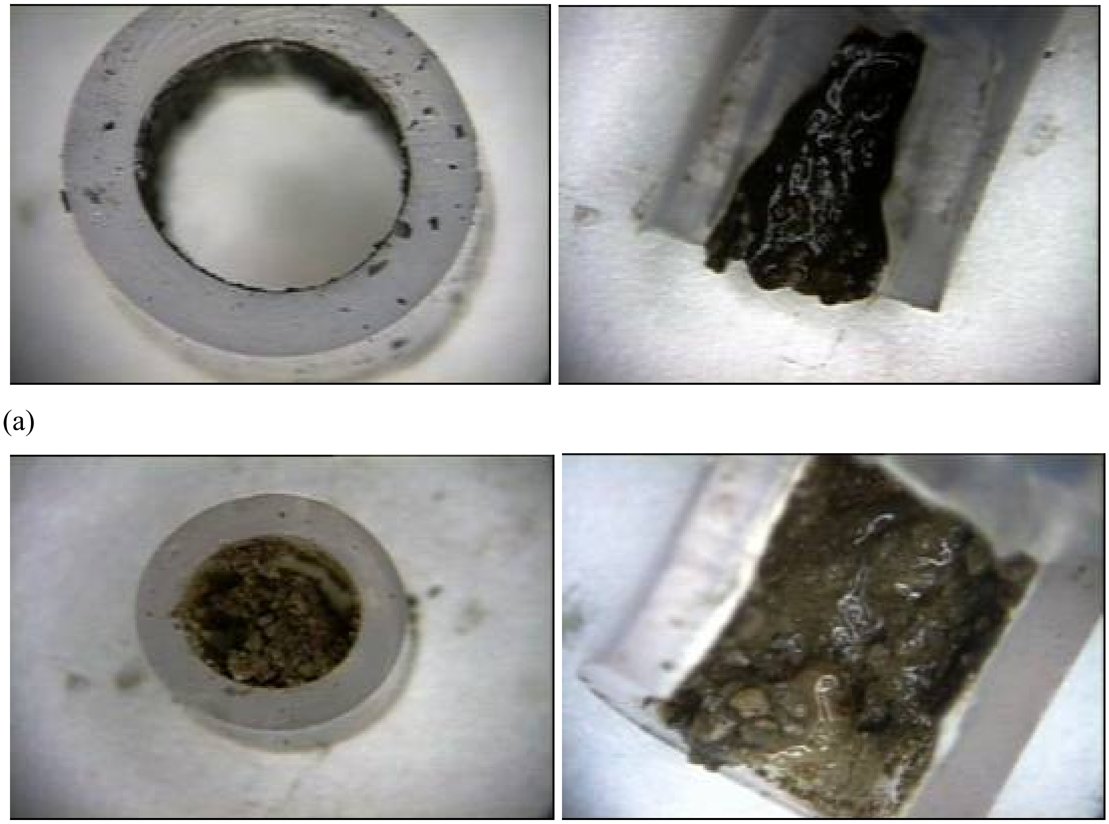


Figure 8. Comparison of the Calcium/Alkalinity and Calcium/TDS Ratios in Leachates from Lysimeters Containing Monofills or Co-disposal.

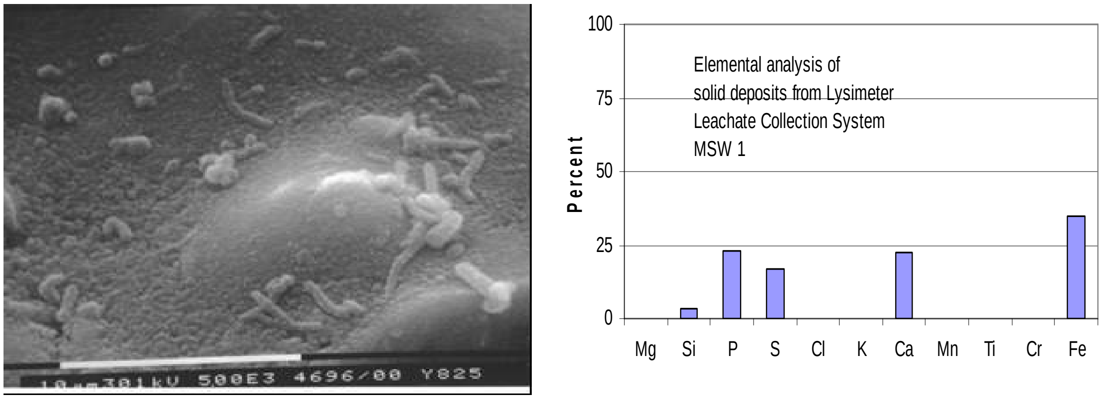


(a)

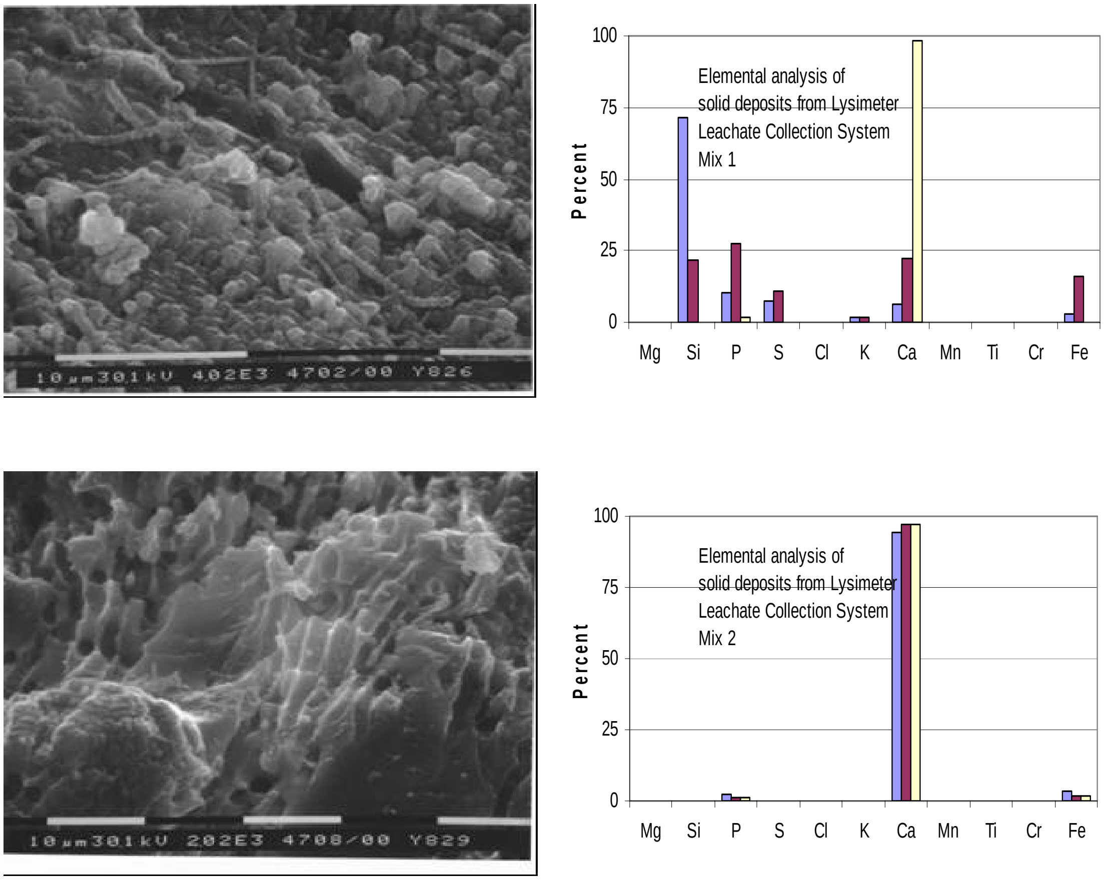
(b)

Figure 9. Photograph of Deposits in Leachate Collection Tubing from a.) MSW Monofill Lysimeter, and b.) Co-disposal Lysimeters. Tubing has an ID of 8 mm and OD of 10 mm.

To provide additional insight into the characteristics of the clogged material in the lysimeter tubing, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were used to analyze the surface characteristics of the deposits. Deposits were preserved using 2.5% glutaraldehyde, dehydrated in ethanol, and sputter coated with carbon. Example electron micrographs and distributions of dominant elements associated with the deposits from lysimeters containing MSW monofill or co-disposal are shown in Figure 10.



(a)



(b)

Figure 10. Scanning Electron Micrographs and Dominant Elements of Deposits in Leaching Collection Tubing from a.) MSW Monofill Lysimeter, and b.) Co-disposal Lysimeters.

The dominant elements associated with the deposits included calcium, silica, phosphorus, sulfur, and iron. The deposit composition varied among the samples, but calcium levels tended to be higher in deposits formed in the lysimeters containing a combination of MSW, ash, and treatment plant residuals as would be expected from the leachate characteristics. There was evidence of bacteria in all of the deposits suggesting that microorganisms play a role in the deposition process.

4.5. Comparison of leachates from lysimeters and landfill leachates

The co-disposal lysimeters in this study were designed to simulate conditions at the North County Resource Recovery Facility landfill in Palm Beach County, FL, and to identify factors that may contribute to the development of deposits within the leachate collection systems. Monitoring data for a four year period from Cell 6 at the Palm Beach landfill was used to compare the characteristics of landfill leachates to laboratory generated leachates which reflected relatively short-term waste degradation conditions.

A comparison of pH, temperature, and the ratios of calcium to TDS and to alkalinity for the leachates from the Palm Beach landfill and leachates from the five lysimeters is shown in Figure 11 in a boxplot format. The boxes represent 50% of the data, the horizontal line represents the median value, and the lines extending above and below the boxes represent the 95% confidence intervals. The relative height of the boxes provides a measure of the degree of variability associated with each measurement.

The pH levels of leachates from the MSW dominated lysimeters and the landfill were not significant different, while significantly higher temperatures were associated with field conditions. The percent of the TDS that consisted of calcium was slightly higher in the lysimeters than the landfill leachates. The calcium to alkalinity ratios were highly variable in the landfill leachate, reflecting changes in biological activity; less variability was observed in the lysimeters, perhaps due to the relatively consistent application of moisture.

