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Assessment of Biogeochemical Deposits in Landfill Leachate Drainage Systems

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LIST OF ABBREVIATIONS

BA	Bottom Ash
BOD	Biochemical Oxygen Demand
Ca	Calcium
$CaCO_3$	Calcium Carbonate
CDM	Camp Dresser & McKee, Inc.
CE	Capillary Electrophoresis
Cl-	Chloride
CO_3^{-2}	Carbonate
COD	Chemical Oxygen Demand
DAPI	4,6-diamidino-2-phenylindole
DGGE	Denaturing Gradient Gel Electrophoresis
EDS	Energy Dispersive Spectroscopy
FA	Fly Ash
FDEP	Florida Department of Environmental Protection
Fe	Iron
FL	Florida
HDPE	High Density Polyethylene
ID	Internal Diameter
K	Potassium
$K_{solubility}$	Solubility Product
Mg	Magnesium
Mn	Manganese
MSW	Municipal Solid Waste
mV	Millivolt
N	Nitrogen
NCDC	National Climate Data Center
NH_3	Ammonia
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Units
OD	Outer Diameter
ORP	Oxidation Reduction Potential
PBL	Palm Beach Leachate
PO_4^{-3}	Phosphate
RCRA	Resource Conservation and Recovery Act
RDF	Refuse Derived Fuel
S	Sulfur
Si	Silicon
SiO_2	Silicon Dioxide or Silica
SEM	Scanning Electron Microscopy
TDS	Total Dissolved Solids
UV	Ultraviolet
VA	Volatile Acids
WTE	Waste-to-Energy

KEY WORDS

ABSTRACT

Design, operation, and closure practices for Class I municipal solid waste (MSW) landfills are based on RCRA Subtitle D requirements for control of leachates and gases generated during the life of the landfill. Because leachate is generated as a result of water percolating through the landfill and waste consolidation, it contains dissolved and suspended materials that reflect the characteristics of the material it contacts. Over the past two decades significant changes have occurred in the characteristics of the waste streams that are disposed in landfills. In addition, many Florida municipalities have implemented Waste-to-Energy (WTE) systems. The WTE ash is either disposed in monofills or co-deposited with MSW and/or residuals from water and wastewater treatment facilities.

Leachate collection systems consist of: underdrains, collection trenches and pipes, line clean-out ports, pumps and lift stations, and storage tanks or wet wells. 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. The occurrence of clogging of leachate collection systems has been attributed to several factors including sedimentation and deposition of fines, biological clogging, and chemical and/or biogeochemical precipitation. This project was conducted to investigate the impact of waste mixtures and associated characteristics of leachate chemistry and microbiology on the development of mineral precipitates that lead to clogging.

The project involved three components: 1) testing of leachates and clog material from a Class I landfill; 2) conduct of laboratory lysimeter tests to compare leachate characteristics from monofills of MSW or combustion residues to leachates generated by mixtures of MSW, combustion residues, and residuals from water and wastewater treatment; and 3) conduct of batch leaching tests to evaluate dominant constituents that leach from combustion residues generated by Waste-to-Energy (WTE) facilities. Laboratory lysimeters were operated for a period of eight months. Chemical and microbiological characterization tests were conducted throughout the operating period.

The dominant constituent identified in clog material from leachate collection systems was calcium, with co-precipitation of carbonates, sulfates, iron, phosphorus, and other elements. Leachates generated from MSW dominated lysimeters tended to have relatively high concentrations of organics and alkalinity and a robust microbial community that modulates with changes in the bioavailability of waste components and redox conditions. Leachates generated from ash dominated lysimeters tended to be high in ionic strength, chloride, sodium, potassium, and calcium.

During the course of the lysimeter study, deposits developed in the leachate collection tubing associated with the waste mixtures (MSW, combustion residues, and treatment plant residuals). Biomass associated deposits formed in the MSW monofills, while minimal deposition occurred in the ash dominated lysimeters. Based on the data generated by this project, co-disposal of MSW and combustion residues yields leachates supersaturated in carbonate (from biological activity) and calcium (from combustion residues) leading to the formation of mineral precipitates that can clog leachate collection systems. Batch leaching tests provided a method for predicting the leachate composition associated with landfilling of combustion residues and allowed for comparison of the mineral leachability associated with different types of ash processing methods.

EXECUTIVE SUMMARY

The prevention of mineral deposition in leachate collection systems is of importance in the long-term maintenance of landfills. This project was designed to provide an initial assessment of the degree to which waste characteristics influence the formation of mineral precipitates in Class I landfill leachate collection systems and identify environmental conditions that may accelerate this process. The specific objectives are:

1. Survey the extent to which leachate clogging occurs in Class I landfills in Florida.

2. Determine the dominant components of clogged materials obtained from leachate collection systems.

3. Conduct laboratory lysimeter tests to evaluate the influence of waste composition on the degree of leachate solidification associated with co-disposal of MSW, WTE combustion residues, and residuals from water and wastewater treatment facilities.

4. Compare the characteristics of leachates generated in laboratory lysimeters to landfill leachates.

5. Conduct batch tests to evaluate the leaching properties of WTE combustion residues that are typically landfilled.

The project involved testing of field samples, evaluating leachate characteristics from laboratory lysimeters and batch tests, and assessing key factors that may lead to the formation of mineral clogs.

Leachate characteristics. Leachates from active Class I landfills contained varying amounts of calcium and alkalinity depending on the types of wastes disposed in the landfill, the age of the landfill, and the relative amount of moisture available. Ash monofill leachates were dominated by calcium whereas landfills receiving MSW and combustion residues contained higher levels of alkalinity. The higher ionic strength characteristic of ash monofill leachates can act to increase the solubility of minerals, thereby decreasing the potential for formation of solid precipitates. More sample events would be needed to verify these trends, but it is evident that the leachate from disposal of MSW in combination with combustion residues is more susceptible to formation of mineral precipitates due to the relative quantities of constituents that could co-precipitate (i.e. calcium, magnesium, iron, carbonate, and sulfate).

Calcified bacterial particles were identified in the leachate from the ash monofill. These types of bacteria, sometimes referred to as nanobacteria, are capable of forming crystalline calcium phosphate and this may be of significance in initiation of precipitate formation. Limited information is currently available on the abundance of these bacterial particles in landfill leachates.

Precipitate characteristics. Elemental analysis of solid precipitates from leachate collection systems identified the dominant element in all precipitates as calcium. Elements that co-precipitate with calcium include phosphorus, silica, magnesium, and sulfur. The physical structure and particle size of the precipitates varied with elemental composition.

Lysimeter studies. Laboratory lysimeters were developed to assess the relative role of waste material distribution and bottom design in the production of leachate. Eight lysimeters were operated in parallel for a period of eight months. The lysimeters included two ash monofills (80% bottom ash and 20% fly ash), two MSW monofills (RDF process rejects), and four reactors containing MSW (60%), combustion residues (30%) and treatment plant residuals (water and wastewater waste materials). The lysimeters were initiated by saturating the wastes to field capacity and providing additional liquid (distilled water) to generate leachate. The leachate was applied in a flood and drain pattern and recirculated once every 24 hours. Leachate characteristics were monitored weekly over an eight month period.

Based on operation of laboratory lysimeters for a period of eight months, several trends were observed. Ash dominated leachates tended to have higher pH levels and higher concentrations of TDS, calcium, sodium, potassium, and chloride than MSW dominated leachates. MSW dominated leachates tended to contain higher concentrations of microorganisms, alkalinity, volatile solids, TOC, turbidity, nitrogen, phosphorus, and silica than ash dominated leachates. The concentration of calcium decreased over time and the concentration of potassium increased over time in the ash dominated leachates. Mixtures containing ashes, MSW, and treatment plant residuals tended to have higher concentrations of magnesium and lower concentrations of phosphorus than would be expected based on relative contributions of MSW and ashes.

After about four months of lysimeter operation, operational problems developed within the lysimeter leachate collection system due to the development of deposits within the leachate collection tubing of MSW dominated lysimeters. 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 a lower density of granular material than did the deposits from the lysimeters containing mixtures of MSW, ash, and treatment plant residuals.

A comparison of the relative species diversity associated with each phase of lysimeter operation suggested that the bacterial community structure changes in response to the availability of substrates and electron acceptors. As time progressed, the diversity of bacterial species decreased in each lysimeter. Follow-up testing is needed to further identify the bacterial speciation.

Comparison of lysimeter results with landfill leachates. Landfill leachates and leachates from the lysimeter tests were similar in chemical composition, but the field samples had three to five fold higher TDS levels than the lysimeter leachates, reflecting higher ionic strength. Alkalinity and calcium levels were variable in landfill and lysimeter leachates, with higher levels of alkalinity associated with leachates from the MSW dominated lysimeters. The percent of the TDS that consists of calcium was much higher in the lysimeters than the landfill leachates and did not seem to be significantly different for the ash dominated lysimeters as compared to the MSW dominated lysimeters.

In addition to differences in the amount of moisture available for waste degradation and the age of the landfill as compared to the laboratory lysimeters, another qualitative difference between the lysimeter leachates and the landfill leachates was temperature. Typical temperatures associated with landfill leachates ranged from 56 to 101 ^{o}F with average temperatures ranging from 87 to 91 ^{o}F. Laboratory lysimeters were operated at room temperature with typical leachate temperatures ranging from 70 to 85 ^{o}F. Temperature variations can impact mineral solubility, biological growth rates, and reaction kinetics.

The laboratory lysimeters provided an effective model system for study of the reactions that might impact clogging of leachate collection systems. Further operation of the lysimeters at higher ionic strength and higher temperatures may yield leachates that are more chemically similar to the leachates produced in the field.

Use of batch tests to assess leaching potential. Two types of batch tests were used to evaluate the leaching potential of combustion residues from different sources. Leachates derived from different types of residues varied in composition with respect to the potential for calcium to precipitate. Fly ash tended to yield a highly supersaturated solution for both calcite and gypsum, but the degree of supersaturation decreased with contact time for gypsum, perhaps due to the participation of sulfate in other complexing reactions. Conversely, leachate derived from bottom ash was unsaturated for calcite and gypsum. Even though bottom ash typically comprises 70-90% of the mass of combustion residues, fly ash yields a higher degree of calcium and other constituents that contribute to the formation of deposits. One reason for the higher level of calcium in fly ashes is the use of lime for scrubbing of acid gases generated in combustion facilities. These results suggest that further stabilization of fly ash or development of alternative ash management and disposal practices may help to reduce the extent of clogging associated with co-disposal of ashes and MSW.

CONCLUSIONS

This study has provided an opportunity to investigate relationships between waste characteristics, leachate composition, and the potential for clogging. Several conclusions can be drawn from this study:

1. Leachates from ash monofills are dominated by high concentrations of dissolved calcium and high pH levels, but contain relatively low levels of carbonate species.

2. Leachates from lysimeters containing MSW have higher levels of microbial activity and bicarbonate, but contain lower levels of calcium species than do ash dominated lysimeters.

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.

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

5. Microbial activity as evidenced by volatile acids and monitoring of microbial concentrations influenced the rate and extent of clogging in lysimeter tubing.

6. Data on microbial activity in landfill leachates would be helpful in developing a better understanding of the steps leading to the onset of clogging in leachate collection systems.

7. Landfills containing mixtures of combustion residues and MSW appear to be more susceptible to clogging due to the relative contributions of each waste stream. The combustion residues provide the minerals while the MSW provides biomass, carbonate species, and alternative electron acceptors. In addition, landfilling of treatment plant residuals can introduce more minerals (water treatment) and more biomass sources (wastewater treatment), further exacerbating the problem.

8. Dominant constituents in clogged materials from leachate collection systems include calcium, carbonate, sulfur, phosphorus, iron, and silica. Assessment of solubility indices for these materials in leachates could help to predict the likelihood of precipitate formation.

9. The use of contact time and sequential extraction batch leaching tests provide a tool that can be used to assess the degree of leaching that may occur from exposure of combustion residues and other waste materials to landfill environments. This procedure was adapted from leaching tests that are widely employed for assessment of toxicity associated with waste materials. The use of this test to screen ash stabilization methods may help to reduce the incidence of clogging in leachate collection systems associated with Class I landfills.

RECOMMENDATIONS

This study has provided an initial evaluation of the chemical and microbiological factors that may impact the formation of clogs in leachate collection systems. It is important to develop tools for preventing and correcting problems associated with leachate clogging. Recommendations for further study are:

1. 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 clogging.

2. Methods for control of leachate clogging such as the use of chemical amendments should be evaluated in the context of leachate characteristics. Detailed testing of the impacts of

chemical augmentation (acids, chelating agents, etc.) is needed to identify the optimum approach for controlling clogging.

3. Methods for assessment of microbial community structure have been developed through this project. It would be valuable to apply these methods to field samples to obtain a better understanding of the relative role of microbial growth in the genesis of solid precipitates.

4. 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 of the leachate collection system.

5. The impacts of current combustion technologies and ash handling protocols on the leaching characteristics of residues from combustion facilities may help to develop protocols for stabilization of residues prior to landfilling.

FINAL REPORT

Assessment of Biogeochemical Deposits in
Landfill Leachate Drainage Systems

INTRODUCTION

Landfill leachate forms through a sequential process that is initiated by saturation of the waste materials to field capacity, followed by consolidation of saturated wastes with concurrent release of moisture. Liquid-solid interactions occur continuously due to sorption, degradation, solubilization, and precipitation reactions mediated by the microbial community within the landfill matrix. The net volume and composition of leachate reflects a balance between losses due to evaporation, the influx of water from rainfall in conjunction with chemical and biological reactions that occur within the landfill. Evaporation serves to increase the concentration of dissolved constituents, whereas precipitation can either increase or decrease dissolved concentrations depending on the extent to which leaching and microbiological reactions have reached equilibrium. Typically, leachate percolates vertically through the layers of waste until it reaches the landfill liner, then it flows laterally into the collection system. It is not uncommon for horizontal migration of leachate to occur, causing washout of side slopes. The extent of horizontal migration is impacted by the type and integrity of the cover material, the density of compaction, and the effectiveness of the leachate collection system for controlling the flow pathways.

The chemical composition of landfill leachates is influenced by a variety of factors including: waste characteristics and age; the net quantity of liquid that has percolated through the landfill; the degree and extent of biological activity; and the status of chemical complexation and solubility reactions. The waste composition reflects societal habits associated with a given region such as socioeconomic factors, the degree of recycling and composting, the extent to which packaging materials are disposed, the proliferation of electronic devices, commercial and industrial byproducts, etc. Other factors that may influence waste composition and leachate quality include the amount and type of industry in a region, the effectiveness of State and local hazardous waste programs in keeping unauthorized materials out of landfills, the frequency and effectiveness of household hazardous waste collection events, and waste minimization programs.

In addition to municipal solid wastes (MSW), many landfills accept residuals from combustion processes (thermoelectric power production, waste to energy facilities) and from water and wastewater treatment facilities. Collectively, the relative amounts of MSW, process residues, and other waste materials disposed in a landfill impact the short-term and long-term composition of leachates and the biogeochemical reactions that result from waste degradation and consolidation during the life of the landfill.

Combustion residuals 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 (quenching, mixing of fly ash and bottom ash), etc. (Berenyi 1996, Brereton 1996, USEPA 2004). Thus, the co-disposal of combustion residues with MSW has the potential to introduce metals, minerals and other non-biodegradable materials to the leachate matrix. Leachable components associated with residuals from water treatment processes can include iron, aluminum, calcium, magnesium, manganese, biomass, and some organics depending on the type of treatment process and the source water characteristics. Wastewater residuals (biosolids) tend to be high in organics, nutrients, metals, and biomass. In addition to impacts from the heterogeneity of waste materials, the chemical composition of leachates is influenced by the available moisture, and landfill operations such as the degree of leachate recirculation, the extent of waste submergence, and gas management practices.

Leachate collection systems consist of: underdrains, collection trenches and pipes positioned above the landfill liner, line clean-out ports, pumps and lift stations, and storage tanks or wet wells and are designed to function in a free-flowing gravitational mode for the entire active and post-closure periods. In some landfills, the formation of solid deposits in leachate collection systems has resulted in clogging that can ultimately lead to failure of the drainage system. To control the formation of precipitates and prevent clogging of leachate collection systems, it is important to understand factors that influence leachate characteristics.

This project was designed to provide an initial assessment of the degree to which waste characteristics influence the formation of mineral precipitates in Class I landfills and identify environmental conditions that may accelerate this process. The specific objectives are:

1. Survey the extent to which leachate clogging occurs in Class I landfills in Florida.

2. Determine the dominant components of clogged materials obtained from leachate collection systems.

3. Conduct laboratory lysimeter tests to evaluate the influence of waste composition on the degree of leachate solidification associated with co-disposal of MSW, WTE combustion residues, and residuals from water and wastewater treatment facilities.

4. Compare the characteristics of leachates generated in laboratory lysimeters to landfill leachates.

5. Conduct batch tests to evaluate the leaching properties of WTE combustion residues that are typically landfilled.

BACKGROUND

Design, operation, and closure practices for Class I municipal solid waste (MSW) landfills are based on RCRA Subtitle D requirements for control of leachates and gases generated during the life of the landfill. Class I MSW landfills are permitted to receive a combination of MSW, bottom and fly ash from combustion processes, sludges from water and wastewater treatment facilities, construction wastes, and other materials. To better understand the potential for clogging of leachate collection systems, it is important to evaluate current design and operating practices. A summary of the regulatory framework for leachate collection systems is provided in this section. Background information is also provided on clogging of leachate collection systems.

Regulatory Requirements for Leachate Collection Systems

Class I landfills are required to have liners and leachate collection systems to prevent the migration of leachates into groundwater. Typically, landfill leachate collection systems are positioned above the liner and are designed to function in a free-flowing gravitational mode for the entire active 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 1. As shown, the composite liner serves as the landfill base and consists of an impermeable layer (clay) with a hydraulic conductivity of less than 1×10^{-7} cm/sec (USEPA, 1993). The clay layer is overlain by a flexible membrane liner that provides an additional barrier to prevent leachate migration into the subsurface. To prevent accumulation of leachate above the composite liner, leachate collection systems are designed to maintain the leachate depth below 30 cm except under extenuating circumstances (USEPA, 1993, Bagchi 1990).
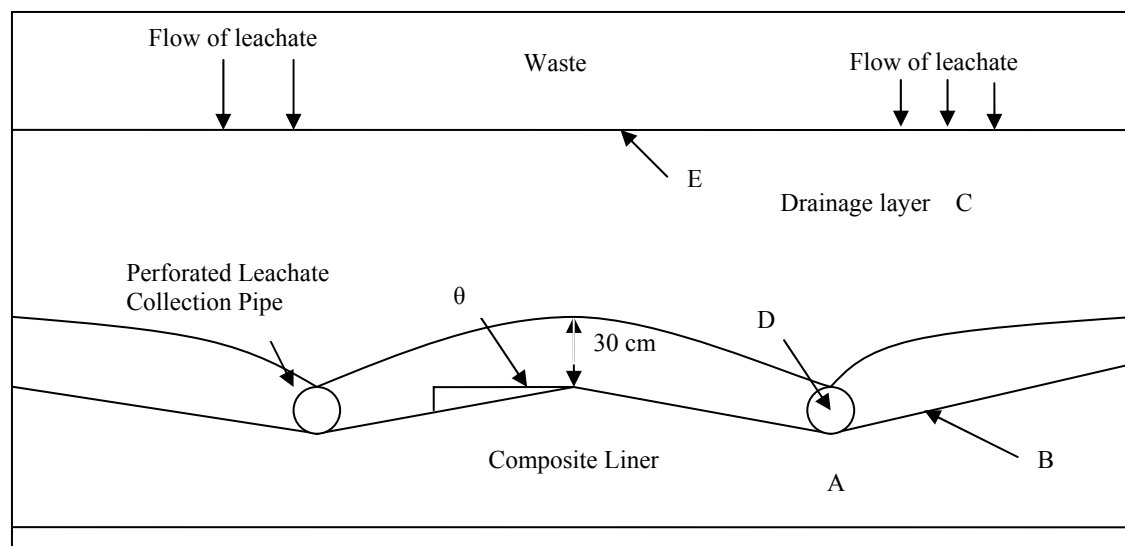
Figure 1. Schematic of the leachate collection system of an engineered landfill. The characteristics of points A-E are given in Table 1.

Table 1. Description of 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 1×10^{-7} cm/sec;	A
		Slope > 2%	
	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 1×10^{-3} cm/sec;	C
		Slope > 2%	
	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;	E
		Protects drainage layer from physical clogging	

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

The transport of leachate from waste matrix occurs through a series of perforated pipes embedded in a drainage layer. The perforated pipes are a minimum 6-inch diameter plastic pipe capable of supporting the combined weight of the drainage layer and the waste at design capacity (USEPA, 1993). The conductivity of the drainage layer material must be at least 1×10^{-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 entering the drainage layer and the collection pipes.

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

Clogging of Leachate Collection Systems

The occurrence of clogging of leachate management systems has been attributed to several factors including sedimentation and deposition of fines, biological clogging, and chemical and/or biogeochemical precipitation (Cooke et al, 2000; Cooke et al. 2001). In some cases, evidence of clogging has been observed to occur within 4 years of landfill initiation (Rowe et al. 2002). Typically, clogs are caused by the formation of biofilms and insoluble mineral deposits that fill the void spaces within the drainage layer and the perforated collection pipes (Paksy et al. 1998).

Drainage media has been implicated in the formation of clogs in landfill leachate collection systems (Rowe et al. 2000; 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. 2000). Regardless of the size of the drainage media, the flow of the leachate 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 experience less clogging than saturated regions due to differences in available substrate for microbial activity. During times of high flow, increased microbial activity can lead to biofilm production and the precipitation of insoluble minerals. In reality, the environment within the leachate drainage and collection system cycles between saturated and unsaturated conditions depending on precipitation patterns and the degree of biological activity. Changes in the quantity of leachate and the extent of cycling between saturated and unsaturated conditions has been reported to result in increased clogging potential (Paksy et al. 1998; Rowe et al. 2000).

The formation of insoluble minerals can interfere with the hydraulic conductivity of the drainage layer. Analysis of the clog material removed from landfills in Canada, Great Britain, and the US identified calcite, $CaCO_3$, as the major constituent in the clog material (Manning and Robinson, 1999; Maliva et al. 2000; Rowe et al. 2000). Other minerals containing iron, sulfide, sulfate and carbonate were also identified in the solid. It has been suggested that the amount of calcium carbonate in the precipitate can be estimated from the mass ratio of Ca^{2+} to CO_3^{2-} in leachates (Rowe and Booker, 1998),. If the ratio is greater than 0.67, excess calcium is available to precipitate with other anions. When the ratio is lower than 0.67 excess carbonate is available to precipitate with other cations. 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).

Chemical characterization of leachates associated with clogging material reflects the composition of the precipitate. In models of leachate chemistry, CO_3^{2-} and SO_4^{2-} have been reported to be the dominant anions, regardless of the pH, and are considered supersaturated (Manning and Robinson, 1999). Typically, leachates are saturated with respect to $CaCO_3$, $FeCO_3$, $MgCO_3$, and $Ca_5(PO_4)_3OH$ (Rowe et al. 2002). There are also high concentrations of sodium, potassium and chloride in leachates but due to the highly soluble nature of these ions, they are not commonly found in precipitates.

In addition to observations from active landfills, laboratory lysimeter studies have been used to assess the clogging process. It has been 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, drainage material consisting of sand or gravel with a nominal particle size less than 10 mm should be avoided.

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).

Survey of leachate clogging in Class I landfills

Limited information is available on the extent to which clogging occurs in Class I landfills. To try to quantify the prevalence of clogging, an internet based survey was developed as part of this project. The survey was designed to compile information on landfill size, age, waste stream characteristics, operating characteristics, leachate management practices, and the extent of clogging that has been experienced. The initial focus of the survey was on Florida landfills. The website for the survey is:

http://ceweb.eng.usf.edu/msw/login.asp

The survey is divided into three sections: *General Facility Operations*, *Landfill Operations*, and *Leachate Management*. The *General Facility Operations* section queries users about the landfill ownership (public versus private), landfill classification, age and remaining life, quantity of waste received per year, and types of wastes that are received with specific questions addressing combustion residues. The operations questions query the user about liners, cover materials, and leachate collection systems, and the leachate management questions are focused on the incidence of clogging.

Data from the survey are compiled into an ACCESS database that can be used to assess trends and conduct statistical analyses. A list of potential participants for the survey was compiled from the Florida Department of Environmental Protection (FDEP) website on Class I landfills. User names and passwords were set up for 40 participants and they were invited via e-mail to participate. To date, we have only received 4 responses (10 percent response rate) making it difficult to compile meaningful statistics.

CHARACTERISTICS OF LEACHATE AND PRECIPITATE FROM FLORIDA LANDFILLS

The formation of precipitates within leachate collection systems is related to landfill operations, leachate characteristics, and environmental factors. To gain a better understanding of the characteristics of the clogged material that forms in leachate collection systems, samples were obtained from two locations.

One location is a Class I landfill in southeast Florida that has a history of problems with clogging of the leachate collection system (Maliva et al. 2000, Missimer International 2000). The landfill is divided into contiguous cells, which have been constructed separately over the life of the landfill. MSW, combustion residues from RDF (fly ash and bottom ash), byproducts from water and wastewater treatment, and other materials are co-disposed in the Class I cells. Perforated pipes, located at the bottom of the cells, collect leachate generated from the disposed material in the landfill. The leachate is then conveyed through a series of gravity flow pipes and pumped into a deep injection well system for disposal. Under typical operations, the perforated pipes are partially filled with leachate and the remaining volume is filled with landfill gas (primarily methane and carbon dioxide). Clogging has occurred in various parts of the leachate collection system. Samples of leachate and clogged material were obtained from the site. Solid samples were characterized using scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS) to characterize surface features of precipitates and derive an elemental analysis.

The second location that was sampled is an ash monofill in west central Florida. The Class I monofill receives quenched combustion residues (combined fly-ash and bottom-ash) from a mass burn facility. Leachate from the monofill is treated on-site. Extensive clogging has not been reported to occur in the leachate collection system, but some solid material has deposited in the gravity system. Samples of leachate from the ash monofill were collected for comparison to the leachate from the southwest Florida landfill.