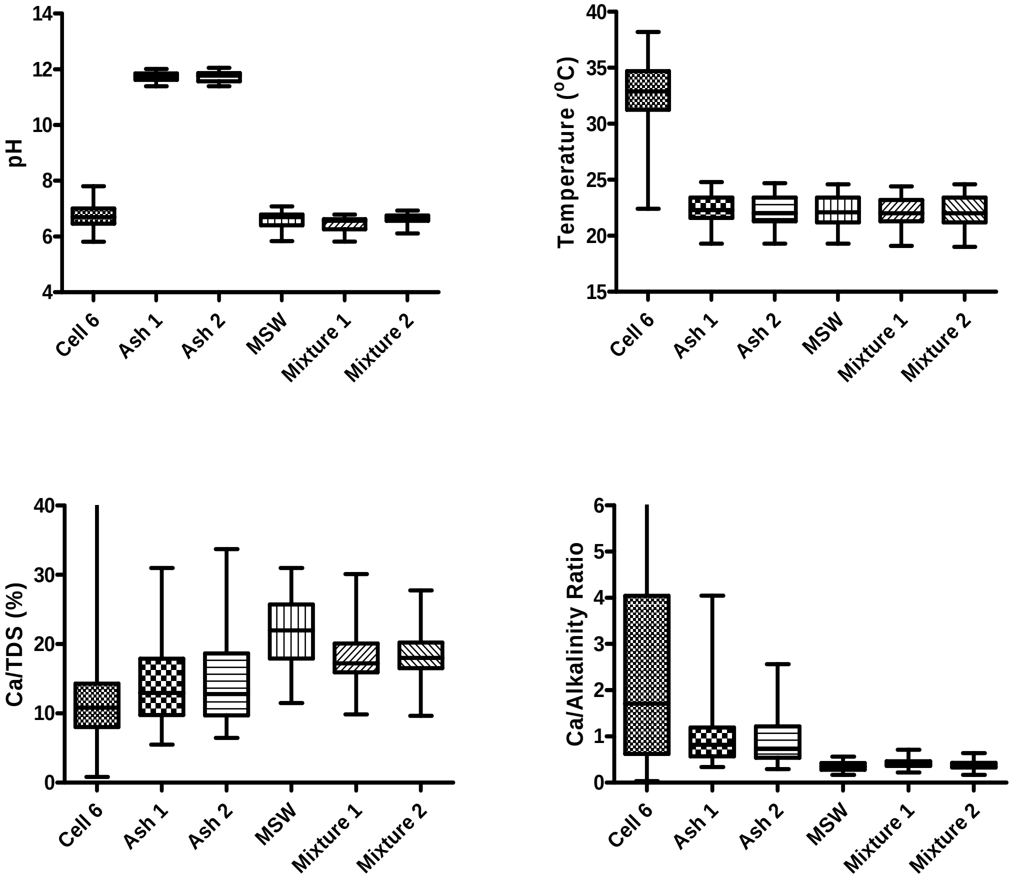


Figure 11. Comparison of pH, Alkalinity, and the Calcium to TDS and Calcium to Alkalinity Ratios from Monitoring Data for Landfill (4 years) and Lysimeters Leachates (7 Months).

5. SUMMARY

Based on operation of laboratory lysimeters for a period of seven months, several trends were observed. Leachates from ash dominated lysimeters tended to have high levels of pH, TDS, and calcium to alkalinity ratios than did MSW dominated leachates.

The higher pH levels inhibited biological activity and the production of volatile acids, while the potential for formation of solid precipitates was modulated by the relatively high ionic strength which can increase the solubility of minerals.

MSW dominated leachates tended to contain higher alkalinity, volatile solids, and calcium to TDS ratios than ash dominated leachates. Leachates from the MSW monofill lysimeter had the lowest calcium to alkalinity ratios, suggesting that the formation of precipitates was not limited by the availability of carbonate but by the sources of available calcium and other minerals. The co-disposal of MSW, combustion residues, and treatment plant byproducts generated leachates with calcium to alkalinity ratios in a higher range than leachates associated with the MSW monofill, but a lower range than that observed in leachates from ash monofill lysimeters. The results from this study suggest that, when MSW is co-disposed with residues from combustion processes and treatment plant byproducts, the contributions from each type of waste produce a more susceptible environment for formation of mineral precipitates, due to the relatively higher quantities of constituents that could co-precipitate.

The chemical composition of leachates from lysimeter tests were within the range of reported values for landfill leachates (Table 1 and Figure 9). Although leachate compositions vary widely depending on moisture content, age of landfill, and the events preceding the time of sampling (Tchobanoglous et al. 1993), laboratory lysimeters provided an effective model system for study of the reactions that might impact clogging of leachate collection systems.

It is important to evaluate the degree to which the lysimeter leachates simulate leachates produced in landfills. Besides the differences in the amount of moisture available for waste degradation and landfill age, different temperature ranges are associated with biologically active landfill as compared to the laboratory environment. Landfill leachate temperatures have been reported to range from 15 to 38 ^{o}C (Figure 9). Laboratory lysimeters were operated at room temperature with typical leachate temperatures ranging from 21 to 30 ^{o}C. Temperature variations can impact mineral solubility, biological growth rates, and reaction kinetics.

6. CONCLUSIONS

This study has provided an opportunity to investigate relationships among waste characteristics, leachate composition, and the potential for clogging. Based upon experimental results obtained during the investigation, the following conclusions can be drawn:

1. Leachates from lysimeters containing actively degrading MSW have higher levels of microbial activity and bicarbonate, but contain lower levels of calcium species than do ash dominated lysimeters. Calcium to alkalinity ratios in leachates from the MSW monofill lysimeter ranged from 0.8 to 0.4.

2. Leachates from ash monofill lysimeters are dominated by high concentrations of dissolved calcium and high pH levels, but contain relatively low levels of carbonates with calcium to alkalinity ratios ranging from 3.8 to 0.5. When the carbonate alkalinity is related to the concentration of calcium in the leachates, these ratios can range from 20 to 4.5.

3. The solids concentrations in leachates derived from the co-disposal lysimeters reflected the relative quantity of ash and MSW within each reactor. Although lysimeters containing MSW either alone or co-disposed with combustion residues generated leachates with higher calcium to TDS ratios, these ratios in leachates from lysimeters containing WTE ash exhibited a more pronounced decrease over time.

4. The use of monofills appears to lead to less clogging of leachate collection systems. For ash monofills, the lower degree of microbial activity in the leachate results in lower concentrations of carbonate species, thus restricting the extent of chemical precipitation, while leachates from MSW monofills contain adequate carbonate, but fewer sources of calcium and other insoluble minerals.

5. Landfills practicing co-disposal of WTE ash and MSW appear to be more susceptible to clogging due to the relative contributions of each waste stream. The WTE ash provides the minerals while the MSW provides biomass, carbonate species, and alternative electron acceptors. Additional inputs of treatment plant residuals can introduce more minerals (water treatment) and more biomass sources (wastewater treatment), further exacerbating the problem.

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ASSESSMENT OF LEACHATES DERIVED FROM LANDFILLING OF WASTE-TO-ENERGY RESIDUES: IMPLICATIONS FOR LEACHATE COLLECTION SYSTEM DESIGN

Antonio J. Cardoso[1]; Lisa R. Rhea[2], and Audrey D. Levine[1]
[1]Department of Civil and Environmental Engineering;
University of South Florida. 4202 East Fowler Ave., Tampa, FL 33620
[2]Jones, Edmunds and Assoc., Inc.
324 S. Hyde Park Ave., Suite 250; Tampa, FL 33606
ajcardos@eng.usf.edu; lrhea@jea.net; Levine@eng.usf.edu

Abstract: Laboratory lysimeters were used in conjunction with batch tests to predict short- and long-term leaching characteristics of un-combusted residues from Waste-to-Energy (WTE) facilities. Two parallel laboratory lysimeters were filled with refuse derived fuel (RDF) combustion residuals (fly ash and bottom ash) and saturated to field capacity using distilled water to simulate rainfall and generate leachate. Leachates were recirculated daily and solubilization of inorganic constituents was assessed over a seven month period. In addition, ash samples obtained from three WTE facilities in Florida (two mass-burn and one RDF) were used in batch tests to assess leaching potential as a function of contact time and liquid to solid ratios. Field leachates and laboratory leachates were similar in chemical composition, although field leachates had higher concentrations of TDS and more neutral pH levels. The tests proved to be useful tools for simulation of field conditions and predicting the degree to which WTE residuals contribute inorganic constituents to the leachate matrix. The role of inorganic constituents leached from WTE residuals in forming precipitates in leachate collection systems is discussed.

Keywords: Batch tests; Leachate collection systems; Lysimeters; WTE combustion residues

1. INTRODUCTION

To reduce the quantity of Municipal Solid Wastes (MSW) requiring landfilling, many municipalities have adopted Waste-to-Energy (WTE) facilities that yield energy in the form of combustible gases and noncombustible residues (fly ash and bottom ash). There are options for using ash residues in different construction applications, but the most common practices for disposal of WTE residuals include landfilling in monofills or co-disposal with MSW and other materials such as residues from water and wastewater treatment facilities (Tchobanoglous and Kreith, 2002; Wiles, 1996)

Due to the potential leaching of contaminants, landfilling of WTE residues may have long-term consequences for the environment. Since properties of WTE residues are very different from those of un-combusted MSW, it is important to understand factors that influence leaching characteristics of wastes for effective management of leachates generated in landfills (Hjelmar, 1996). The purpose of this article is to assess the use of laboratory lysimeters in conjunction with batch tests to predict short-term and long-term leaching characteristics of noncombustible residues from WTE facilities.

2. BACKGROUND

From a technical perspective, the development of strategies for disposal of WTE combustion residues and management of the leachate should be based on extensive knowledge of leaching behaviors. The relative contribution of solubilized minerals from WTE residues in landfill leachates depends on the relative amount of residues that are entombed in landfills in conjunction with the net combustion efficiency, ash handling practices, the net volume of liquid that percolates through the landfill, biological activity, the age of the landfill, whether ashes are disposed in monofills or co-disposed with other material, along with site-specific factors (Kylefors et al., 2003). The short- and long-term leaching and release of contaminants constitute the most important potential environmental problems related to disposal of WTE residues (Johnson et al., 1999).

2.1. Waste-to-Energy residues

Ash residues are produced and discharged at various locations in a WTE facility. Combustion residues vary in composition depending on the source of the combusted material, degree of pre-processing (mass-burn, refuse derived fuel, material recovery), the efficiency of the combustion process, the ash management practices, emission control systems, and the methods of residue collection (Berenyi, 1996; Brereton, 1996; USEPA, 2004). These residues differ in terms of water solubility and the potential of leaching and release of components, which are important properties in relation to landfilling of the residues and management of leachates. In general, WTE residues have low organic contents and the major elements include Al, C, Ca, Cl, Fe, K, Na, and O, while minor elements are Cr, Cu, Mg, Mn, Pb, and Zn (Hjelmar, 1996; Wiles, 1996). Different types of ash and their characteristics are summarized in Table 17.

Over the past several years there has been significant controversy concerning the proper management of the residues from WTE facilities and their regulatory classification as hazardous or non-hazardous waste. It has been suggested that monofill or co-disposal of WTE combustion residues and MSW may lead to sub-optimal management solutions in terms of resource conservation and environmental safety (Hjelmar, 1996). Co-disposal of combustion residues with MSW has the potential to introduce metals, minerals and other non-biodegradable materials to the leachate matrix; the acids generated by decomposing MSW could increase concentrations of soluble toxic metals in the collected leachate (Hasselriis, 2002). WTE ash would provide minerals while MSW would provide biomass, carbonate species, and alternative electron acceptors, resulting in clogging of leachate collection systems due to mineral precipitation (Levine et al., 2005).

Table 17. Summary of Different Types of Ash Residues from a WTE Facility.

Residue	Location	Characteristics
Bottom ash	Material discharged from the bottom of the furnace, primarily the grate, after the waste has progress down the stoker.	Consists of inert residues, glass and metallic objects, 2 to 10% carbon. It is usually quenched with water, although it can also be collected in a dry state.
Stoker grate siftings	Fall through clearances in the grates and are collected with bottom ash.	May include unburned organic matter.
Boiler ash	Carried by combustion gases. It may fall onto the stoker into the bottom ash, or it may be collected in hoppers.	Consists of flying particles and condensable metal vapor which may attach to refractory and water-cooled walls.
Fly ash	Carried by combustion gases through the furnace, boiler, and scrubber. It is collected by the particulate control device.	Reaction products of primarily calcium chlorides and un-reacted lime. Includes volatiles condensed during gas cooling.
Scrubber reaction products	Collected at the bottom of spray-dry or dry lime-injection acid gas scrubbers.	Include fly ash and reacted or partially reacted alkaline reagent (such as lime) and some carbon.
Mixed ash	Various locations from the combustion and emission control equipment.	May contain siftings, bottom ash, boiler and scrubber residues, fly ash, and scrubber products.