Characterization of leachates

Two samples of leachate from the cell at the southeast Florida landfill that experiences the highest degree of clogging were collected as part of this project. One sample was obtained in March 2004 and the other in November 2004. A summary of the results from the two samples is presented in Table 2. While a complete analysis was not conducted for both sample events, there were differences in many of the measured parameters, most notably alkalinity, solids, nitrogen, phosphorus, and sodium. To further interpret these data, it would be useful to identify potential differences in collection system operation associated with the two sample events such as pipe cleaning, the use of chelating chemicals, and the incidence of clogging. March 2004 was during the dry season, whereas the November sample may reflect increased leaching due to the high levels of rainfall experienced during the fall of 2004.

Table 2. Characteristics of leachate samples collected from southeast Florida landfill cell that experiences frequent clogging.

Parameter	Method[a]	Storage and Preservation	Detection Limits	Apr-04	Nov-04
pH, Standard pH units	4500-H+ B. Electrometric Method, inoLab pH probe, calibrated at pH=4, 7, 10	Test immediately	0.01 pH unit	6.85	7.64
Alkalinity, mg as $CaCO_3$ / L	2320 B Titration Method	Store at 4°C and analyze within 6 hours	20	1300	7033
Solids mg/L	2540 B Total Solids and 2540 E Volatile Solids	Store at 4°C and begin test within 3 days	10	3190	9777
Total Nitrogen, mg/L as N	4500-N C. Persulfate Method	Acidify to pH< 2 with concentrated sulfuric acid	0.05	87.3	1650
Total Phosphorous, mg/L as PO_4	4500-P C. Vanadomolybdophosphoric Acid Colorimetric Method	Acidify to pH< 2 using concentrated sulfuric acid and store at 4°C for up to 28 days	0.005	9.9	49
Aluminum, mg/L	3500-Al B. Eriochrome Cyanine R Method	Acidify with concentrated nitric acid to pH=2	0.01		0.343
Calcium, mg/L	3111 B Direct Air-Acetylene Flame Method using a PerkinElmer Flame AA	Add 5mL/L of concentrated nitric acid. Re-adjust to pH=4	0.01	170	125
Iron Digested, mg/L	3111 B Direct Air-Acetylene and 3111 C Extraction/ Air Acetylene Flame Method using a PerkinElmer Flame AA, EPA Mild Digestion Method 3005A-2	Add 5mL/L of concentrated nitric acid. Re-adjust to pH=4	0.01	14.1	
Magnesium, mg/L	3111 B Direct Air-Acetylene Flame Method using a PerkinElmer Flame AA	Add 5mL/L of concentrated nitric acid. Re-adjust to pH=4	0.008	64.3	32.62
Sodium, mg/L	3111 B Direct Air-Acetylene Flame Method using a PerkinElmer Flame AA	Add 5mL/L of concentrated nitric acid. Re-adjust to pH=4	0.1	660	5309
Bromide, mg/L	4140 B Capillary Ion Electrophoresis with indirect UV	Refrigerate at 4°C and process as soon as possible	0.1		162
Chloride, mg/L	4140 B Capillary Ion Electrophoresis with indirect UV	Refrigerate at 4°C and process as soon as possible	0.1		3413
Sulfate, mg/L	4140 B Capillary Ion Electrophoresis with indirect UV	Refrigerate at 4°C and process as soon as possible	0.1		403

[a] Standard Method 20th edition

Microscopic examination of the leachate sample from March 2004 was conducted to assess the presence of microorganisms and also the types of solid material in the leachate. A light micrograph of stained bacterial cells in the sample is shown in Figure 2a and a scanning electron micrograph is shown Figure 2b. As shown, there is significant evidence of microbial activity in the leachate.
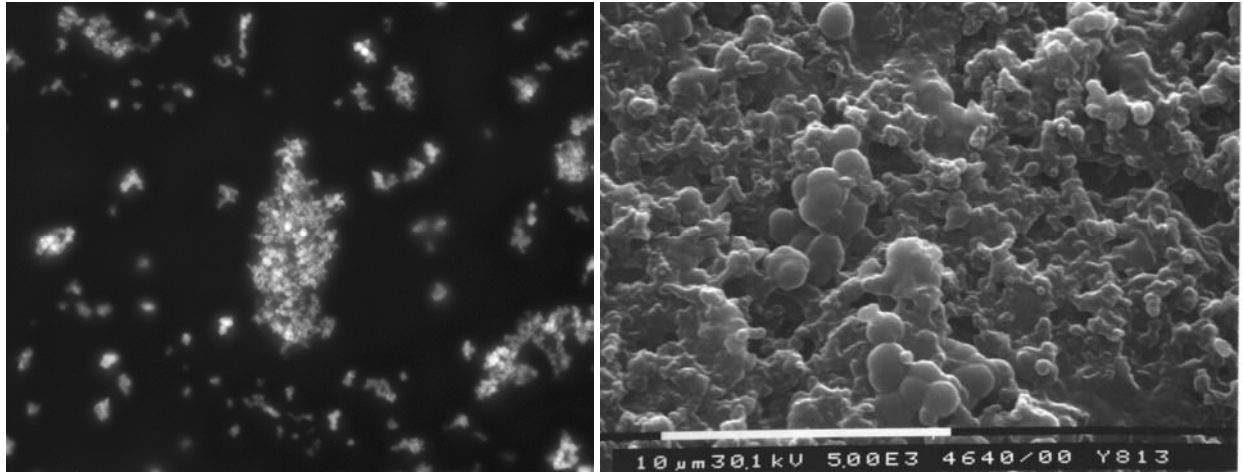
Figure 2. Particles in leachate sample from cell 6 collected in March 2004. a.) Light micrograph of bacterial cells in leachate sample from cell 6 collected in March 2004. The scale is 2 mm ≈ 1 μm. b) Scanning Electron Micrograph of particles in leachate from cell 6; the white line represents 10 μm.

An elemental analysis of the suspended particles in the leachate is shown in Figure 3. As shown, the dominant component of the suspended material is calcium, with some evidence of magnesium, phosphorus, and silica. It is likely that the solid material is dominated by calcium carbonate. The elemental analysis is consistent with the analysis of the dissolved constituents.
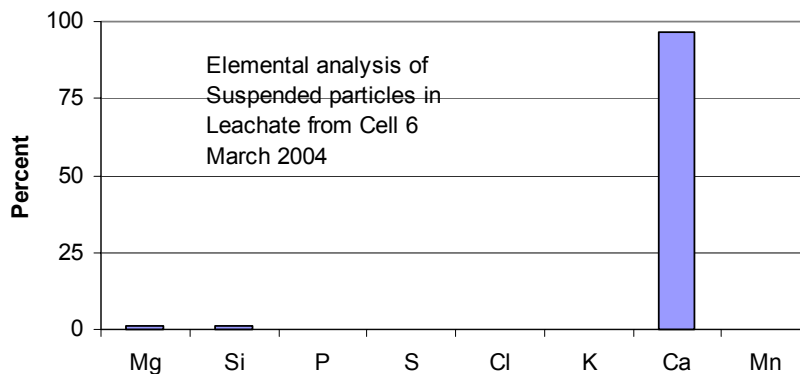
Figure 3. Elemental analysis of suspended particles in leachate from cell 6 analyses using scanning electron microscopy and energy dispersive spectroscopy.

Leachate samples were also collected from an ash monofill in west-central Florida. A photograph of the monofill is shown in Figure 4. The monofill receives co-mingled fly ash and bottom ash from a mass burn waste to energy facility.

Figure 4. Ash monofill in west central Florida

A comparison of the leachate characteristics from the ash monofill and from the southeast Florida Class I landfill is shown in Table 3. While the data shown are based on single grab samples obtained from each site, there are some important differences between the types of leachate. The ash monofill leachate has lower levels of alkalinity, nutrients, and magnesium than the levels associated with the leachate from the southeast Florida landfill. Conversely, levels of total dissolved solids (TDS), calcium, and chloride are at least an order of magnitude higher in the ash monofill leachate. Based on comparing the calcium to alkalinity ratio it is evident that the ash monofill leachate is dominated by calcium whereas the southeast Florida landfill leachate is dominated by carbonate. The higher ionic strength characteristic of the ash monofill leachate can act to increase the solubility of minerals, thereby decreasing the potential for formation of solid precipitates. More sample events would be needed to verify these trends, but it is evident that the leachate from the southeast Florida landfill is more susceptible to formation of mineral precipitates due to the relative quantities of constituents that could co-precipitate (i.e. calcium, magnesium, iron, carbonate, and sulfate).

Table 3. Comparison of leachate characteristics from west central Florida ash monofill and southeast Florida Class I landfill.

Parameter	Ash Monofill Leachate[1]	Class I Landfill Leachate	
	Oct-04	Apr-04	Nov-04
Alkalinity, mg $CaCO_3$ / L	140	1,300	7,033
pH, standard pH units	5.81 (0.15)	6.85	7.64
Solids (TDS), mg/L	24,983 (25)	3,190	9,777
TOC, mg/L as C	7.32 (0.03)		
Nutrients			
Total Nitrogen, mg/L as N	23.1 (6.7)	87.3	1,650
Total Phosphorous, mg/L as PO_4	11.0 (2.5)	9.9	49
Metals			
Aluminum, mg/L			0.343
Calcium, mg/L	5,384 (50)	170	125
Copper, mg/L	0.41 (.921)		
Iron, mg/L	7.02 (0.823)	14.1	
Magnesium, mg/L	4.65 (0.066)	64.3	32.6
Manganese, mg/L	0.67 (0.040)		
Potassium, mg/L	1,778 (8.6)		
Silica, mg/L as SiO_2	1.1 (0.2)		
Sodium, mg/L	2,704 (452)	660	5,309
Zinc, mg/L	0.183 (0.006)		
Anions			
Bromide, mg/L			162
Chloride, mg/L	9,183		3,413
Sulfate, mg/L	517 (14)		403
Ratios			
Calcium/TDS, percent	21.5	5.3	1.3
Calcium/Alkalinity, mg/mg	38.5	0.13	0.02

[1]Standard deviations are shown in parentheses.

Leachate from the ash monofill was relatively clear when it was sampled. However, upon storage the turbidity in the sample increased within a few hours. Changes in oxidation-reduction potential due to exposure to atmospheric oxygen may have contributed to the formation of particles. SEM/EDS was conducted to identify the dominant constituents associated with the turbidity in the stored leachate from the ash monofill. Example micrographs of the particles isolated from the ash monofill leachate are shown in Figure 5. In the upper micrograph, iron is the dominant element associated with the particles and it co-precipitated with calcium, sulfur, phosphorus, and silica. In the lower micrograph, the dominant element is calcium with co-precipitation of silica, phosphorus, sulfur, and chloride. Iron is also present in some of the precipitates. It is interesting to note the differences in the morphology of the particles that form in the leachate. The shape, size, and surface properties can impact the extent to which this material could initiate the clogging process.
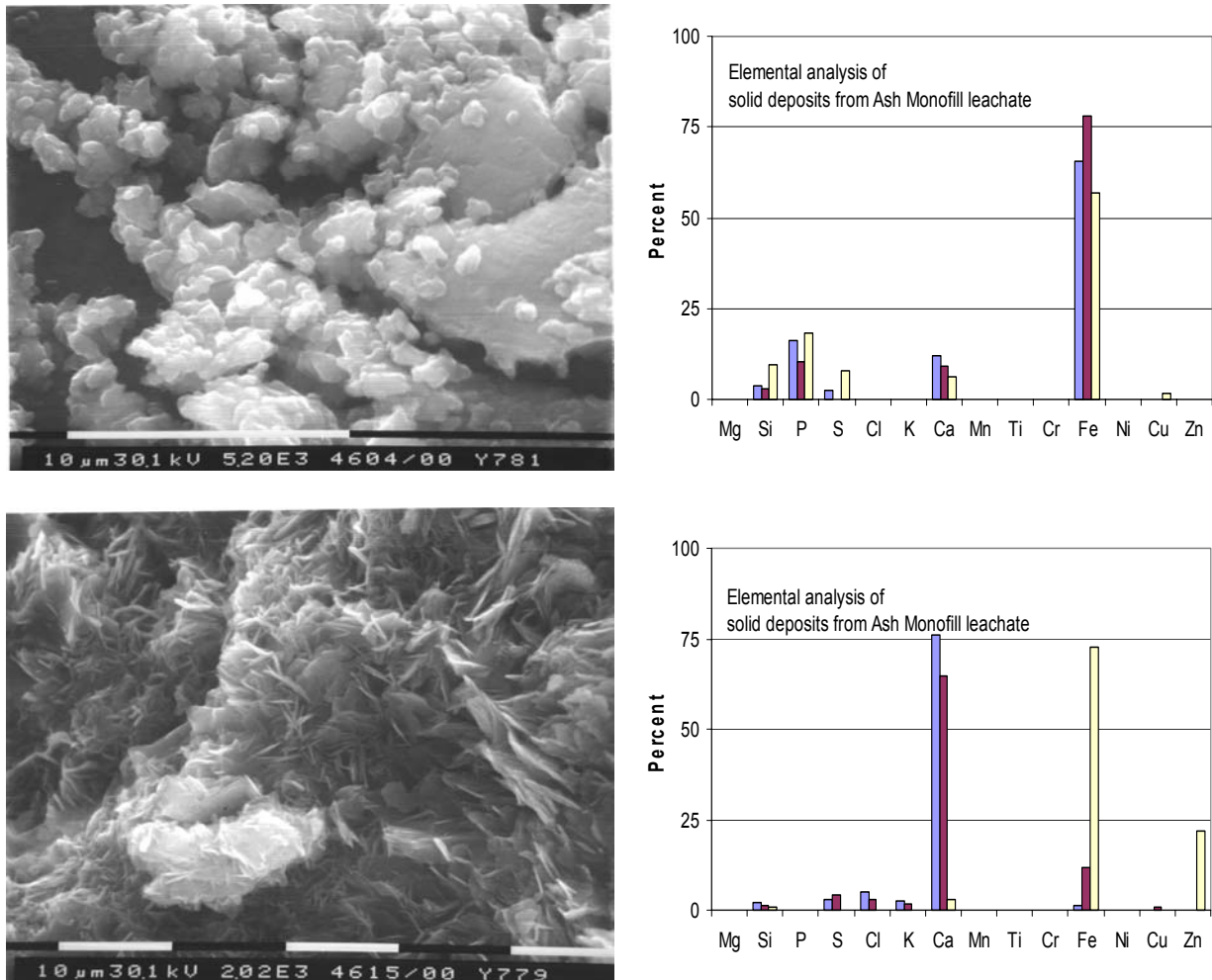
Figure 5. Example scanning electron micrographs and elemental analysis of particles in leachate from the west central Florida ash monofill.

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Calcified bacterial particles were also identified in the leachate from the ash monofill. These types of bacteria, sometimes referred to as nanobacteria, are capable of forming crystalline calcium phosphate that can serve as a seed for the development of mineral deposits (Hudelist et al. 2004). Limited information is currently available on the abundance of these bacterial particles in landfill leachates.
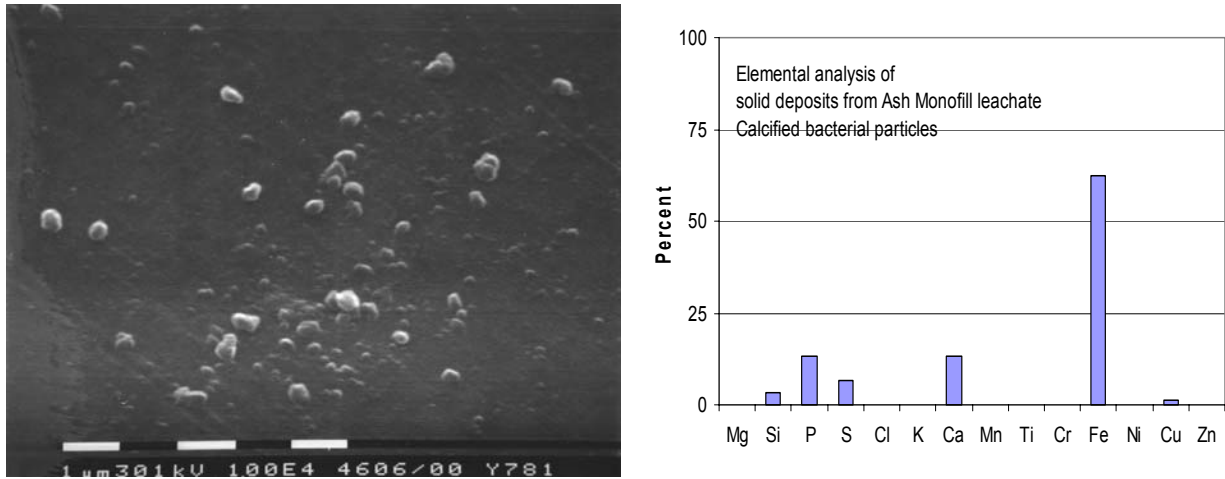
Figure 6. Calcified bacterial particles from ash monofill leachate

Characterization of solid precipitates

Solid precipitates were obtained from the leachate collection system of the southeast Florida landfill and from one of the gravity lines at the ash monofill. Physical characterization tests were conducted to quantify the composition of mineral deposits using SEM/EDS.

A photograph of the southeast Florida landfill is shown in Figure 7 along with a partially blocked pipe. The material in the pipe had a lava-like consistency and was evaluated using SEM/EDS. Example micrographs are shown in Figure 8-11 in comparison to the elemental analysis associated with the particles depicted in each micrograph. Because the samples were received in a dry form, it was not possible to assess microbial activity.

Figure 7. Southeast Florida landfill and clogged 8 inch pipe removed from leachate collection system.

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As shown, the dominant element in each precipitate is calcium and the other elements that co-precipitate include phosphorus, silica, and sulfur. This method is not useful for detection of carbonate, however, it is likely that carbonate is a constituent of each of the precipitates. The physical structure and particle size of the precipitates vary with elemental composition. These findings are similar to those reported by other studies on this landfill (Maliva et al. 2000, Missimer International 2000).
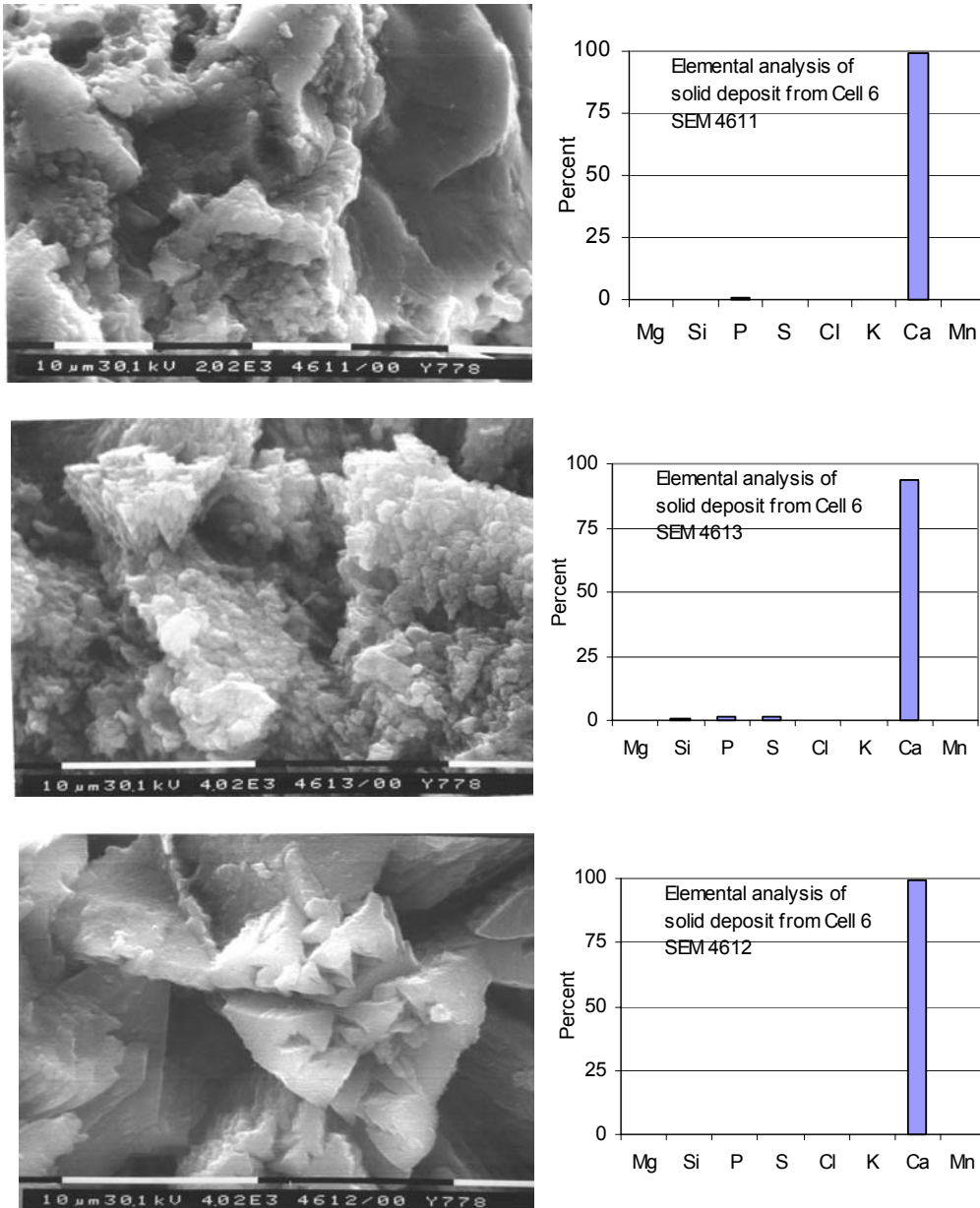
Figure 8. Example scanning electron micrographs of the solid material collected in the leachate collection system from the southeast Florida landfill (cell 6). The white line in each micrograph represents 10 μm.
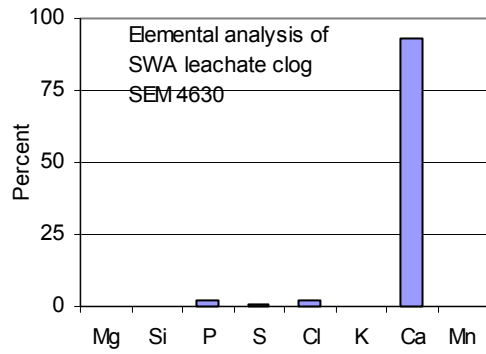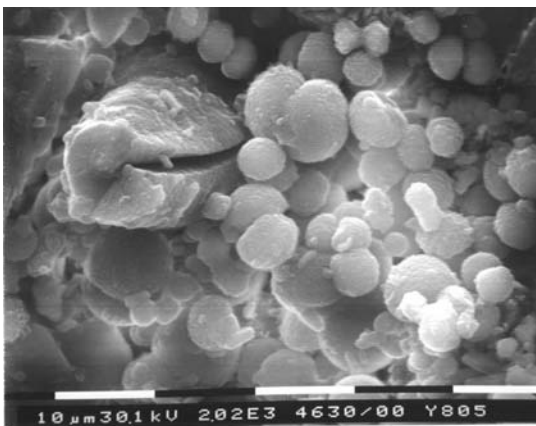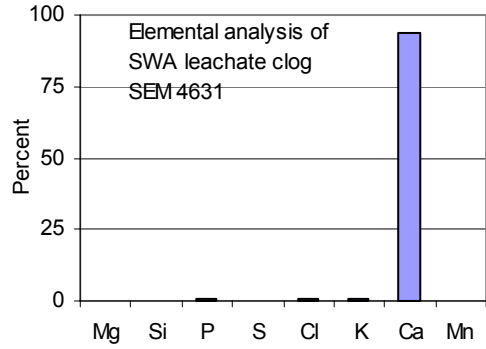
Figure 9. Example scanning electron micrographs of the solid material in a solid sample removed from a clogged pipe from the southeast Florida landfill. The white line in each micrograph represents 10 µm.
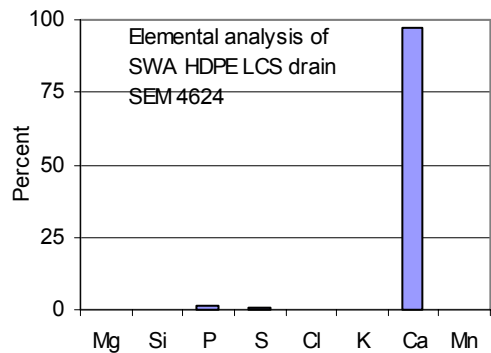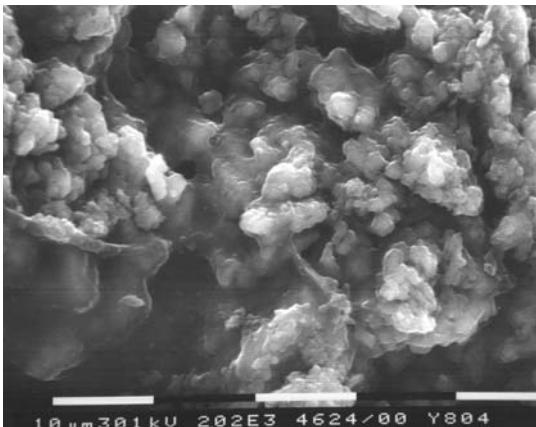
Figure 10. Example scanning electron micrographs of the solid material in a solid sample removed from a HDPE leachate collection system drain. The white line in each micrograph represents 10 µm.
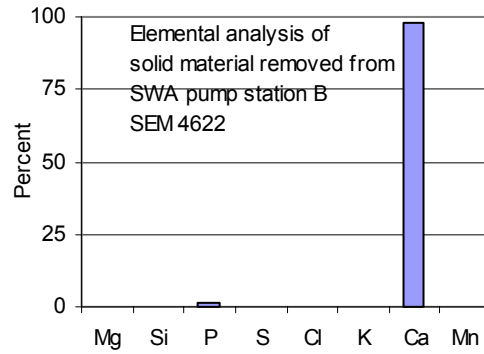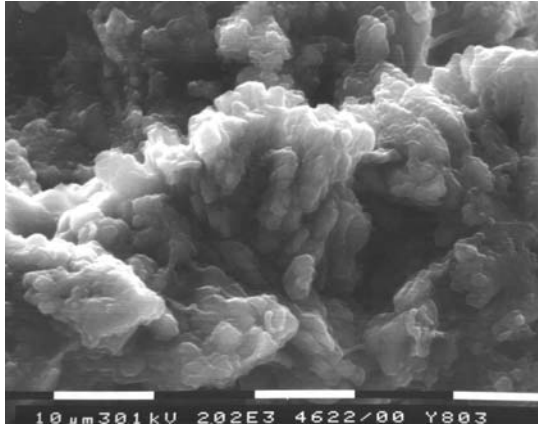
Figure 11. Example scanning electron micrographs of the solid material in a solid sample removed from the southeast Florida landfill pump station B (samples provided by CDM).