2.2. Leachates from Waste-to-Energy residues

Leachates are the longest lasting emission from landfills and the development of strategies for leachate management should be based on knowledge of wastes leaching behavior. Leachate collection systems consist of a series of pipes within a granular drainage blanket with low permeability liners installed below to restrict leachate percolation. It has been reported that in some landfills, solid precipitates deposit in the collection system resulting in clogging and malfunctions of the drainage system. The formation of precipitates is linked to the chemical and biological stability of the leachate generated within the landfill. A comparison of leachate characteristics from ash monofills is given in Table 18.

Table 18. Comparison of Leachate Quality from Ash Monofills.

Parameter	Bagchi (1990)	Cambotti and Roffman (1993)	Hjelmar (1996)	Lundtorp et al. (2003)
pH (pH units)	8.47 – 9.94	5.7 – 7.5	8.7 – 10.5	11.19 – 11.20
Conductivity (mS/cm)	2.5 – 18.7	n/a	1,400 – 3,900	2.4 – 310
Aluminum (mg/L)	2.3 – 88.8	n/a	n/a	0.230 – 0.420
Arsenic (mg/L)	< 0.187	BDL – 0.40	0.005 – 0.025	n/a
Cadmium (mg/L)	0.004 – 0.300	BDL – 0.60	BDL – 0.001	BDL – 3.50
Calcium (mg/L)	n/a	1,300 – 16,000	32 – 1,000	450 – 4,500
Chloride (mg/L)	32.6 – 305.0	n/a	2,400 – 11,400	25 – 390,000
Chromium (mg/L)	< 0.010 – 0.044	BDL – 0.03	BDL – 0.080	0.220 – 0.460
Copper (mg/L)	0.026 – 0.103	BDL – 0.60	BDL – 0.210	BDL – 0.035
Iron (mg/L)	< 0.01 – 0.10	BDL – 32.0	< 0.010 – 0.760	0.020 – 0.054
Lead (mg/L)	0.15 – 0.60	BDL – 0.14	BDL – 0.040	0.008 – 1,600
Magnesium (mg/L)	0.006 – 0.057	n/a	n/a	n/a
Mercury (mg/L)	< 0.0002	BDL	BDL – 0.003	BDL – 0.003
Nickel (mg/L)	0.01 – 0.03	n/a	n/a	0.001 – 0.017
Potassium (mg/L)	3.66 – 79.80	520 – 6,900	600 – 4,300	98 – 85,000
Sodium (mg/L)	11.5 – 48.5	3,000 – 9,300	2,800 – 7,300	800 – 70,000
Sulfate (mg/L)	105 – 1,400	n/a	2,000 – 7,200	n/a
Zinc (mg/L)	0.002 – 0.012	BDL – 1.60	< 0.010 – 0.590	0.016 – 0.068

BDL = Below Detection Limits
n/a = Not Available

WTE combustion residues show systematic leaching patterns that have been evaluated by several researchers (Abbas et al., 2003; Bruder-Hubscher et al., 2002; Hage and Mulder, 2003; Kim et al., 2003; Kim and Batchelor, 2001; Kylefors et al., 2003; Song et al., 2004; van der Sloot, 1998). The most significantly variables which impact solubility, leaching, and release potential of minerals in WTE residues are final pH of the solution, biological activity, redox conditions, ionic strength, complexing inorganic ions and organics, and the liquid-to-solid ratio. The major leachate constituents are salts and hydroxides, while the main salts constituents are chloride, sulfate, calcium, potassium, and sodium (Johnson et al, 1999).

2.3. Leaching tests

Tests that can be used to evaluate the leaching characteristics of WTE residues include field tests, simulator (lysimeter) tests, and batch tests. A comparison of these tests is given in Table 19. The tests differ mainly in duration and the presence or absence of biological activity; the results from these tests can be used to help predict the short- and long-term leaching behavior of noncombustible residues from WTE facilities (Hage and Mulder, 2003).

Table 19. Tests Used to Characterize the Leaching Potential of Landfill Materials.

Category	Description	Advantages	Disadvantages
Field	Monitors leachate characteristics produced by wastes in an established landfill.	Established microbial communities; heterogeneity of waste constituents.	Can take several years; limited access to the reacting materials; inability to determine the contribution of waste constituents to leachate quality.
Simulator	Waste is placed in a column, commonly called a lysimeter, and allowed to react over several months.	Establishment of microbial populations; mimics a landfill; controlled flow of leachant; access to the reacting materials in select locations.	Can take months to complete; inability to determine the contribution of the individual waste constituents to the characteristics of the leachate.
Batch	Select wastes are placed in non-reactive containers with leachant for a specific length of time.	Can be completed in weeks; identification of the contribution of waste constituents to leachate quality.	Missing microbial activity; limited interaction among different types of waste.

In lysimeter tests, wastes are placed in parallel reactors where temperature, moisture content, and the degree of leachate recirculation can be controlled and gas production and leachate composition can be monitored. In addition, the composition of the wastes can be characterized more completely than in a landfill setting. In many ways lysimeters are black boxes, since the ability to determine a direct relationship between individual materials and leachate characteristics is unknown. To determine leaching characteristics of individual wastes, batch tests can be used having as main variables the liquid to solid mass ratio (L/S), the leaching medium, temperature, contact time, and the separation technique.

3. MATERIAL AND METHODS

Laboratory lysimeters and batch tests were used to assess the leaching potential of WTE combustion residues as a function of contact time and liquid to solid ratios. Details on lysimeter design and operation, batch tests, and monitoring methods are summarized in this section.

3.1. Lysimeter design and operation

Two lysimeters were designed as cylindrical reactors with a volume of 0.42 m^3 and a surface area of 0.30 m^2. Each lysimeters was constructed using 1.4 m long, 30.5 cm diameter, schedule 40 PVC pipes. Leachate generated in the lysimeters was collected in 32 mm diameter PVC pipe with 9.5 mm diameter perforations, which were spaced at intervals of 15 cm with two staggered rows separated by 120°. Peristaltic pumps and leachate reservoirs were attached to the lysimeters as shown in Figure 12.

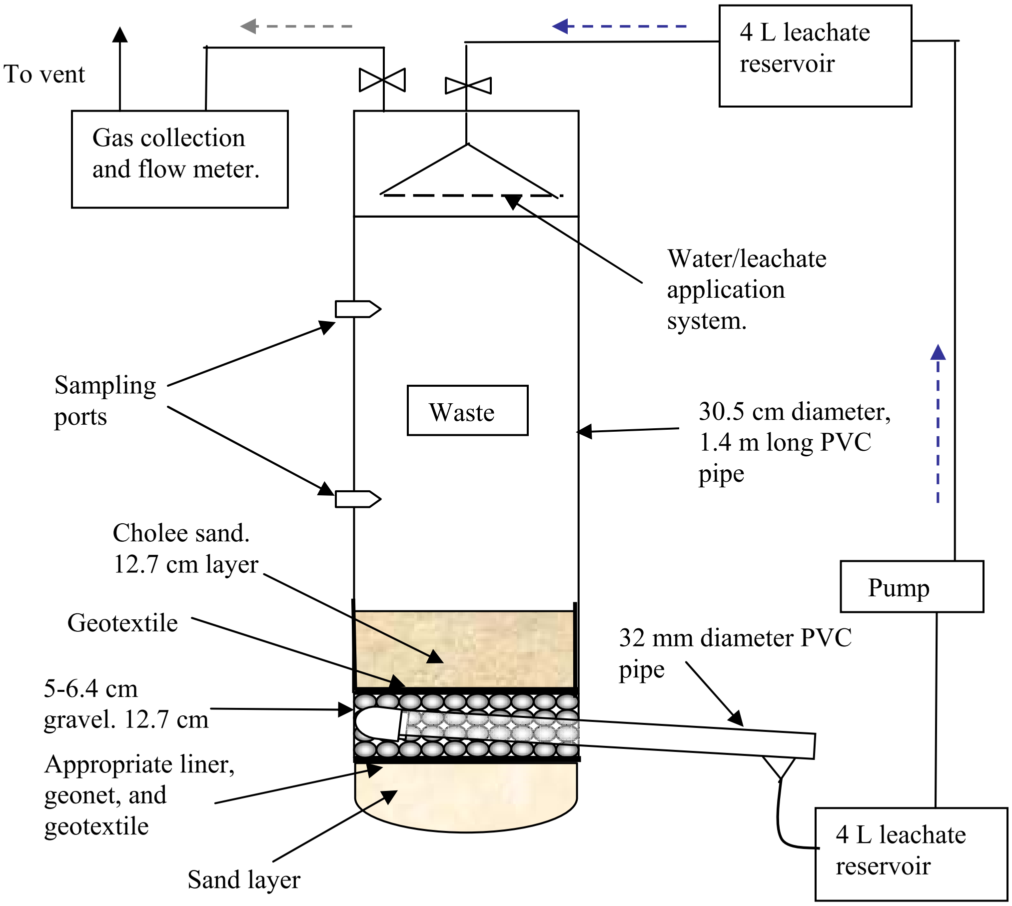


Figure 12. Schematic of Lysimeter Design Used in this Study.

A geonet was placed above the drainage layer and WTE residuals were introduced into each lysimeter above the geonet. The WTE residues were obtained from a Refuse Derived Fuel (RDF) WTE facility (Palm Beach County, FL.). The depth of the WTE layer was about 2.4 ft (0.73 m) and consisted of a mixture of 159 kg (350.54 lbs) of bottom ash and 22 kg (48.5 lbs) of fly ash. The relative amounts of bottom ash (80%) and fly ash (20%) were intended to simulate conditions typical of WTE facilities.

After compacting the WTE residues, the contents of each lysimeter were saturated to field capacity using distilled water. An additional four liters of distilled water was applied to each lysimeter to generate leachate and the lysimeters were capped and sealed. On a daily basis, three liters of leachate was pumped to the upper reservoir and distributed to the top of each lysimeter through a 12 inch horizontal perforated plate designed to simulate a rain event of 15 to 20 minutes. Leachate samples were collected over a seven month period and analyzed as depicted in Table 20. The volume of leachate that was withdrawn for each sampling event was replaced with an equal amount of distilled water to maintain a constant volume of liquid within the lysimeter.

3.2. Batch tests

Two different types of batch tests were used in this project: contact time (CT) and sequential extraction (SE). The CT batch test was used to assess the rate at which different elements reach equilibrium while SE batch tests were developed to predict the net capacity of soluble material to be released from combustion residues based on liquid to solid ratios spanning the range of conditions likely to be encountered over the lifespan of a landfill.

Batch testing methodology was adapted from the Method for Accelerated Leaching of Solidified Waste (Department of Nuclear Energy, 1990) as shown in Figure 13. All tests were conducted using Nalgene amber high-density polyethylene (HDPE) wide mouth bottles. Distilled water was used as a leachant to mimic the chemical composition of rainwater. To simulate internal landfill temperatures, batch tests were incubated at 35°C. Leachates from batch tests were analyzed following the parameters described in Table 20.