An example of solid material recovered from a gravity drain line from the ash monofill is shown in Figure 12. As was evident from the leachate analysis, there is less carbonate available for production of carbonate based precipitates. The dominant elements observed in the monofill drainage system were consisted of iron or calcium complexing with sulfur, phosphate, and/or silicate. The dry material was powdery in nature and consisted more of a gypsum-like material than was observed in the deposits associated with the southeast Florida landfill.
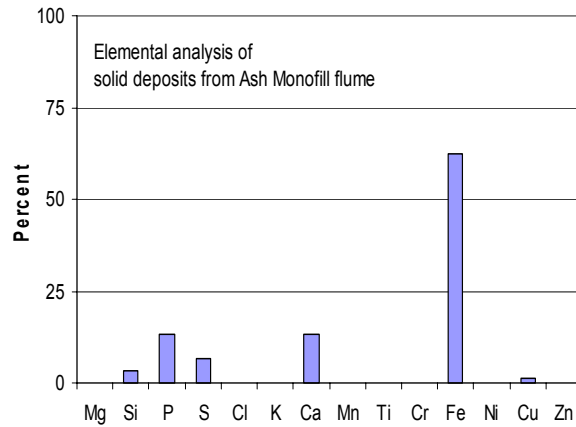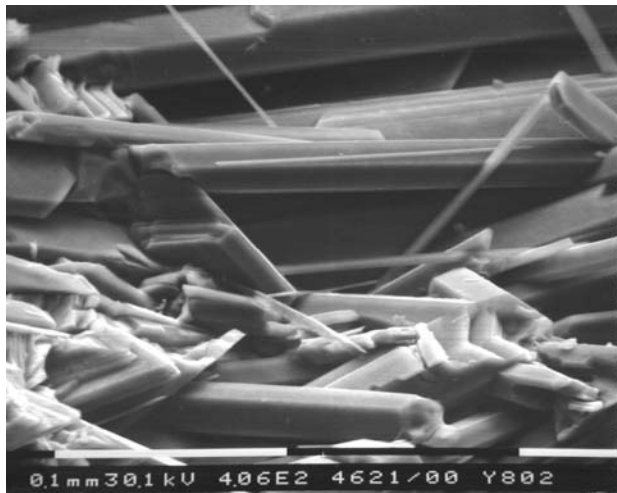
Figure 12. Example scanning electron micrograph of the solid material deposit from a gravity leachate drain line at the ash monofill.

LYSIMETER TESTS

Lysimeter tests provide an opportunity to evaluate the waste degradation process and leachate generation under controlled conditions. Wastes are placed in a reactor 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. The use of lysimeters can provide an opportunity to evaluate the formation of leachate and the potential formation of collection system clogs under controlled conditions (van der Sloot, 1998). To develop a better understanding of the mechanisms that initiate clogging of leachate collection systems, lysimeter tests were conducted. The lysimeter design was developed from a literature review of lysimeter studies. Lysimeter design parameters from published studies are compared in Table 4.

Table 4. Select Design Parameters for Lysimeters.

Lysimeter Geometry and Size			Lysimeter structure	Packing Material	Reference:
Column:			PVC: Schedule 40	6-mm diameter glass beads	Rowe et al. (2002)
	Diameter:	50 mm			
	Height:	700mm			
Box:			PVC	Drainage blanket: clear stone	Fleming et al. (1999)
	Width:	250 mm		MSW:5-10yr old waste	
	Length:	600 mm		Geotextile: separating MSW	
	Height:	700 mm		from drainage blanket	
Box:			Brick and concrete	Liner: HDPE	Blight et al. (1999)
	Width:	1.76 m		Drainage layer: 100-mm gravel,	
	Length:	1.06 m		MSW	
	Height:	1.76 m			
Column:			MDPE/HDPE	Drainage layer: limestone /	Paksy et al. (1998)
	Diameter:	230 mm		Thames gravel	
	Height:	900 mm		MSW: 4-5 yr old waste	

Laboratory lysimeter tests

A set of eight lysimeters were constructed to provide a basis for comparing the impacts of waste components, degree of mixing of waste components, and the type of material surrounding the leachate collection system. The waste materials were obtained from the North County Resource Recovery Facility in Palm Beach County, FL. and included processed municipal solid waste (MSW), bottom ash and fly ash from the RDF combustion facility, and residuals from water and wastewater treatment facilities in the landfill service area. The distribution of the wastes entombed in each lysimeter is detailed in Table 5. The moisture content and density of each component was evaluated prior to lysimeter start-up and are given in Table 6.

Table 5. Distribution of waste materials used in each lysimeter.

Number	Description[a]	MSW[b]	WTE[c] ash		Treatment process residuals[d]	
			Fly ash	Bottom ash	Water treatment: lime softening	Wastewater Treatment: Biosolids
1	Ash 1	0%	20%	80%	0%	0%
5	Ash 2	0%	20%	80%	0%	0%
2	MSW 1	100%	0%	0%	0%	0%
6	MSW 2	100%	0%	0%	0%	0%
3	Mixture 1	60%	6%	24%	5%	5%
7	Mixture 2	60%	6%	24%	5%	5%
4	Layer 1	60%	6%	24%	5%	5%
8	Layer 2	60%	6%	24%	5%	5%

[a] Group 1: gravel above the leachate collection pipe; Group 2: sand above the leachate collection pipe;
[b] 25 ft^3 of processed municipal solid waste obtained from SWA in April 2004; [c] 10 ft^3 of bottom ash and 5 ft^3 of fly ash from Waste-to-Energy Facility (RDF) at SWA obtained in April 2004; ; [d] 1 ft^3 of Residuals from water and wastewater treatment facilities in SWA service area obtained in April 2004.

Table 6. As received densities of materials obtained from SWA for use in laboratory lysimeters.

Sample	Moisture Level	Lysimeter application	Density, g/mL	Density, lb/yd^3
Sand 1 (Cholee)	Dry	Drainage layer above leachate collection pipe and above geotextile for Group 2 lysimeters (5-8)	1.23	2065
Sand 2	Dry	Five inch layer used below leachate collection system and liner in all lysimeters	1.47	2485
Wastewater treatment plant residuals	Wet	Lysimeters containing mixtures (Mix 1, Mix 2, Layer 1, Layer 2)	0.482	812
Water treatment plant residuals	Wet	Lysimeters containing mixtures (Mix 1, Mix 2, Layer 1, Layer 2)	1.26	2120
Fly Ash	Dry	Ash monofills (Ash 1 and Ash 2) and lysimeters containing mixtures (Mix 1, Mix 2, Layer 1, Layer 2)	0.50	834
Bottom Ash	Dry	Ash monofills (Ash 1 and Ash 2) and lysimeters containing mixtures (Mix 1, Mix 2, Layer 1, Layer 2)	0.90	1512
MSW (Process Rejects)	Wet	MSW monofills (MSW 1 and MSW 2) and lysimeters containing mixtures (Mix 1, Mix 2, Layer 1, Layer 2)	0.64	1084
MSW (Process Rejects)	Dry	Used to evaluate initial moisture content	0.24	410
MSW (RDF)	Wet	Not used in lysimeters	0.67	1123
MSW (RDF)	Dry	Used to evaluate initial moisture content	0.19	317

Lysimeter design and start-up

Each lysimeter consisted of a 4½-foot tall, 12-inch diameter PVC pipe to hold the wastes underlain by a leachate collection system and capped with valves to allow for gas collection. Sampling ports were installed at the leachate collection system, gas taps, and two locations along the body of the reactor.

The leachate collection system was designed to simulate field conditions and consisted of a perforated 1¼-inch diameter PVC pipe containing two rows of 3/8-inch diameter openings six inches apart and separated at an angle of 120°. The lysimeters were lined with 1.53 mm (60mil) thick HDPE liners (Agru America, Inc.). The leachate collection pipes were surrounded by gravel (2 to 2½ inch) and geotextiles were used above and below the gravel layers. The drainage system separating the waste from the leachate collection pipe was five inches of granular material (1 to 1½ inch gravel or Cholee sand). A 5-inch layer of sand below the leachate collection pipes was used to provide support. The Viton tubing used for leachate recirculation had an ID of 0.25 inches, OD of 0.3125 inches, and wall thickness of 0.03125 inches.

The materials used in construction of the collection system were obtained from North County Resource Recovery Facility in Palm Beach County, FL. A pump and leachate reservoirs were attached to each lysimeter to manage the leachate. The lysimeters were designed in groups of four with the main difference between the two groups being the material that covered the drainage system. In lysimeters 1-4, five inches of 1 to 1½ inch gravel was placed over the leachate collection pipes; whereas in lysimeters 5-8, a five inch layer of sand was used. A diagram of the main features of the lysimeters is shown in Figure 13 and photographs of the components are shown in Figure 14.
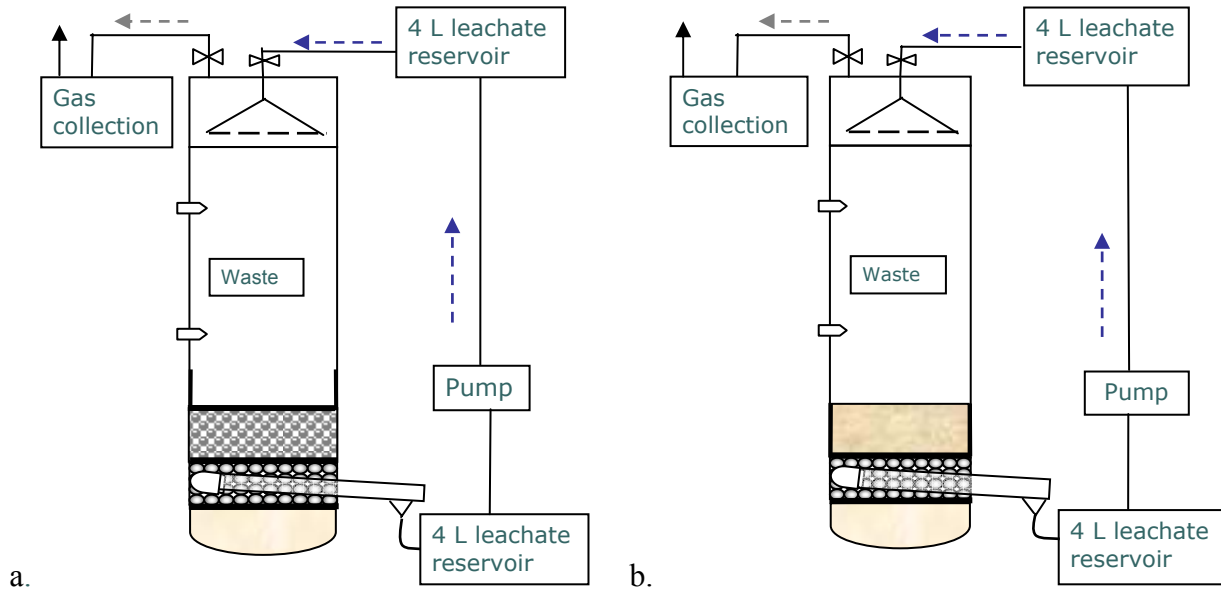
Figure 13. Schematic of lysimeters used in this study: a.) Group 1 lysimeters (1-4) with gravel over the leachate collection pipe; and b.) Group 2 lysimeters (5-8) with sand above the leachate collection pipe.

Prior to emplacement of the wastes in the lysimeters, the liners, pipes, geotextiles, and drainage material were installed and flushed with copious amounts of water to remove fines and other contaminants. A 2 m tall compaction tool (see Figure 19c) was used to install the liners and geomembranes. After the leachate collection systems were in place, each lysimeter was leak-tested. The leak testing consisted of filling each lysimeter with about 20 liters of water, shutting all valves, and observing the lysimeters for evidence of leaks over a 24 hour period. All leaks were sealed with sealants (Marine Adhesive Sealant 5200 or State Formuflex Clear Adhesive Sealant with UV inhibitor) and the process was repeated until all apparent leaks were sealed.

Figure 14. Photographs of laboratory lysimeters and materials used for leachate collection system and leachate application system. Diameter of all components is 12 inches: a.) Lysimeter under construction showing funnels used for leachate distribution system; b.) Bank of 4 lysimeters with leachate collection systems and pumps; c.) Compaction device used during emplacement of wastes; d.) Sand used for leachate drainage system in lysimeters 5-8; e.) Gravel used for leachate drainage system in lysimeters 1-4; f.) Leachate application system used in all lysimeters consisting of an inverted funnel and perforated plate; g.) Liner material; h.) Bottom of geotextile; i.) Top view of geotextile; j.) Lysimeter cap with leachate application system; k.) Liquid flowing through leachate distribution system.

A 24 hour batch extraction test was conducted on the sands to assess the degree to which minerals could leach from the drainage material. In each case samples of sand were dried, preweighed, mixed with distilled water in a liquid to solid ratio of 10 g/g, and incubated at 35 $^\circ$C for 120 hours. Following the incubation period, the liquid leachate was removed and tested for alkalinity, pH, total solids, total organic carbon (TOC), aluminum, calcium, magnesium, potassium, and sodium. Negligible amounts of aluminum, magnesium, potassium, and sodium were leached from the sand. A summary of the results is shown in Table 7. The Cholee sand leached about six times more alkalinity than did the bottom sand and about a two fold higher amount of organic carbon. There was no significant difference in the amount of calcium leached from either of the two sands.

Table 7. Comparison of the amount of the leachate pH and the amount of alkalinity, calcium, and TOC leached from the two types of sand used in the lysimeters in a 120 hour batch leaching test.

Parameter	Cholee sand: used in lysimeters 5-8 above leachate collection pipe	Bottom sand: used in all lysimeters below leachate collection pipe
pH, standard pH units	8.24	8.00
Alkalinity, mg/kg	1216.70	201.67
Total solids, mg/kg	5576.54	100.84
TOC, mg/kg	67.73	32.77
Aluminum, mg/kg	5.37	3.93
Calcium, mg/kg	59.62	77.34
Magnesium, mg/kg	0.87	1.59
Potassium, mg/kg	4.87	0.40
Sodium, mg/kg	7.00	2.42

After ensuring that the lysimeters were free of leaks, they were filled with the appropriate mass of ash, MSW, and process residuals as outlined in Table 5. The ash (Ash 1 and Ash 2) and MSW (RDF process rejects) (MSW 1 and MSW 2) monofill lysimeters were filled with the waste material to a depth of about 2.5 ft above the drainage layer (after compaction). About 181 kg of combustion residues (159 kg bottom ash and 22 kg fly ash) were mixed and placed in each of the ash monofills and 143 kg of MSW were placed in each of the MSW monofills.

The lysimeters containing combinations of ash, MSW, and treatment process residuals were set up in two different ways: either mixed or layers. The contents of each lysimeter consisted of 60% MSW (86 kg) with the remaining mass derived from residues from RDF combustion and from water and wastewater treatment plants. The mixtures (Mix 1 and Mix 2) were derived by combining the materials according to the mass distribution shown in Table 5 in a 60 L container and manually mixing the contents.

For the lysimeters containing layers, four discrete layers were set up that consisted of two layers of MSW separated by treatment process residuals and overlain by combustion residues (fly ash and bottom ash). The layers (Layer 1 and Layer 2) were developed by first subdividing the MSW into two similar portions by weight. The first layer of MSW (30%) was placed at the bottom of the lysimeter, overlain by a layer of treatment process residuals (5% water treatment sludge and 5% wastewater process residuals). The third layer from the bottom consisted of the remainder of the MSW (30%) and the top layer (30%) consisted of fly ash (6%) and bottom ash (24%). Each waste layer was manually compacted using the compaction tool (See Figure 14) prior to closing off the lysimeters.

After emplacement of the wastes, distilled water was applied to each lysimeter to saturate the wastes. A measured quantity of water was slowly added to the top of each lysimeter until the wastes were completely submerged. The lysimeters were covered and allowed to absorb the water for a 72 hour period. Following the absorption period, the liquid was drained by gravity and the volume of water 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 8.

Table 8. Field capacity of each type of lysimeter.

Lysimeter[a]	Volume Added, L	Volume Recovered, L	Volume Absorbed, L	Liquid:Solid Ratio, g/g
Ash 1; Ash 2	40	24	16	0.09
MSW 1; MSW 2	70	52	18	0.13
Mix 1; Mix 2	60	43	17	0.11
Layer 1; Layer 2	50	33	17	0.11

[a] See Table 5 for descriptions of lysimeter contents

After the field capacity test, the lysimeter caps were installed. Four liters of distilled water were applied to each lysimeter through the leachate application system (see Figure 13 and 14) to produce leachate and initiate waste degradation. Three liters of leachate were recirculated every 24-hours using the recirculation pumps and the leachate application system. This mode of operation was intended to simulate rainfall and 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. In addition, the use of the leachate application systems, helped to limit excessive channeling of the water and promoted exposure of the entire lysimeter contents to liquid on a regular basis.

Lysimeter operation

Leachates from each lysimeter were monitored to identify changes in biological activity, and to assess redox conditions, the concentrations of dominant electron acceptors, the dissolved mineral content, and buffer capacities. For the first two months of operation, lysimeters were monitored daily for pH, conductivity, temperature, oxidation-reduction potential, turbidity, volatile acids, and alkalinity. A more complete characterization was conducted twice per week including microbial concentrations.

After two months of operation, the sampling frequency was reduced to twice per week for routine monitoring and once per week for complete characterization. A summary of the parameters monitored and the frequency of monitoring under steady-state operation is given in Table 9. The amount of leachate that was withdrawn for each sampling event was replaced with an equal amount of distilled water to maintain a relatively constant volume of liquid within each lysimeter.

Leachate Characterization

The chemical composition of the leachates from each lysimeter was evaluated to identify dominant constituents, indicators of microbiological activity, and determine the potential for precipitate formation. Microbiological tests were conducted to quantify the concentration of bacteria in each lysimeter and to develop tests to determine the microbial community structure.

Chemical Characterization of leachates

A summary of the chemical characterization tests is given in Table 9 with information on the detection limits and frequency of monitoring. During the start-up phase of operations, the leachates were monitored daily for routine parameters. After two months of operation, the monitoring frequency was reduced to twice weekly for routine parameters and once/week for comprehensive chemical characterization.

Table 9. Parameters monitored on leachate samples from laboratory lysimeters.

Test	Method[a]	Instrument	Detection Limit	Frequency
pH	4500-H+ B. Electrometric Method	inoLab pH probe	0.01 pH unit	Twice/week
Conductivity	2510 B. Laboratory Method	inoLab conductivity probe		Twice/week
Turbidity	2130 B. Nephelometric Method	Hach 2100AN Turbidimeter	0.02 NTU	Twice/week
Temperature	2550 B. Laboratory Method	inoLab temperature probe	0.1 $^{\circ}$ C	Twice/week
ORP	2580 B. Electrometric Method	Hach ORP probe	-1400 mV +1400 mV	Twice/week
Total Alkalinity	2320 B. Titration Method	Titration	20 mg/L as $CaCO_3$	Twice/week
Volatile Acids	DiLallo and Albertson (1961). Dual Titration Method.	Titration	10 mg/L as Acetic acid	Twice/week
Bacterial concentration	DAPI Stain, DNA extraction	Microscope	1/100 mL	Twice/week
Solids, Total and volatile	2540 B Total Solids and 2540 E Volatile Solids	Gravimetric	2 mg/L	Weekly
Nitrogen, Total, ammonia	4500-N C. Persulfate Method	Hach DR 4000 Spectrophotometer	0.2 mg/L	Weekly
Phosphorus, Total	4500-P C. Vanadomolybdophosphoric Acid Colorimetric Method	Hach DR 4000 Spectrophotometer	0.2 mg/L	Weekly
Calcium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer Flame AA	0.01 mg/L	Weekly
Iron, total and dissolved	3111 C Extraction/ Air-Acetylene EPA Mild Digestion Method 3005A-2	PerkinElmer Flame AA	0.01 mg/L	Weekly
Magnesium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer Flame AA	0.01 mg/L	Weekly
Potassium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer Flame AA	0.01 mg/L	Weekly
Sodium	3111 B. Direct Air-Acetylene Flame Method	PerkinElmer Flame AA	0.1 mg/L	Weekly
Chloride	4140 B. Capillary Ion Electrophoresis with indirect UV Detection.	Beckman	0.1 mg/L	Weekly
Silica	4500-SiO_2 Molybdosilicate Method	Hach DR 4000 Spectrophotometer	0.3 mg/L	Weekly
Sulfate	4140 B. Capillary Ion Electrophoresis with indirect UV Detection.	Beckman	0.1 mg/L	Weekly
Total Organic Carbon	5310 C. Persulfate-UV Method	Sievers 800 TOC Analyzer	0.05 mg/L	Monthly

[a]Standard Methods, 20th Edition (1998).

Several quality assurance practices were integrated into the sampling and analysis program. All probes (pH, conductivity, ORP) were calibrated regularly using standard buffers. All instruments (Flame AA, Capillary Electrophoresis, TOC analyzer) were calibrated each time they were used and during each sample run. All analyses were run in triplicate.

All data were compiled into EXCEL spreadsheets and validated in several ways. Average and standard deviations were calculated for each analysis and data anomalies were verified with repeat testing. Two internal checks were calculated on each sample. The measured TDS was compared to the sum of the dissolved constituents and to the conductivity. If the ratio of measured TDS/calculated TDS was not between 0.8 and 1, samples were rerun, if possible. In addition, an anion-cation balance was calculated on each sample. Samples with differences in anion and cation concentrations over 5% were retested, if possible.

Microbiological testing

Microbiological testing involved monitoring the concentration of bacteria using a staining technique. Samples were 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. An example micrograph of DAPI stained cells is shown in Figure 15. Cells are counted and the concentration is reported as number of cells/mL.
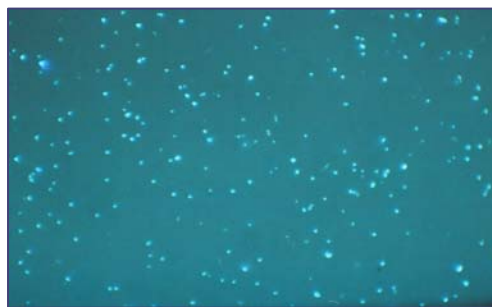
Figure 15. Example of DAPI staining used to differentiate bacterial cells from lysimeter leachate samples.

For DNA extraction, leachate samples were filtered through membrane filters with a pore size of 0.45 μm (Fisherbrand Cat. #09-719-2D) and the filters were stored at -20 °C. Community DNA was extracted from the filters using the Ultraclean Soil DNA Kit (MoBio Laboratories, Inc. Cat. #12800-100). The extracted DNA was stored at -20 °C for further analyses.

Polymerase Chain Reaction (PCR): Bacterial 16S rRNA genes were amplified using GC-clamped primers 1070f (5'-ATGGCTGTCGTCAGCT-3') and 1392r (5'-CACGGGCGGTGTGTAC-3'). PCR was performed in a T-personal thermocycler as follows: an initial denaturation step of 94 °C for 2 min, followed by 30 cycles of 94 °C for 45 s, 55 °C for 45 s, and 72 °C for 45 s and finally an elongation step of 72 °C for 3 min. The PCR products were loaded on a 1% agarose gel and electrophoresed at 70 V for 90 minutes to visualize the bands.

Denaturing Gradient Gel Electrophoresis (DGGE): DGGE was conducted using the Bio-Rad DCode Universal Mutation Detection System (Cat. #170-9080). A 1 mm thick 7% (wt/vol) polyacrylamide (acrylamide:bis acrylamide 37.5:1) (Fisher Scientific Cat. #BP 1410-1) gel containing a linear denaturing gradient of 45% - 60% formamide (ACROS Organics Cat. #327235000) and urea (ACROS Organics Cat. #327380010) was prepared. The gradients are shown in Table 10. The ingredients were mixed and the volume was brought up to 100 mL using nanopure water. To prepare the gels, 15 mL of the 45% gradient was poured into the reservoir chamber and 15 mL of the 60% gradient was poured into the mixing chamber of the gradient maker. A 7% ammonium persulfate (MP Biomedicals Cat. #802829) solution was prepared by measuring 0.07 g of ammonium persulfate and dissolving it in 1 mL of water. 150 µL of this solution was added to each chamber of the gradient maker followed by an addition of 15 µL of TEMED (N,N,N',N'-Tetramethylethylenediamine, Fisher Biotech Cat. #BP 150-20) to the 2 chambers. The valve between the 2 chambers was opened to allow the 2 gradients to be mixed and the gel was poured between the glass plates using a peristaltic pump. A small amount of the mixture was collected in a sterile tube to check for polymerization.

Table 10. Components of denaturating gradients used for DGGE analysis of lysimeter leachates.

Denaturing Gradient	Bis Acrylamide	50X TAE	Formamide	Urea
45%	17.5 ml	2 ml	18 ml	18.9 g
60%	17.5 ml	2 ml	24 ml	25.2 g

Following polymerization, gels were placed in an electrophoresis tank containing 7 liters of 1X TAE buffer (40 mM Tris-acetate, 1 mM EDTA, pH 8.0). The PCR products were mixed with 10 µL of loading dye (prepared by dissolving 10 g sucrose and 15 mg of Bromophenol blue {free acid} in 20 mL of nanopure water) and loaded into the gel using a pipetman and sequencer tips. The standard lanes were created by loading positive controls *Clostridium perfringens* (Sigma D5139) and *Escherichia coli* ATCC 9637 mixed with 10 µL of loading dye. The gel was electrophoresced at 47 V, 60 °C for 16 hours. After 16 hours, the gel was immersed in 300 mL of 1X TAE, stained with 20 µL of SYBR Green I (Molecular probes, S-7567) and placed on a shaker for 15 minutes. An image of the gel was obtained using a fluorescent green filter in a Foto/ Analyst Imaging System (Fotodyne Inc., Cat. #6-1500P). Gel images were further analyzed using Bionumerics software.

Results of Lysimeter Operation

Leachate characteristics for each lysimeter were evaluated to assess the variability of parameters that might impact the clogging potential such as pH, alkalinity, calcium, and total dissolved solids. After four months of operation, clogging occurred in some of the leachate recirculation tubing providing an opportunity to examine the characteristics of the clogged material. Key results of leachate characteristics are presented in this section. Data summaries are provided in Appendix A.