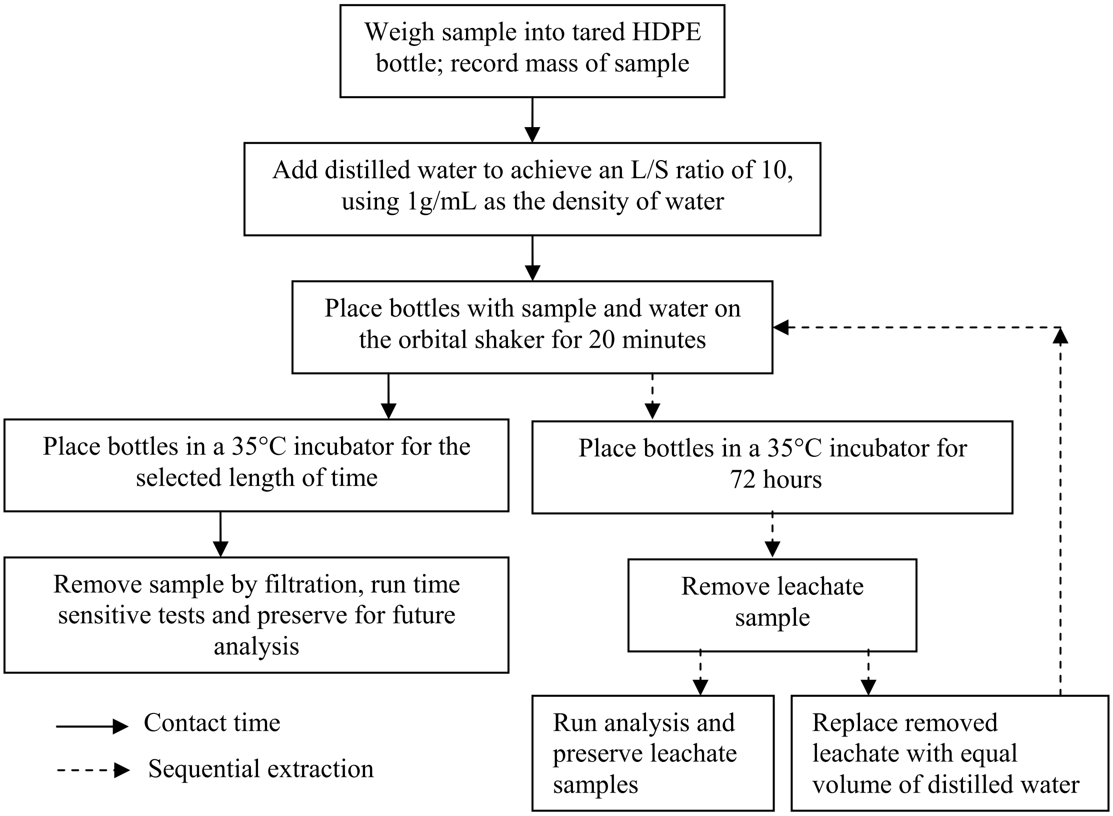


Figure 13. Overview of Contact Time and Sequential Extractions Batch Tests.

The contact time batch test was designed to yield a static view of the interaction between the waste material and the leachant. To insure a broad view of the interaction between combustion residues and leachant, the tests were conducted up to 21 days with three replicates per time interval. On the other hand, the sequential extraction batch test was designed to provide a dynamic view of the interaction between WTE residuals and leachants. The time interval between extractions was set at 72 hours, to allow apparent equilibrium to be reached while providing adequate time to test each sequential step. The duration of the sequential extraction tests was determined by the L/S ratio, which started at 10 g/g and increased with each subsequent extraction until the cumulative ratio reached 100 g/g.

3.3. Analytical Methods and Equipment

Water quality analyses were conducted on the leachate samples to identify dominant electron acceptors, redox conditions, dissolved mineral content, and buffer capacity. Chemical characterization of the leachates from lysimeters, CT, and SE tests were analyzed following the parameters listed in Table 20.

Table 20. Summary of the Chemical Test Performed on the Leachate Samples.

Test	Method[A]	Instrument	Detection Limits
General			
Alkalinity, Total	2320 B. Titration Method	Burette	20 mg/L as $CaCO_3$
Conductivity	2510 B. Laboratory Method	inoLab conductivity meter	1 µS/cm
Organic Carbon, Total	5310 C. Persulfate - Ultraviolet Method	Sievers 800 Portable TOC Analyzer	0.1 mg/L
ORP	2580 B. Electrometric Method	Hach ORP probe	1 mV
pH	4500-H+ B. Electrometric Method	Fisher Scientific AR50 pH meter	0.01
Solids (TS, TDS)	2540 B. Total Solids and 2540 C. Total Dissolved Solids	AG245 Mettler Toledo and Fisher Scientific Isotemp® Muffle	6.0 mg/L
Temperature	2550 B. Laboratory Method	inoLab temperature probe	0.1 °C
Anions			
Chloride	4140 B. Capillary Ion Electrophoresis with indirect UV Detection	Beckman P/ACE System 5500 Capillary Electrophoresis	0.1 mg/L
Sulfate			
Cations			
Calcium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer AAnalyst 100 Atomic Absorption Spectrometer	0.01 mg/L
Iron			
Magnesium			
Potassium			
Sodium			

[A] All methods from Standard Methods 20th edition (1998).

4. RESULTS AND DISCUSSION

A comparison of selected results from the Contact Time (CT) tests and the Sequential Extraction (SE) tests is provided and compared to characteristics of leachates from laboratory lysimeters (Ash 1 and Ash 2) and field samples. Key leachate variables include pH, alkalinity, concentrations of dissolved minerals, and concentrations of calcium in the systems.

4.1. pH and Alkalinity

The leachates generated from lysimeters and batch tests were relatively clear and free of particles and biomass. All samples had relatively high levels of pH regardless of residue source or leachate extraction method, probably due to the presence of $Ca(OH)_2$ and alkali metal hydroxides. The pH associated with leachates from an ash monofill in Florida (mass burn) ranged from 7.0 to 11.0, suggesting that environmental factors and biological activity may have impacted leachate characteristics.

Alkalinity levels in lysimeter leachates were fairly consistent, converging at approximately 2000 mg/L as $CaCO_3$ after seven months of operation. Only 10% of the total alkalinity in the lysimeter leachates was attributed to carbonate alkalinity. Alkalinity levels in batch test leachates varied with the source of the ash. Alkalinity concentrations tended to decrease with increasing liquid to solid ratios in the SE tests and during the first six extractions, alkalinity values decreased by 18% to 83%. After encountering a mass of water equal to 100 times the initial mass of ash, the final alkalinity values were similar to those of typical groundwater ranging from 60 to 110 mg/L as $CaCO_3$. Alkalinity and pH levels for leachates from lysimeters and batch tests are summarized in Table 21.

Table 21. Summary of pH and Alkalinity for Lysimeter and Batch Tests Leachates.

Test	pH		Alkalinity (mg/L as $CaCO_3$)	
	Mean	Range	Mean	Range
Lysimeter[A]				
Ash 1	11.7	11.4 – 12.0	1,872	1,064 – 2,133
Ash 2	11.7	11.4 – 12.1	1,905	1,227 – 2,250
Contact Time (0 – 500 hours)				
Mass burn bottom and fly ash 1	11.7	11.6 – 12.0	1,407	1,057 – 1,590
Mass burn bottom and fly ash 2	11.8	11.7 – 12.0	1,292	850 – 1,557
Bottom ash from RDF	11.6	11.4 – 11.9	613	470 – 667
Fly ash from RDF	11.6	11.4 – 11.7	1,537	1,953 - 1323
Sequential Extraction				
Liquid to Solid Ratio 10 g liquid/g ash				
Mass burn bottom and fly ash 1	11.8	11.8 – 11.8	1,217	1,216 – 1,218
Mass burn bottom and fly ash 2	11.7	11.7– 11.8	1,167	1,163 – 1,171
Bottom ash from RDF	12.1	12.0 – 12.1	637	635 – 639
Fly ash from RDF	11.2	11.1 – 11.2	1,303	1,302 – 1,304
Liquid to Solid Ratio 100 g liquid/g ash				
Mass burn bottom and fly ash 1	10.7	10.7 – 10.7	127	124 – 130
Mass burn bottom and fly ash 2	11.0	11.0 – 11.0	107	105 – 109
Bottom ash from RDF	11.2	11.2 – 11.2	113	110 – 116
Fly ash from RDF	11.5	11.5 – 11.6	390	388 – 393

[A] Seven months of continuous operation

4.2. Total Dissolved Solids

Concentrations of Total Dissolved Solids (TDS) provide an estimate of the amount of minerals available for formation of precipitates and the ionic strength of the leachate. A comparison of the concentrations of TDS in the leachates from the batch tests and the lysimeters is shown in Figure 14. The TDS concentrations in the lysimeter leachates ranged from 10,000 to 15,000 mg/L, reflecting the relative contributions of the bottom and fly ash in the reactors.

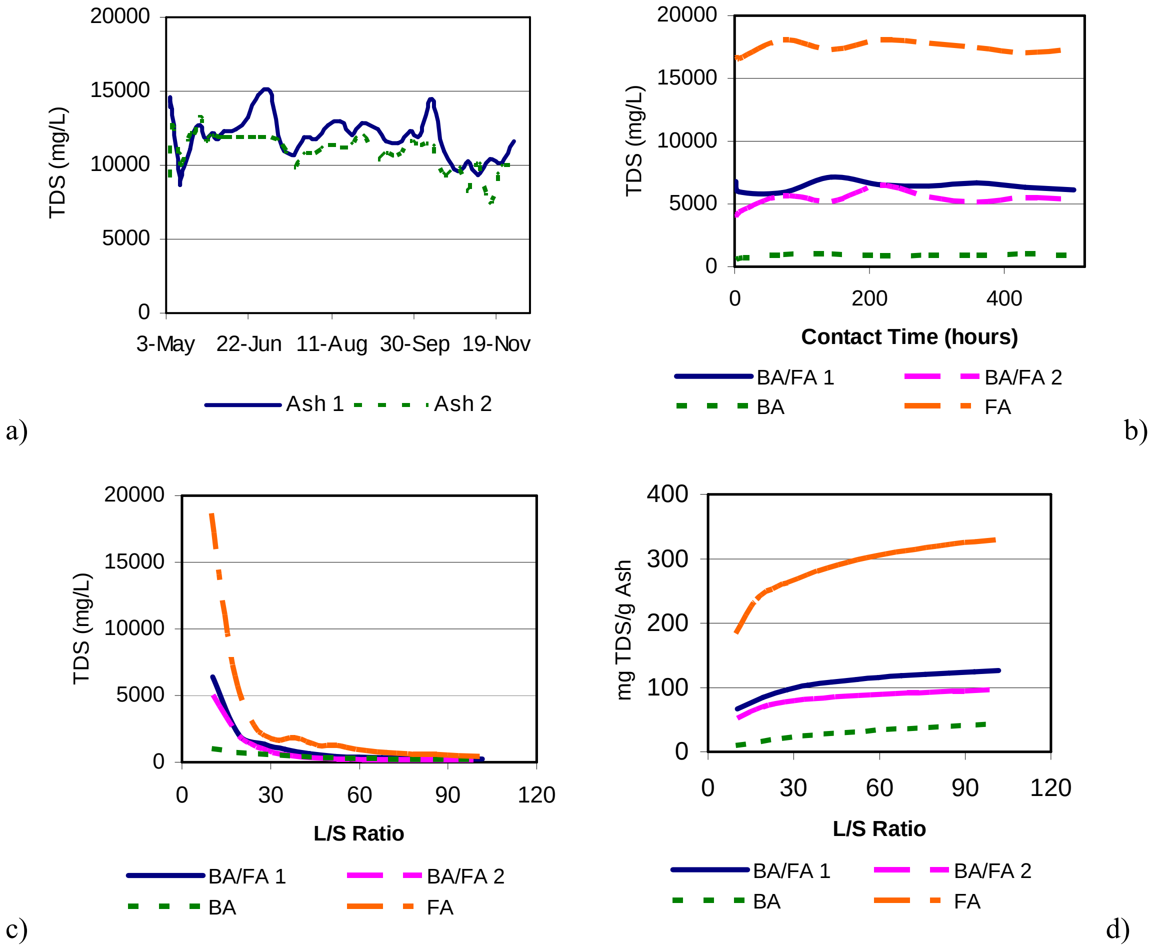


Figure 14. Comparison of TDS Concentrations Leached from Combustion Residues in a) Lysimeters; b) Contact Time Tests; c) Sequential Extraction Tests; and d) mg TDS/g Ash in Sequential Extraction Tests.

In the CT tests, the fly ash yielded about a three fold higher concentration of TDS than did the mixed combustion residues. During the SE test, the greatest decrease in TDS concentration for all samples occurred during the first three extractions, suggesting that the readily soluble ions were washed out of the ash quickly, leaving behind less soluble constituents. Most of the samples had a decrease greater than 80% from the initial TDS values after six or seven extractions.

The mass of solids solubilized from the bottom ash and mixed ashes ranged from 0.35 to 0.55 g TDS/kg of ash per liter of liquid, whereas about a fourfold higher mass of solids was leached from fly ash (about 1.30 g/kg per unit increase in L/S ratio). Even at L/S ratios of 100 g/g, dissolution of solids had not stabilized. The L/S mass ratio of the lysimeters after seven months of operation was about 0.15 g/g. TDS concentrations in field leachate samples ranged from 20,000 to 25,000 mg/L, suggesting higher liquid to solid ratios than the ones attained in lysimeter tests.

4.3. Concentrations of Dissolved Minerals

The dominant ions in the leachates from batch tests and lysimeters were calcium, potassium, sodium, chloride, and sulfate. Sodium, potassium, and chloride ions are readily soluble and not usually found in deposited materials. Since calcium can precipitate with several ions including carbonate, sulfate, and hydroxide, it will be discussed in a different section. A summary of the concentration of the main ions present in leachates from lysimeters, CT, and SE tests is presented in Table 22.

The sodium, potassium and chloride ions are dominant constituents of the TDS in all leachate samples, influencing the ionic strength of the leachate and changing the activities of precipitate-forming ions. It is interesting to note that the concentrations of potassium in leachates from the lysimeters increased at a rate of about 4 mg/L-d (correlation coefficient, R^2, about 0.75). The rate of potassium increase is about 0.25% of the rate of calcium decrease (~0.1 meq/day for potassium and ~0.4 meq/d for calcium) suggesting some type of ion exchange occurring within the solid matrix or the drainage layer. The results for the batch tests followed the same patterns as seen above; the CT tests established equilibrium while the SE tests showed the most important reduction in concentrations during the first six or seven extractions.

Table 22. Summary of Concentrations (mg/L) of Main Ions Present in Leachate Samples.

Test	Cl		SO_4		K		Na	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Lysimeter[A]								
Ash 1	5,150	3,330 – 7,430	72	25 – 123	1,065	350 – 1,500	1,985	808 – 2,502
Ash 2	4,565	1,240 – 8,210	97	25 – 460	950	255 – 1,340	1,865	568 – 2,870
Contact Time[B]								
Mass burn bottom and fly ash 1	2,080	1,805 – 2,615	266	168 – 334	171	150 – 200	404	330 – 456
Mass burn bottom and fly ash 2	1,546	1,230 – 1,856	324	190 – 577	143	110 – 205	265	212 – 342
Bottom ash (RDF)	76	36 – 120	11	4.2 – 18	22	19 – 26	50	43 – 58
Fly ash (RDF)	8,470	7,450 – 9,055	366	71 – 624	1,043	830 – 1,137	1,650	1,378 – 2,350
Sequential Extraction								
L/S Ratio 10 g liquid/g ash								
Mass burn bottom and fly ash 1	2,152	1,984 – 2,300	244	235 – 251	243	238 – 250	446	436 – 480
Mass burn bottom and fly ash 2	1,463	1,188 – 1,710	320	316 – 333	150	133 – 161	256	249 – 263
Bottom ash (RDF)	35	22 – 41	16	12 – 20	52	50 – 55	61	55 – 67
Fly ash (RDF)	7,652	7,590 – 7,900	512	505 – 520	1,164	995 – 1,210	1,834	1,750 – 1,990
L/S Ratio 100 g liquid/g ash								
Mass burn bottom and fly ash 1	3.0	2.6 – 3.5	40	37 – 44	3.2	2.9 – 3.4	1.6	0.9 – 2.2
Mass burn bottom and fly ash 2	2.0	1.9 – 2.2	35	30 – 37	0.1	0.1 – 0.2	0.7	0.2 – 1.5
Bottom ash (RDF)	0.4	0.3 – 0.5	30	28 – 33	0.2	0.1 – 0.2	0.5	0.1 – 1.1
Fly ash (RDF)	15	13 – 18	20	15 – 25	7.0	6.0 – 9.0	0.3	0.2 – 0.3

[A] Seven months of continuous operation.
[B] 0 – 500 hours.

4.4. Calcium Concentrations

Based on analysis of clogged materials from leachate collection systems and on previous studies (Manning and Robinson, 1999; Rowe et al., 2002; VanGulck et al., 2003; VanGulck and Rowe, 2004), it has been established that calcium plays an important role in the formation of precipitates. A comparison of calcium levels observed in leachates from lysimeters and batch tests is shown in Figure 15.

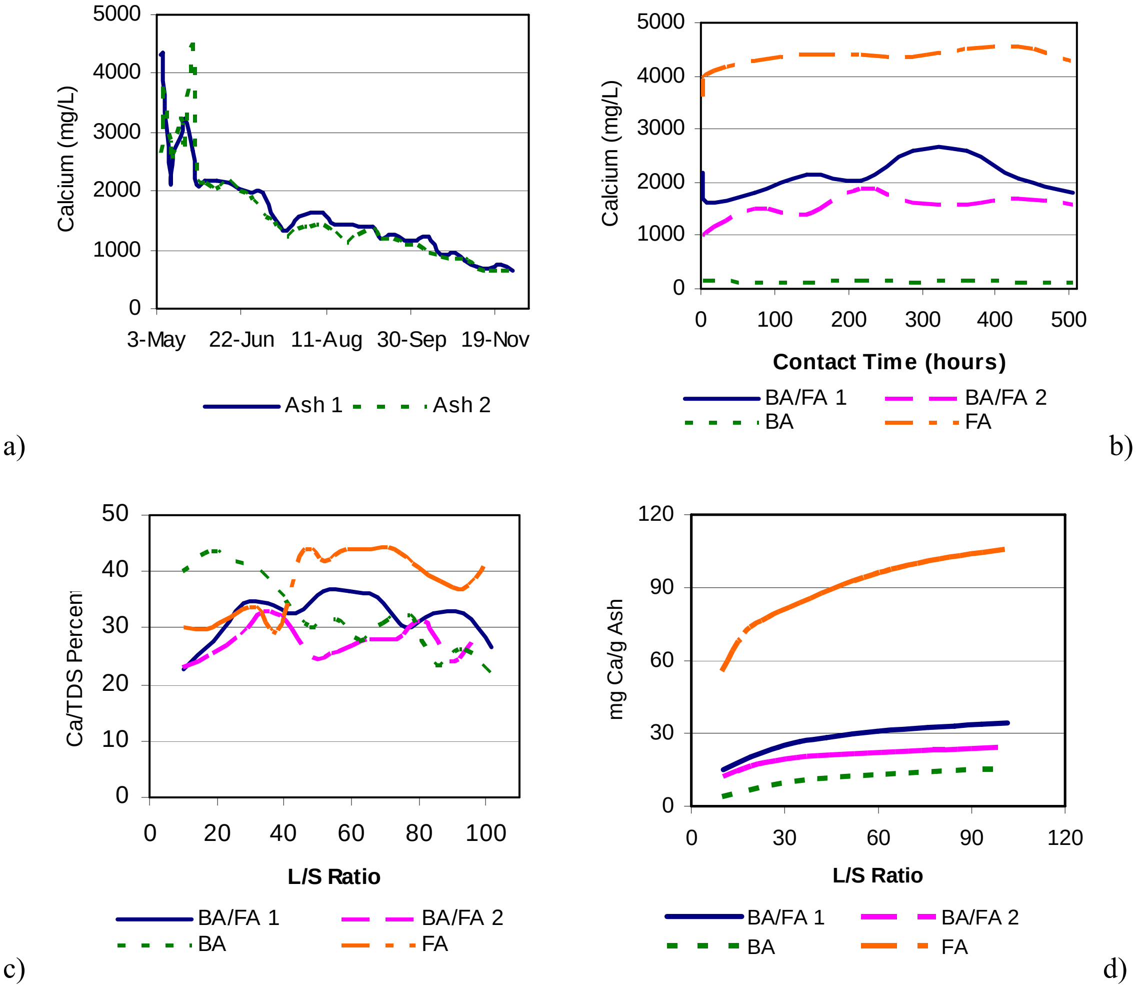


Figure 15. Comparison of Calcium Leached from Combustion Residues in a) Lysimeters; b) Contact Time Tests; c) Ca/TDS Percent in Sequential Extraction Tests; and d) mg Ca/g Ash in Sequential Extraction Tests.

The relative amount of calcium, carbonate, and sulfate in leachates can impact the potential for formation of precipitates; if the molar ratio of calcium to either carbonate or sulfate is greater than one to one, the solution is supersaturated. Further insight into the predictive capability of the batch tests is shown in Figure 16 in terms of saturation indices for calcite and gypsum associated with each of the WTE combustion residues in the CT tests. As shown, the fly ash yields a highly supersaturated solution for both calcite and gypsum, but the degree of supersaturation decreases with contact time for gypsum, perhaps due to the participation of sulfate in other complexing reactions. Leachate derived from bottom ash was unsaturated for calcite and gypsum. These results suggest that further stabilization of fly ash or development of alternative disposal practices may help to reduce the extent of mineral precipitation and clogging of landfill leachate collection systems.