Leachate characteristics

The leachates from the ash monofill lysimeters were significantly different than leachates from the lysimeters containing MSW in terms of pH, total dissolved solids, and the concentration of microorganisms. A photograph of the leachate samples from the four types of lysimeters is shown in Figure 16. As shown, the ash monofill lysimeter leachates were relatively clear and free of particles and biomass.

Figure 16. Photograph of leachates from lysimeters. From left to right the samples represent Ash, MSW, Mixture, and Layers.

A comparison of the pH, alkalinity, calcium and calcium to alkalinity ratio for each lysimeter over the 8 month monitoring period is shown in Figure 17 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 leachates from the ash monofills were significantly different from the other leachates in terms of pH and alkalinity. Calcium levels associated with the leachates from the ash lysimeters were slightly higher than concentrations in leachates containing MSW or a mixture of MSW, ashes, and sludges, but the differences were not significant. In general, the type of drainage material (sand vs gravel) above the leachate collection pipe did not impact the leachate characteristics. The method of waste placement, layering vs. mixture, resulted in significantly lower levels of alkalinity for the layered wastes than for the mixtures, with alkalinity levels similar to those observed for the ash dominated lysimeters. Perhaps the presence of a concentrated layer of ash at the top of the lysimeter provides an opportunity for carbonate complexation with minerals and metals within the ash matrix that does not occur in the mixed waste or the MSW monofill.
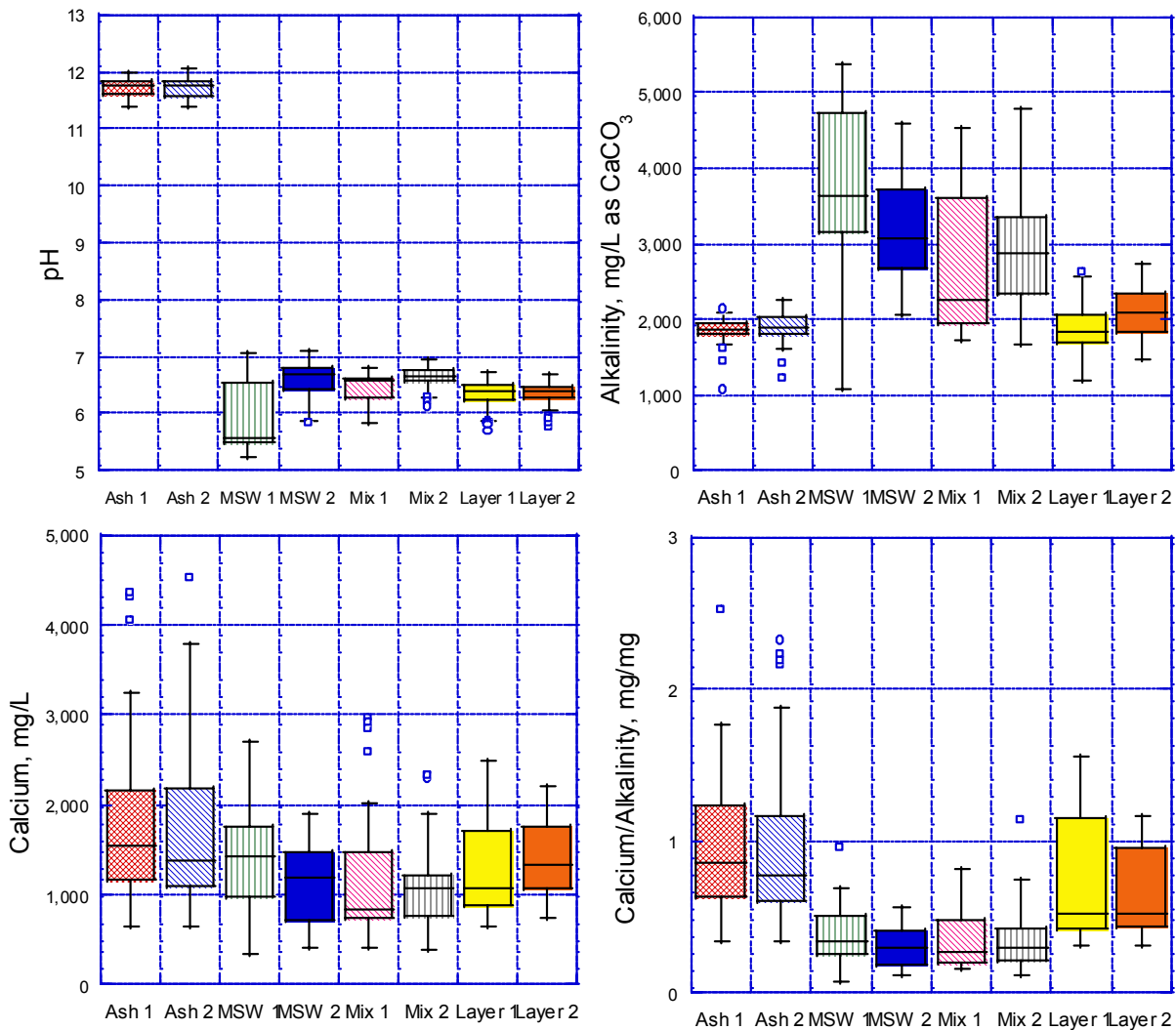
Figure 17. Comparison of pH, alkalinity, calcium and the calcium:alkalinity ratio from monitoring data for the 8 lysimeters.

A comparison of the steady-state bacterial concentrations associated with each type of lysimeter is given in Table 11. The six lysimeters that contained MSW all had steady state bacterial concentrations ranging from 0.5 to 4 x 10^9 cells/mL with the highest concentrations associated with the MSW monofills (MSW 1 and MSW 2). The leachates from the ash monofill lysimeters (Ash 1 and Ash 2) did not have any cells as determined by DAPI staining. This could be due to the high pH (approximately pH 11.0 to 12.0) of the leachate in these lysimeters. During the first month of operation, the DAPI cell count obtained from the other lysimeters increased consistently. After about a month, the cell numbers in these lysimeters 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.

Table 11. Comparison of the steady-state bacterial concentration in each type of lysimeter operated between May and December 2004.

Lysimeter type	Steady state bacterial concentration
Ash monofill (Ash 1 and Ash 2)	< 100 cells/mL
MSW Monofill (MSW 1 and MSW 2)	2-4 x 10^9 cells/mL
Waste, ash, and sludge mixtures (Mix 1 and Mix 2)	1 x 10^9 cells/mL
Waste, ash, and sludge layers (Layer 1 and layer 2)	0.5-2 x 10^9 cells/mL

Leachate characteristics that impact microbiological activity include the availability of organic carbon substrates and electron acceptors (oxygen, nitrate, sulfate, iron, manganese). An indicator of biological activity is the volatile acids concentration. Turbidity is an indirect measure of biological activity in that turbidity can consist of microorganisms and suspended and colloidal material generated by biological activity. A comparison of the oxidation reduction potential (ORP) of each lysimeter over the eight month course of operation is shown in Figure 18, As shown, all lysimeters sustained a reducing environment (ORP < 0) with more fluctuations associated with the MSW dominated lysimeters, most likely due to biological activity.
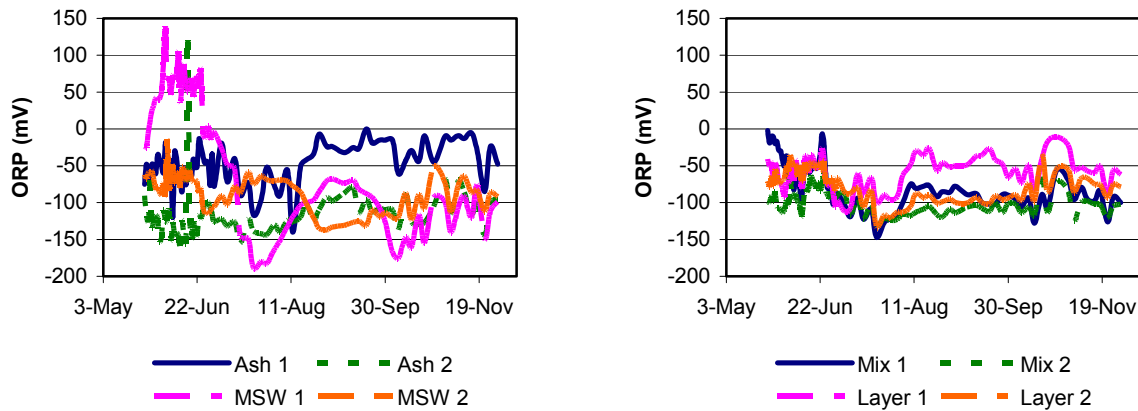
Figure 18. Comparison of the oxidation-reduction potential (ORP) for the ash monofill (Ash 1 and Ash 2), MSW monofill (MSW 1 and MSW 2) and composite lysimeters (Mix 1, Mix 2, Layer 1, Layer 2).

A boxplot comparison of the concentrations of volatile acids, TOC, iron, manganese, sulfate, and turbidity is shown in Figure 19. The ash monofill lysimeters had lower concentrations of TOC, volatile acids, and turbidity than the MSW dominated lysimeters suggesting that minimal biological activity occurred. All of the MSW dominated lysimeters appeared to sustain adequate concentrations of organic substrate and electron acceptors to support microbiological activity.
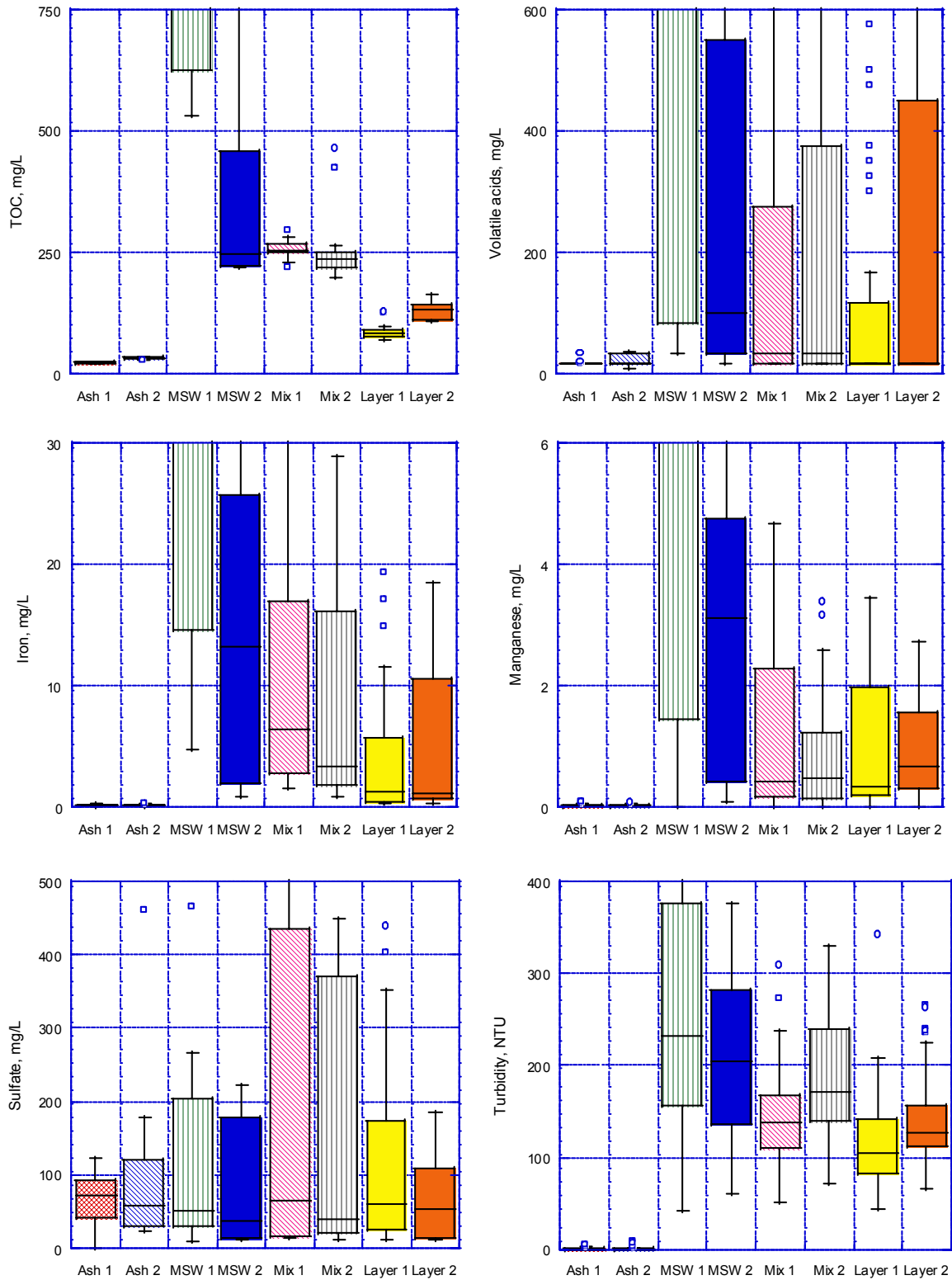
Figure 19. Boxplot comparison of volatile acids, TOC, iron, manganese, sulfate and turbidity levels in lysimeter leachates between May and December 2004. See Table 5 for lysimeter descriptions.

Variation in leachate characteristics over time

For purposes of comparing all of the data, the lysimeters were grouped as monofills or mixtures. The monofills include the ash monofills (Ash 1 and Ash 2) and the MSW monofills (MSW 1 and MSW 2). The mixtures include the lysimeters containing MSW, ash, and treatment plant residuals that were either mixed before emplacement in the lysimeters (Mix 1 and Mix 2) or layered during emplacement (Layer 1 and Layer 2).