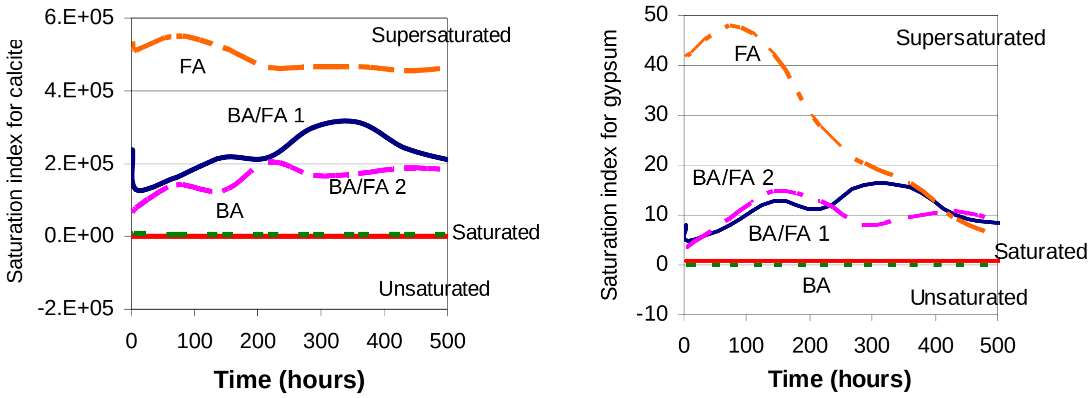
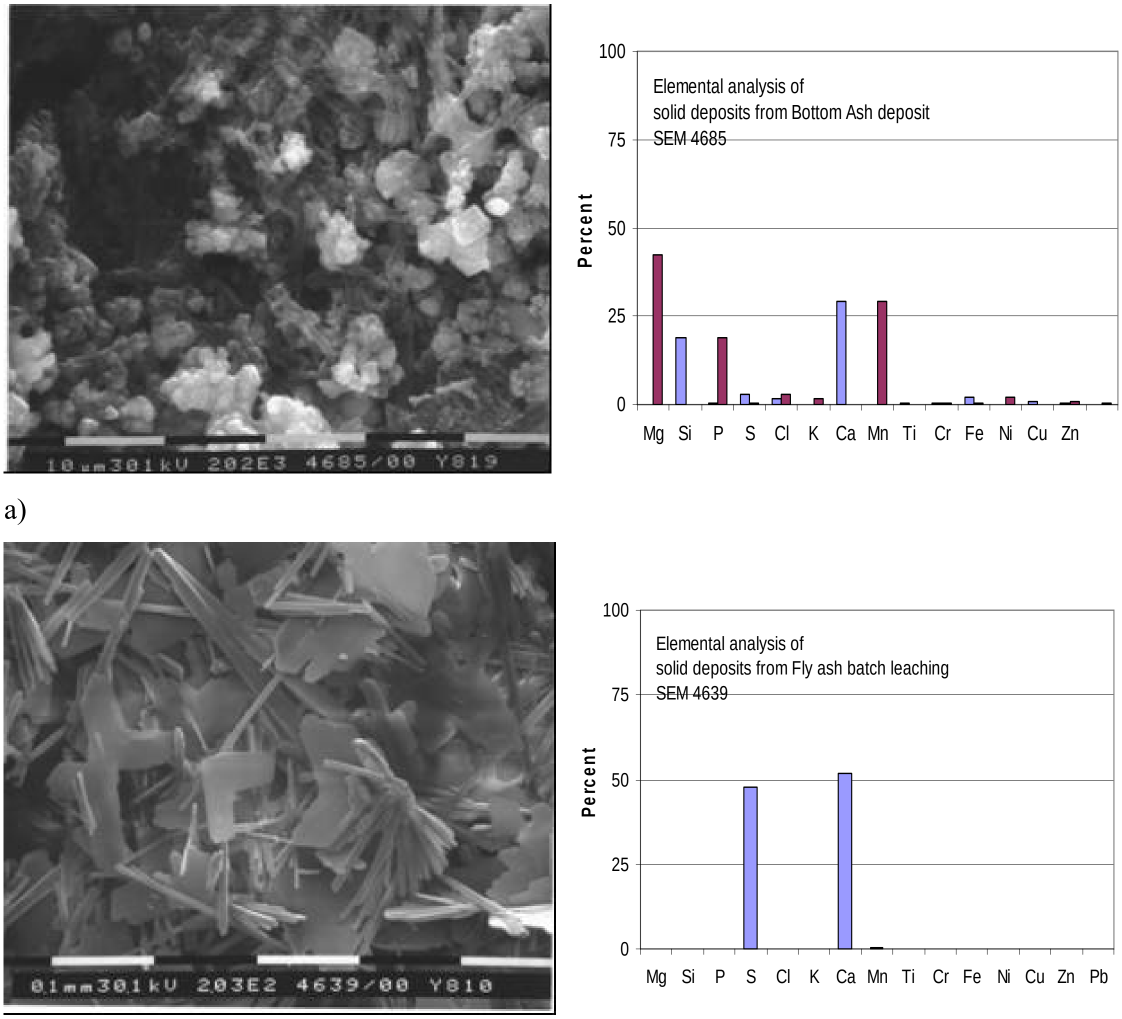


Figure 16. Comparison of Saturation Indices for Calcite (Left) and Gypsum (Right) from CT Batch Tests.

4.5. Formation of Precipitates

Leachates associated with different types of WTE combustion residues can be supersaturated with respect to minerals that tend to precipitate. Some type of perturbation to the leachate chemistry such as modification of the oxidation-reduction potential, stimulation of the growth of bacteria, or addition of various cleaning agents can induce deposit formation. One type of cleaning agent that is widely applied for clean-out of leachate collection systems is the use of acid with the goal of solubilizing minerals.



a)

b)

Figure 17. SEM/EDS Analysis of Precipitates Formed from the Addition of Sulfuric Acid to Leachates from CT Tests at a L/S Mass Ratio of 10; a) Bottom Ash, and b) Fly Ash.

In this study, acid was added to samples from lysimeters and batch testing as a preservative. However, precipitates formed within the leachate solutions upon the addition of sulfuric acid. Examples of the precipitates that formed are shown in Figure 17 for samples of bottom ash batch test leachates at a liquid to solid mass ratio of 10 and for fly ash batch leaching test samples. As discussed above, all of these samples were undersaturated for gypsum due to the relatively low concentrations of sulfate. It is interesting to note that in addition to the plate-like gypsum material that formed, other calcium and magnesium dominated precipitates were also present, perhaps due to changes in the oxidation-reduction conditions. It should also be noted that there was no evidence of microbial interactions in these reactions, since the pH level in the leachates samples was an inhibitory factor.

5. CONCLUSIONS

This study has provided the opportunity to evaluate the leaching behavior of different WTE combustion residues through the use of lysimeters, contact time, and sequential extraction batch tests. Predictions of the contributions of the different WTE residuals and the potential for the formation of mineral precipitates were discussed. The major conclusions of this study are:

1. Lysimeter tests allowed for a detailed evaluation of one-set of conditions over an extended time period allowing for examination of changes in leachate composition. The reactors were useful tools to simulate landfill conditions in a laboratory environment.

2. Batch leaching tests provided a means to estimate the rate and extent of mineral leaching as a function of contact time and liquid to solid ratios. The contact time (CT) test provided insight into the dominant solubilizable components and the chemical stability of leachates generated by WTE combustion residues, while the sequential extraction (SE) test provided a means to quantify the leaching behavior resulting from sequential exposure to rainwater as it percolates through a landfill.

3. Comparisons between batch tests, lysimeter tests, and field samples suggest that laboratory solubilization studies may provide useful tools for predicting the impacts of alternative ash management practices and various combinations of wastes on leachate composition and stability.

4. All leachates samples from lysimeter and batch tests contained high concentrations of calcium, potassium, sodium, chloride, and sulfate. Although sodium, potassium, and chloride were highly soluble, these ions increased the ionic strength of the leachate, thereby reducing the activity of the less soluble ions in the leachate.

5. The high degree of calcium solubilization associated with WTE residue leachates can impact the stability of landfill leachates, particularly when combustion residues are co-disposed with MSW. Results from leaching and solubilization studies can help to predict the potential for formation of calcium-based precipitates in leachate collection systems and possibly lead to the development of improved leachate management practices.

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Conclusions

This study has provided an opportunity to investigate relationships among waste characteristics, leachate composition, and the potential for formation of precipitates. The goal was to provide a means for predicting the contributions of different waste streams to potential clog formation in landfill leachate collection systems. The major conclusions from this project are:

1. The use of monofills appears to lead to less clogging of leachate collection systems. For ash monofills, the lower degree of microbial activity in the leachate results in lower concentrations of carbonate species, thus restricting the extent of chemical precipitation, while leachates from MSW monofills contain adequate carbonate, but fewer sources of calcium and other insoluble minerals.

2. Landfills practicing co-disposal of WTE combustion residues and MSW appear to be more susceptible to clogging of leachate collection system due to the relative contributions of each waste stream. The WTE ash provides the minerals while the MSW provides biomass, carbonate species, and alternative electron acceptors. Additional inputs of treatment plant residuals can introduce more minerals (water treatment) and more biomass sources (wastewater treatment), further exacerbating the problem.

3. Clogging seems to occur when the equilibrium of calcium species is disrupted by microbial activity, the additional leaching of minerals, and/or a change in oxidation conditions. Microbial activity, as evidenced by volatile acids and

monitoring of microbial concentrations, influenced the rate and extent of clogging that occurred in lysimeter tubing.

4. Batch leaching tests provided a means to estimate the rate and extent of mineral leaching as a function of contact time and liquid to solid ratios. The contact time (CT) test provided insight into the dominant solubilizable components and the chemical stability of leachates generated by WTE combustion residues, while the sequential extraction (SE) test provided a means to quantify the leaching behavior resulting from sequential exposure to rainwater as it percolates through a landfill. The use of this test to screen ash stabilization methods may help to reduce the incidence of clogging in landfill leachate collection systems.

5. Comparisons between batch tests, lysimeter tests, and field samples suggest that laboratory solubilization studies may provide useful tools for predicting the impacts of alternative ash management practices and co-disposal of different types of wastes on leachate composition and stability. All the tests correctly predicted the identities of the dominant ions and the supersaturated or unsaturated nature of the leachate.

6. The high degree of calcium solubilization associated with WTE residue leachates can impact the stability of landfill leachates, particularly when combustion residues are co-disposed with MSW. Results from leaching and solubilization studies can help to predict the potential for formation of calcium-based precipitates in leachate collection systems and possibly lead to the development of improved leachate management practices.

Engineering Implications

Landfills are designed to prevent and control the migration of contaminants to the surrounding environment. Landfill leachate collection systems are integral components of landfill management. This research has provided an initial evaluation of the chemical and microbiological factors that may impact the formation of biogeochemical deposits in leachate collection systems. It is important to develop tools for preventing and correcting problems associated with clogging of landfill drainage material and collection pipes.

Monofills appear to be a better disposal option for WTE combustion residues, rather than co-disposal with MSW and byproducts from water and wastewater treatment. The monofill practice would prevent two leachates with different characteristics from interacting and producing precipitates. WTE combustion residues leachate provides the minerals while the MSW leachate provides biomass, carbonate species, and alternative electron acceptors, creating ideal conditions for the formation of precipitates. Clogging of leachate collection systems allows for accumulation of liquid within the landfill, increasing the failure potential of the liner.

Routine monitoring of biologically related parameters such as volatile acids, chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in landfill leachates may be instrumental in relating the extent of biological activity with the potential for formation of biogeochemical deposits. Comparison of the time period of decreasing calcium to alkalinity ratios with the time periods associated with leachate pipe clogging might provide insight into the potential use of this ratio as a diagnostic or predictive tool for control and establishment of maintenance frequencies for leachate collection system.

Methods for prevention and control of clogging in leachate collection pipes should be evaluated taking into account leachate characteristics and waste interactions. Detailed testing of the impacts of practices such as chemical augmentation with acids and chelating agents is needed to identify the optimum approach for clogging prevention. The equilibrium of supersaturated leachates may be easily disrupted with the addition of cleaning chemicals, increasing the potential for precipitates formation.

The impacts of current combustion technologies and ash handling protocols on the leaching characteristics of residues from WTE combustion facilities may help to develop protocols for stabilization of residues prior to landfilling or beneficial reuse. Laboratory lysimeters and batch tests can provide useful information during the development of treatment alternatives and also in the selection of appropriate materials for construction of landfill leachate drainage systems.

Additional Research

Recommendations for further research of the impacts of co-disposal of MSW, WTE combustion residues, and byproducts of water and wastewater treatment are:

1. Evaluate leachate characteristics through the use of laboratory lysimeters without leachate recirculation. This approach would allow studying the interactions between different types of waste and leachate quality, as new liquid is added every time and a better control on the liquid to solid ratio in the reactors is achieved. This operational mode would also mimics a landfill environment in which the moisture content is an important factor affecting biological activity, redox conditions, and solubility of minerals.

2. Determine the role of increasing temperatures on the formation of biogeochemical deposits. Landfill environments reach higher temperatures than the ones usually found in laboratories. Temperature affects biological activity as well as redox conditions and solubility of minerals in the leachate. By running laboratory lysimeters and batch tests at different temperatures, a relationship between this factor and leachate characteristics can be established.

3. Examine the impact of co-disposal of MSW and byproducts of water and wastewater treatment. Since this type of residuals are also co-disposed in landfills, the use of laboratory lysimeter and batch tests may help in the identification of the individual contributions to the biomass and mineral content of the leachate, due to the presence of biosolids and/or water treatment sludge.

4. Evaluate the production and composition of the biogas during laboratory lysimeter tests. Analyses of the biogas will allow establishing stronger relationships among biological activity, degradation of wastes within the reactors, leachate quality, and formation of precipitates.

5. Develop a relationship to predict the formation of precipitates by studying the sources of carbonate and the depletion of calcium in the leachate. The generation and consumption of volatile acids affects the pH and the carbonate concentration of the leachate. Identification of the composition and behavior of volatile acids may help to identify chemical and biological factors that play a role in the leachate chemical stability.

6. Study the impact of having an anaerobic versus aerobic environment on the clogging of leachate collection system. New landfill management practices include the aeration of landfilled waste to promote faster degradation. Biological activity, redox conditions, and solubility of minerals are affected by this practice and the implications on the formation of biogeochemical deposits are not well understood yet.

7. Perform a statistical analysis of waste disposal practices and the incidences of leachate management problems related to the formation of biogeochemical deposits. This could be achieved by conducting a large scale survey of landfills and comparing the disposal practices (monofills versus co-disposal of MSW, WTE combustion residues, and residuals from water and wastewater treatment) and the formation of precipitates in leachate collection systems.

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Appendices

Appendix A: Chemical Characterization Tests

Metals: Flame AA

Calcium, Copper, Iron, Magnesium, Manganese, Potassium, Sodium, Zinc

Source: *Standard Methods for the Examination of Water and Wastewater*, 20th edition, 3111 B Direct Air-Acetylene Flame Method

Equipment: PerkinElmer AAnalyst 100, Atomic Absorption Spectrometer

Time Frame: 6 months with preservation, store at 4°C.

Preservation of Sample: Preserve by adding 5 mL of concentrated nitric acid to 1 L of sample and the sample can be stored for up to 6 months (EPA Method 3005).

Preparation of Reference Standards: Make up at least three standards. The first should be below the expected concentration, the second should be near the expected concentration and the final standard should be above the expected concentration. The middle standard will be used to re-slope. Prepare by adding the appropriate amount of reference standard to reagent grade water.

Preparation of Sample: If there are large amounts of particulate matter the sample needs to be filtered. If not, there is no preparation required.

Table A-1: Conditions from Analytical Methods for Atomic Absorption Spectrometry, 2000. PerkinElmer

Metal	Wavelength (nm)	Slit (nm)	Relative Noise	Characteristic Concentrations (mg/L)	Characteristic concentration checks (mg/L)	Linear Range (mg/L)
Ca	422.7	0.7	1.00	0.092	4.00	5.0
Cu	324.8	0.7	1.00	0.077	4.00	5.0
Fe	248.3	0.2	1.00	0.110	6.00	6.0
Mg	285.2	0.7	1.00	0.008	0.30	0.5
K	766.5	0.7	1.00	0.043	2.00	2.0
	769.9	0.7	1.40	0.083	4.00	20.0
Na	589.0	0.2	1.00	0.012	0.50	1.0
	330.2	0.7	0.63	1.700	80.00	---
Zn	213.9	0.7	1.00	0.018	1.00	1.0

Recommended Flame: Air-acetylene, oxidizing (lean, blue)

Anions: Capillary Ion Electrophoresis

Chloride, Bromide, Nitrate, Nitrite, Sulfate, Fluoride, o-Phosphate

Source: *Standard Methods for the Examination of Water and Wastewater*, 20th edition, 4140 B: Capillary Ion Electrophoresis with Indirect UV Detection

Equipment: Beckman P/ACE 5000 Series Capillary Electrophoresis System
eCap Capillary Tubing in cartridge: 375 µm O.D., 75 µm I.D., 50 cm L

Preparation: The samples need to be filtered if it contains a high concentration of suspended solids. Once completed the sample may need to be diluted.

Appendix B: Lysimeter Star-up and Operation

Lysimeter Star-up

Placement of the Waste and Field Capacity Test.

Procedure:

1. Select the amount of each type of waste according to its weight and volume. For the co-disposal lysimeters, the wastes were mixed in 60-Liter containers prior to be placed in the reactor.
2. Place the waste in the reactors and close the outlet/sampling valve at the end of the leachate collection pipe. Add distilled water until the wastes are completely submerged. Record the amount of distilled water added to each reactor.
3. Leave the reactors in the submerge mode for 72 hours to allow the waste to absorb enough water to reach its saturation point.
4. Open the outlet/sampling valve and drain the reactors. Measure the amount of water/leachate recovered. Save samples for complete chemical and biological characterization.
5. The amount of water absorbed by the waste, considered to be the field capacity, is going to be the difference between the amount of water added and the amount of water/leachate recovered.
6. Cap the reactors and make sure there are no leaks. Connect the tubing from the top containers to the water/leachate distribution system.
7. Add four liters of distilled water to each lysimeter through the distribution systems to start the generation of leachate.

Lysimeter Operation

Procedure:

1. After addition of four liters of distilled water or recirculation of three liters of leachate, provide enough time to the liquid so it will travel through the reactor and generate leachate.
2. Once most of the four/three liters have been recovered in the bottom container, close the outlet/sampling valve to avoid changes of pressure inside the reactor.
3. Take samples for chemical and biological characterization.
4. Replace the same amount of leachate taken during the sampling event with distilled water and open again the outlet/sampling valve.
5. The removed leachate needs to be promptly tested or preserved.
6. Set the timer for the pumps to start after the samples have been taken. Pumping time should be enough to transfer three liters of leachate from the bottom container to the upper one.
7. Recirculate three liters of leachate into each reactor by tipping the upper containers to simulate a rain event of 15 to 20 minutes.
8. Repeat steps 1 through 7 with a 24 hours time interval.

Appendix C: Summary of Leachate Characteristics from Laboratory Lysimeter Tests Conducted from May 5 through November 29, 2004

Table C-1. Lysimeter Leachate Monitoring Summary. Ash 1: 80% Bottom Ash, 20% Fly Ash.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	11.74	11.76	11.4	12.01	0.16	0.02	-0.28	-0.93	0.03	99
Conductivity (µS/cm)	20.68	23.3	13.41	26.5	4.21	0.42	-0.44	-1.46	17.71	99
Temperature (°C)	22.28	22.3	19.3	24.8	1.43	0.16	-0.34	-0.68	2.04	77
ORP (mV)	-46.91	-44	-140	-0.2	28.09	3.20	-0.83	0.93	788.99	77
Turbidity (NTU)	0.98	0.74	0.15	5.07	0.89	0.09	2.06	5.92	0.79	99
Ammonia (mg/L NH_3)	246.30	54.99	0.51	1,189	314.1	59.35	1.34	1.35	98,640	28
Total Alkalinity (mg/L as $CaCO_3$)	1,872	1,866	1,064	2,133	160.9	18.97	-1.85	8.32	25,904	72
Volatile Acids (mg/L as Acetic Acid)	19.2	16.7	16.7	33.3	5.85	0.83	2.09	2.48	34.17	49
Total Solids (mg/L)	13,118	12,863	11,626	17,826	1,303	217.24	2.40	6.52	1.7E+06	36
Volatile Solids (mg/L)	1,367	916.65	726.7	4,873	932.3	155.39	2.23	5.19	869,253	36
Estimated TDS (mg/L)	11,973	11,999	8,803	14,975	1,547	257.95	-0.001	-0.35	2.4E+06	36
Total Nitrogen (mg/L as N)	8.60	9	< 0.2	20	5.48	0.91	0.44	0.45	29.99	36
Total Phosphorus (mg/L as PO_4)	5.40	5.1	1.5	10.9	2.31	0.38	0.52	-0.21	5.34	36
Silica (mg/L as SiO_2)	4.7	3.8	< 0.3	18.3	4.24	0.71	1.89	4.13	18.01	36
Bromide (mg/L)	172.71	171.6	66.5	305.43	52.92	9.36	-0.009	0.24	2,800.5	33
Chloride (mg/L)	5,148	4,989	3,325	7,431	964.3	167.86	0.49	0.21	929,882	36
Sulfate (mg/L)	71.73	71.4	23.97	122.8	30.97	6.76	-0.03	-1.27	958.95	21
Calcium (mg/L)	1,826	1,556	638.7	4,360	978.9	163.15	1.23	1.14	958,265	36
Magnesium (mg/L)	0.038	0.011	< 0.01	0.855	0.141	0.023	5.920	35.330	0.020	36
Copper (mg/L)	0.176	0.165	0.054	0.376	0.085	0.014	0.618	-0.238	0.007	36
Iron (mg/L)	0.180	0.187	0.073	0.296	0.058	0.010	0.218	-0.412	0.003	36
Manganese (mg/L)	0.023	0.021	< 0.01	0.088	0.022	0.004	1.448	2.147	0.001	36
Zinc (mg/L)	0.250	0.234	0.033	0.362	0.065	0.011	-0.581	2.296	0.004	36
Potassium (mg/L)	1,065	1,217	350.4	1,494	335.6	55.94	-0.691	-0.818	112,650	36
Sodium (mg/L)	1,984	1,974	808	502	730.2	121.71	1.785	7.74	533,240	36
Aluminum (mg/L)	0.099	0.055	< 0.002	0.65	0.121	0.020	2.950	11.627	0.015	36

Table C-2. Lysimeter Leachate Monitoring Summary. Ash 2: 80% Bottom Ash, 20% Fly Ash.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	11.73	11.77	11.4	12.05	0.17	0.02	-0.22	-1.06	0.03	99
Conductivity (µS/cm)	20.06	22.9	12.2	24.8	4.34	0.44	-0.67	-1.24	18.80	99
Temperature (°C)	22.24	22	19.3	24.7	1.45	0.17	-0.18	-0.84	2.09	77
ORP (mV)	-117	-122	-159	121	34.56	3.94	4.38	29.20	1,195	77
Turbidity (NTU)	1.13	0.62	0.13	8.57	1.61	0.16	2.87	8.36	2.58	99
Ammonia (mg/L NH_3)	475.06	86.02	1.36	3,816	864.70	163.41	2.83	8.65	747,698	28
Total Alkalinity (mg/L as $CaCO_3$)	1,904	1,900	1,226	2,250	179.48	21.15	-0.69	2.13	32,211	72
Volatile Acids (mg/L as Acetic Acid)	22.68	16.7	8.33	35.7	8.37	1.20	0.49	-1.63	70.12	49
Total Solids (mg/L)	12,104	11,993	10,700	15,873	1,066	177.66	1.65	3.86	1.1E+06	36
Volatile Solids (mg/L)	1,313	963.35	633.3	3,346	777.17	129.53	1.79	2.05	603,991	36
Estimated TDS (mg/L)	10,922	11,268	7,295	13,425	1,249	208.29	-0.77	1.11	1.5E+06	36
Total Nitrogen (mg/L as N)	7.20	8.5	< 0.2	20	4.41	0.74	-0.07	0.94	19.44	36
Total Phosphorus (mg/L as PO_4)	4.71	4.15	0.9	16.5	2.90	0.48	1.94	6.71	8.40	36
Silica (mg/L as SiO_2)	4.44	3	< 0.3	19.4	3.98	0.66	1.89	5.02	15.81	36
Bromide (mg/L)	178.01	162.7	43.1	777.08	111.42	18.57	4.59	25.21	12,414	36
Chloride (mg/L)	4,562	4,478	1,237	8,209	1,208	201.43	0.09	2.99	1.5E+06	36
Sulfate (mg/L)	96.57	57.96	24.49	460.24	108.07	26.21	2.63	8.19	11,679	17
Calcium (mg/L)	1,727	1,380	640.5	4,526	948.49	158.08	1.14	0.96	899,626	36
Magnesium (mg/L)	0.052	0.01	< 0.01	0.775	0.154	0.026	4.116	16.79	0.024	36
Copper (mg/L)	0.092	0.109	< 0.01	0.16	0.052	0.009	-0.680	-0.996	0.003	36
Iron (mg/L)	0.174	0.165	0.028	0.35	0.067	0.011	0.638	0.628	0.005	36
Manganese (mg/L)	0.023	0.023	< 0.01	0.073	0.021	0.004	1.022	0.498	0.001	36
Zinc (mg/L)	0.240	0.238	0.11	0.344	0.060	0.010	-0.009	-0.618	0.004	36
Potassium (mg/L)	944.5	1,057	254.2	1,340	308.38	51.40	-0.843	-0.486	95,099	36
Sodium (mg/L)	1,864	1,879	568	2,869	580.86	96.81	-0.467	-0.302	337,398	36
Aluminum (mg/L)	0.153	0.16	< 0.002	0.53	0.136	0.023	0.769	0.181	0.019	36

Table C-3. Lysimeter Leachate Monitoring Summary. MSW: 100% MSW.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	6.58	6.7	5.84	7.08	0.31	0.03	-0.87	-0.23	0.10	99
Conductivity (µS/cm)	5.01	5.42	1.80	7.64	1.61	0.16	-0.47	-0.79	2.61	99
Temperature (°C)	22.17	22.1	19.3	24.6	1.45	0.17	-0.19	-0.94	2.10	77
ORP (mV)	-87.38	-83	-137	-14	25.44	2.90	-0.09	-0.38	647.11	77
Turbidity (NTU)	208.54	205	60.1	377	85.79	8.62	0.16	-1.02	7,359	99
Ammonia (mg/LNH$_3$)	1,029	78.2	0.51	8,715	1,984	374.98	2.74	8.24	4E+06	28
Total Alkalinity (mg/L as CaCO$_3$)	3,177	3,083	2,066	4,600	680.8	80.23	0.28	-0.85	463,493	72
Volatile Acids (mg/L as Acetic Acid)	307.16	100	16.7	1,025	314.52	44.93	0.63	-0.93	98,922	49
Total Solids (mg/L)	6,785	7,272	2,940	10,686	2,699	449.85	-0.05	-1.53	7.3E+06	36
Volatile Solids (mg/L)	3,527	4,292	1,160	6,080	1,661	276.97	-0.10	-1.59	2.8E+06	36
Estimated TDS (mg/L)	5,006	4,963	3,201	7,490	1,237	206.23	0.43	-0.62	1.5E+06	36
Total Nitrogen (mg/L as N)	84.56	60	40	180	50.99	8.50	0.85	-1.06	2,600.37	36
Total Phosphorus (mg/L as PO$_4$)	16.89	14.7	0.6	42	13.12	2.19	0.48	-1.01	172.19	36
Silica (mg/L as SiO$_2$)	172.97	164.5	100	268	43.24	7.21	0.50	-0.44	1,869	36
Bromide (mg/L)	2.45	1.65	0.79	9.17	2.49	0.79	2.65	7.44	6.18	10
Chloride (mg/L)	107.67	96.78	39.39	191.69	35.97	5.99	0.93	0.50	1,293	36
Phosphate (mg/L)	417.77	466	17.03	826.71	347.33	96.33	-0.16	-1.92	120,640	13
Sulfate (mg/L)	82.94	36.43	10.85	222	88.10	29.37	0.80	-1.48	7,761	9
Calcium (mg/L)	1,128	1,194	423.7	1,899	452.15	75.36	0.11	-1.26	204,437	36
Magnesium (mg/L)	50.27	50.35	27	73.5	9.66	1.61	-0.12	0.32	93.35	36
Copper (mg/L)	0.045	0.053	< 0.01	0.089	0.033	0.006	-0.202	-1.556	0.001	36
Iron (mg/L)	15.19	13.16	0.829	49.08	13.84	2.307	0.602	-0.694	191.61	36
Manganese (mg/L)	2.996	3.116	0.086	7.65	2.52	0.420	0.375	-1.097	6.352	36
Potassium (mg/L)	102.90	94.85	27.3	165.3	40.42	6.74	-0.24	-0.71	1,633	36
Sodium (mg/L)	177.61	178	60	279	49.53	8.26	-0.31	0.58	2,453	36
Aluminum (mg/L)	0.644	0.685	0.12	0.99	0.215	0.036	-0.451	-0.535	0.046	36

Table C-4. Lysimeter Leachate Monitoring Summary. Mix 1: 60% MSW, 30% WTE Ash, 10% Treatment Residuals.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	6.45	6.56	5.82	6.79	0.25	0.03	-0.85	-0.48	0.06	99
Conductivity (µS/cm)	7.13	7.53	1.96	12.15	2.91	0.29	-0.41	-0.67	8.48	99
Temperature (°C)	22.11	22	19.1	24.4	1.44	0.16	-0.28	-0.74	2.08	77
ORP (mV)	-77.3	-83	-147	-7	30.88	3.52	0.42	-0.23	953.27	77
Turbidity (NTU)	144.54	139	51.7	430	53.43	5.37	1.94	7.84	2,854.98	99
Ammonia (mg/LNH_3)	2,995	75.56	3.06	17,296	4,913	928.53	1.84	2.90	2.4E+07	28
Total Alkalinity (mg/L as $CaCO_3$)	2,670	2,250	1,733	4,533	842.46	99.28	0.61	-1.18	709,734	72
Volatile Acids (mg/L as Acetic Acid)	132.69	33.3	16.7	875	189.86	27.12	1.93	3.88	36,047	49
Total Solids (mg/L)	7,719	5,520	4,526	14,940	3,390	565.02	0.98	-0.36	1.1E+07	36
Volatile Solids (mg/L)	3,307	2,210	1,720	7,593	1,739	289.91	1.11	0.03	3E+06	36
Estimated TDS (mg/L)	5,916	4,870	3,457	9,835	1,845	307.55	0.81	-0.52	3.4E+06	36
Total Nitrogen (mg/L as N)	82.78	61	30	240	55.78	9.30	1.89	2.46	3,110	36
Total Phosphorus (mg/L as PO_4)	4.94	5	< 0.2	9.8	2.78	0.46	-0.16	-0.84	7.72	36
Silica (mg/L as SiO_2)	170.75	145	103	327	57.65	9.61	1.04	0.18	3,323	36
Bromide (mg/L)	39.18	27.985	10.09	172.05	32.48	5.93	2.80	9.21	1,054.8	30
Chloride (mg/L)	1,084	1,052	243.86	1,890	291.12	50.68	0.17	2.60	84,748	36
Phosphate (mg/L)	744.86	659.25	16.13	1,705	665.99	200.81	0.11	-1.82	443,553	11
Sulfate (mg/L)	215.04	65.01	13.77	719	280.64	81.01	1.13	-0.50	78,758	12
Calcium (mg/L)	1,182	842.95	416.1	2,961	712.32	118.72	1.42	1.11	507,399	36
Magnesium (mg/L)	189.55	184.7	123.5	300.7	33.25	5.54	1.14	2.78	1,105.7	36
Copper (mg/L)	0.081	0.060	< 0.01	0.384	0.095	0.016	2.091	4.50	0.01	36
Iron (mg/L)	11.11	6.341	1.527	38.59	10.29	1.715	1.356	1.421	105.87	36
Manganese (mg/L)	1.191	0.414	< 0.01	4.679	1.524	0.254	1.348	0.380	2.322	36
Potassium (mg/L)	128.46	130.1	76.7	229.3	31.29	5.53	0.995	2.389	979.27	36
Sodium (mg/L)	389	377.15	219	520	58.15	9.97	-0.343	1.513	3,381	36
Aluminum (mg/L)	0.5	0.48	0.18	0.86	0.152	0.025	0.477	0.191	0.023	36

Table C-5. Lysimeter Leachate Monitoring Summary. Mix 2: 60% MSW, 30% WTE Ash, 10% Treatment Residuals.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	6.63	6.66	6.11	6.93	0.17	0.02	-0.80	0.59	0.03	99
Conductivity (µS/cm)	6.84	7.62	1.9	11.22	2.62	0.26	-0.72	-0.46	6.87	99
Temperature (°C)	22.12	22	19	24.6	1.49	0.17	-0.21	-0.89	2.23	77
ORP (mV)	-99.64	-102	-131	-57	16.44	1.87	0.51	-0.30	270.16	77
Turbidity (NTU)	187.92	171	71.5	331	62.97	6.33	0.43	-0.71	3,965	99
Ammonia (mg/L NH_3)	3,590	101.32	3.4	15,031	5,309	1,003	1.20	0.02	2.8E+07	28
Total Alkalinity (mg/L as $CaCO_3$)	2,896	2,866	1,666	4,800	690.29	81.35	0.45	-0.36	476,500	72
Volatile Acids (mg/L as Acetic Acid)	172.76	33.3	16.7	675	213.64	30.52	0.94	-0.73	45,640	49
Total Solids (mg/L)	7,009	5,950	4,353	13,540	2,514	419.15	1.18	0.65	6.3E+06	36
Volatile Solids (mg/L)	2,829	2,313	1,853	5,453	1,023	170.60	1.02	0.02	1.1E+06	36
Estimated TDS (mg/L)	5,846	5,696	3,831	9,246	1,472	245.43	0.64	-0.15	2.2E+06	36
Total Nitrogen (mg/L as N)	119.89	109	80	220	38.42	6.40	1.59	1.67	1,476.1	36
Total Phosphorus (mg/L as PO_4)	8.11	8.5	< 0.2	20	4.87	0.81	0.26	-0.37	23.67	36
Silica (mg/L as SiO_2)	160.81	128	55	424	81.01	13.50	1.52	2.22	6,563.2	36
Bromide (mg/L)	30.92	25.03	12.83	82.58	18.43	3.07	2.36	4.31	339.51	36
Chloride (mg/L)	900.01	882.91	427.88	1,323	233.73	38.96	-0.02	-0.49	54,628	36
Phosphate (mg/L)	1,241	1,302	496.56	1,715	385.47	128.49	-0.78	0.44	148,584	9
Sulfate (mg/L)	165.71	39.70	12.22	449	194.19	68.66	0.71	-1.92	37,707	8
Calcium (mg/L)	1,120	1,065	396.4	2,326	497.73	82.96	1.16	0.95	247,734	36
Magnesium (mg/L)	156.90	156	121.3	189.9	16.50	2.75	0.09	-0.41	272.31	36
Copper (mg/L)	0.067	0.068	< 0.01	0.34	0.069	0.011	1.904	5.906	0.005	36
Iron (mg/L)	8.699	3.376	0.801	28.95	9.130	1.522	0.948	-0.631	83.348	36
Manganese (mg/L)	0.819	0.477	< 0.01	3.381	0.899	0.150	1.497	1.587	0.808	36
Potassium (mg/L)	115.76	118.55	75.8	146.5	16.72	2.79	-0.53	0.041	279.53	36
Sodium (mg/L)	306.99	301.25	240	407	34.65	5.78	0.76	1.25	1,200.9	36
Aluminum (mg/L)	0.481	0.485	0.1	0.86	0.189	0.032	-0.180	-0.542	0.036	36