Concentration of solids in lysimeter leachates

A comparison of the concentration of volatile solids and dissolved solids in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, residuals from water and wastewater treatment facilities) is shown in Figure 20. As shown, the volatile solids content of the MSW monofills was four to eight times higher than the volatile solids content of the ash monofills, particularly during the first few months of operation. Conversely, the total dissolved solids content of leachates derived from the ash monofills was two to three times higher than the MSW monofills, due to the higher mineral content of the ashes. Typically, the solids concentrations in leachates derived from the mixtures reflected the relative quantity of ash and MSW within each lysimeter.
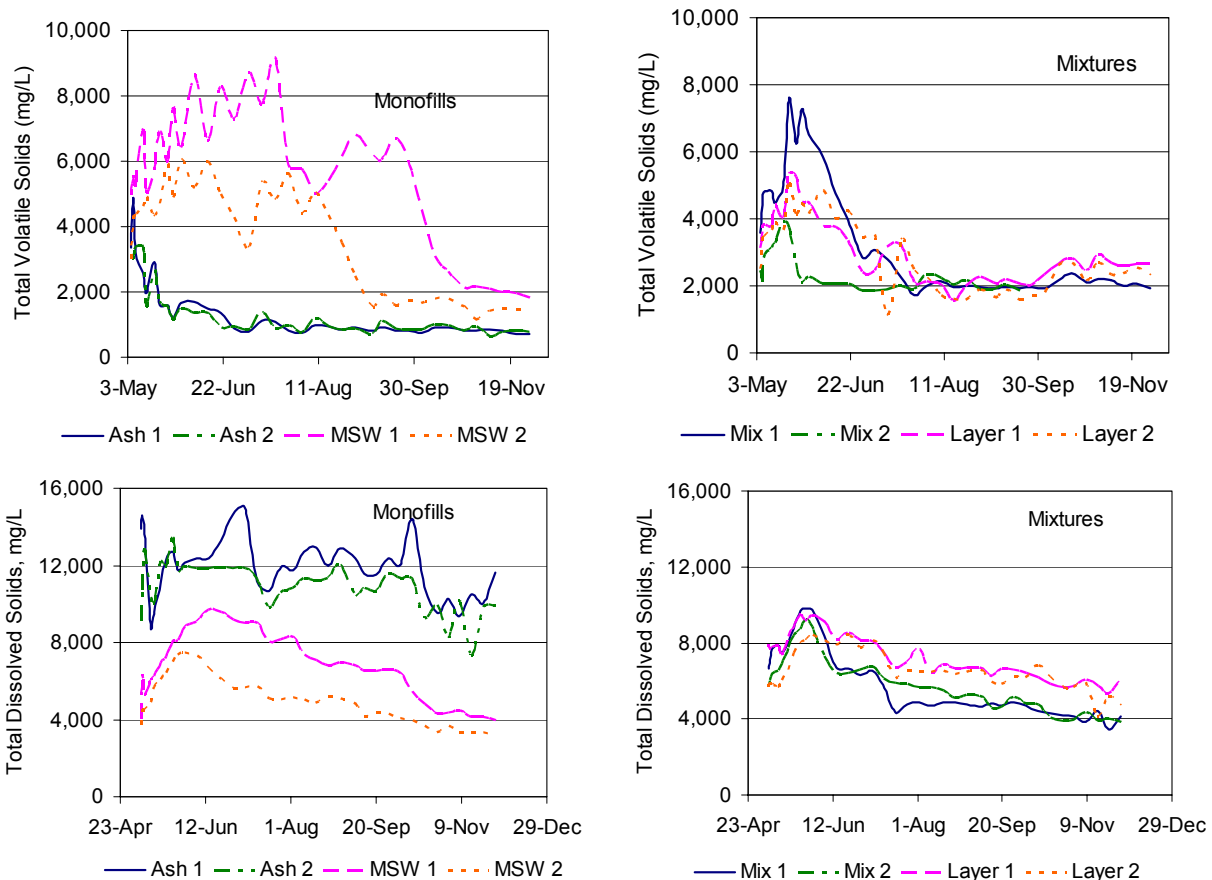
Figure 20. Comparison of the concentration of total volatile solids and total dissolved solids in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

Comparison of pH, turbidity, and alkalinity levels in lysimeter leachates

A comparison of the pH, turbidity, and alkalinity in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, residuals from water and wastewater treatment facilities) is shown in Figure 21. The pH associated with the ash lysimeters was significantly higher than the pH of leachates from the MSW lysimeters or the lysimeters containing mixtures. Turbidity levels were significantly higher in leachates from MSW dominated lysimeters, most likely due to the presence of microbial activity. 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 monofills and 4 to 9 mg/L-day for leachates from lysimeters containing mixtures.
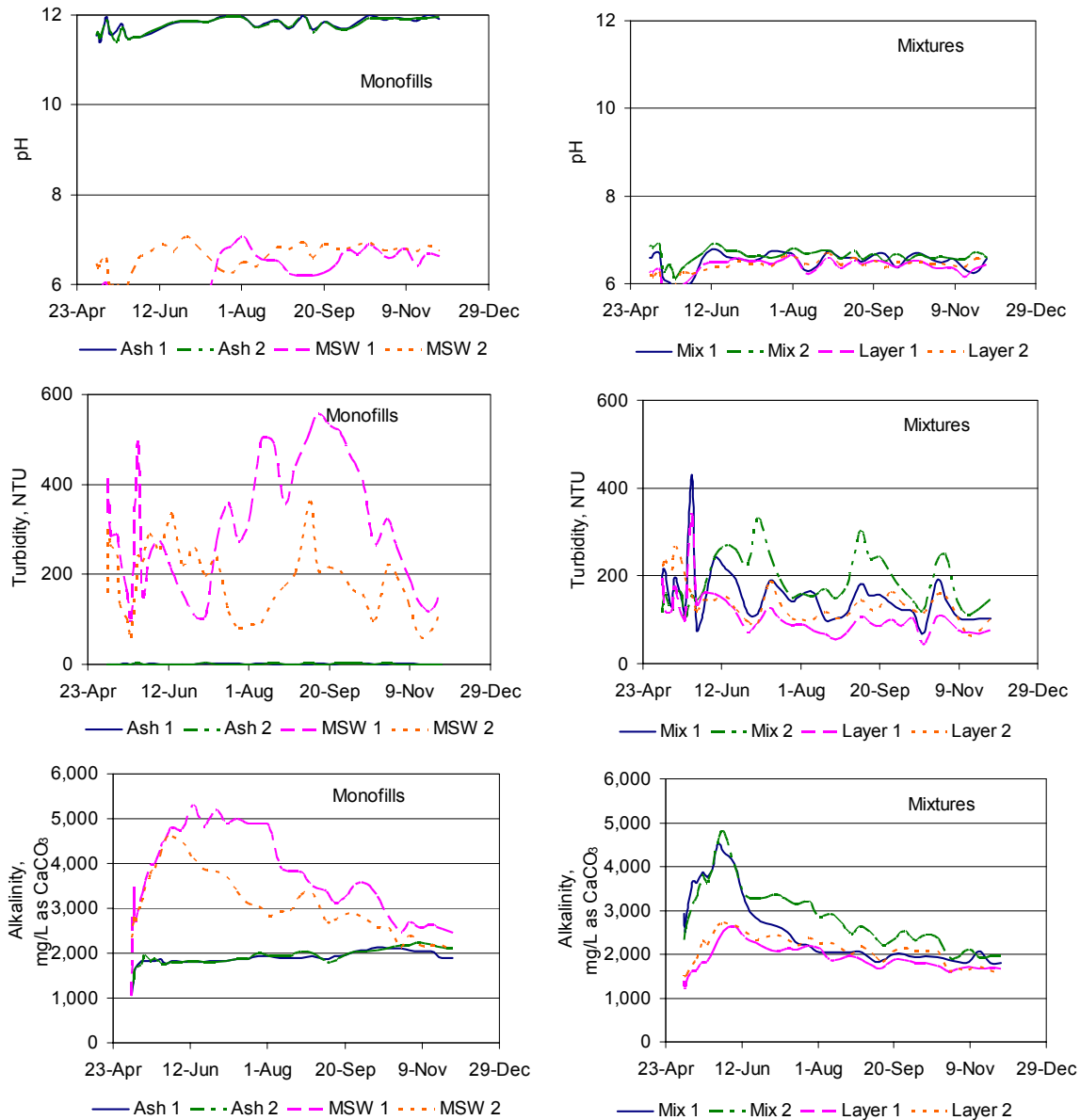
Figure 21. Comparison of the pH, turbidity, alkalinity in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

Comparison of dissolved calcium and magnesium in lysimeter leachates

A comparison of calcium and magnesium concentrations of the leachates from the lysimeters is shown in Figure 22. 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 mixtures. There was no significant difference in the rate of decrease of calcium based on the types of materials in the lysimeters. Magnesium levels were near detection limits for the ash monofills and less than 100 mg/L for the MSW monofills. However, the leachates from the lysimeters containing mixtures contained significantly higher levels of magnesium than the monofill leachates with concentrations ranging from about 100 to over 300 mg/L under steady state conditions. The reason for the higher concentrations and variability of magnesium in the leachates from the lysimeters containing mixtures is most likely due to the presence of treatment plant residuals in the waste mixtures. Unlike the calcium concentrations, there was no trend of decreasing magnesium with time.
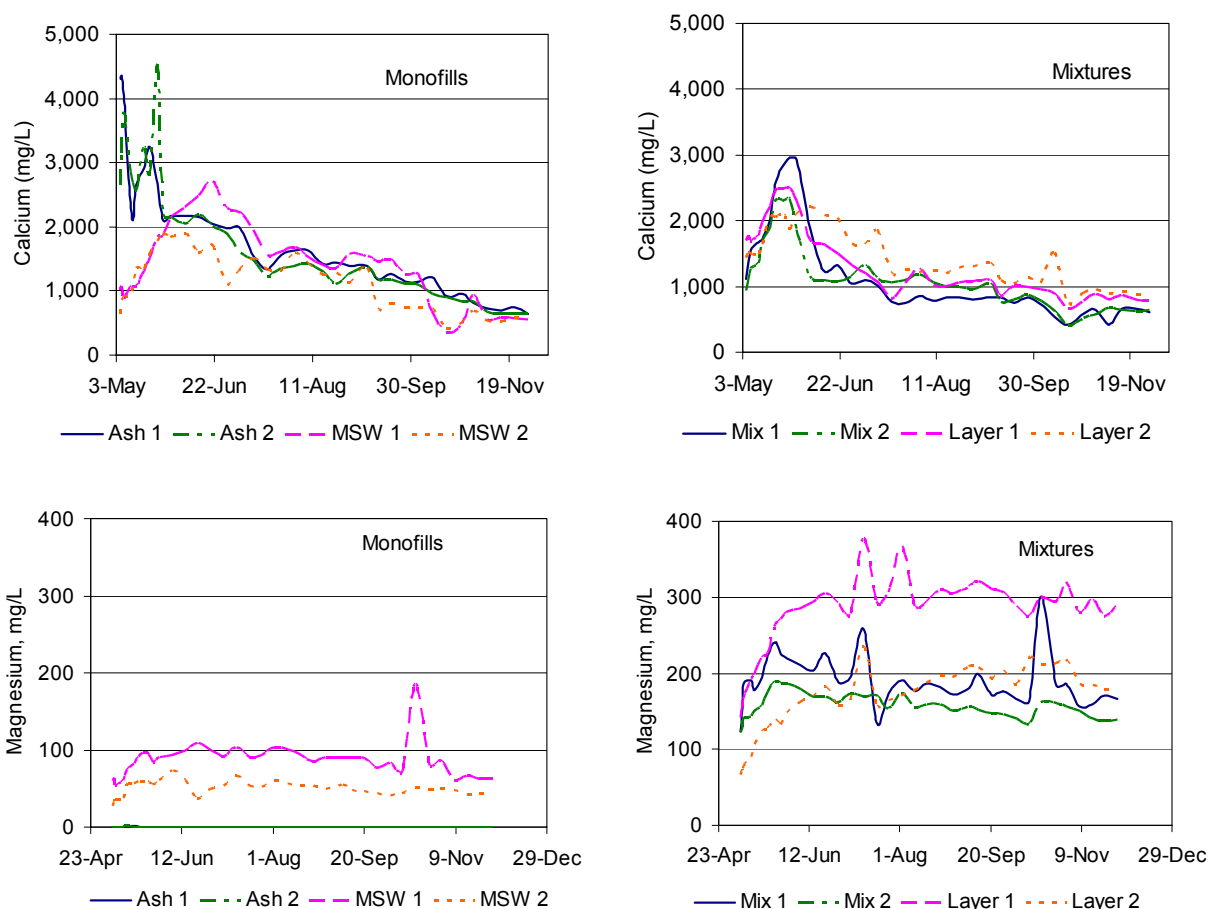
Figure 22. Comparison of the calcium and magnesium levels in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

A comparison of the relationship of calcium to total dissolved solids and calcium to alkalinity is shown in Figure 23 for leachates from lysimeters containing monofills and mixtures. Calcium to TDS ratios tended to be higher for the leachates from lysimeters containing MSW (either monofills or mixtures), 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 mixtures 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.
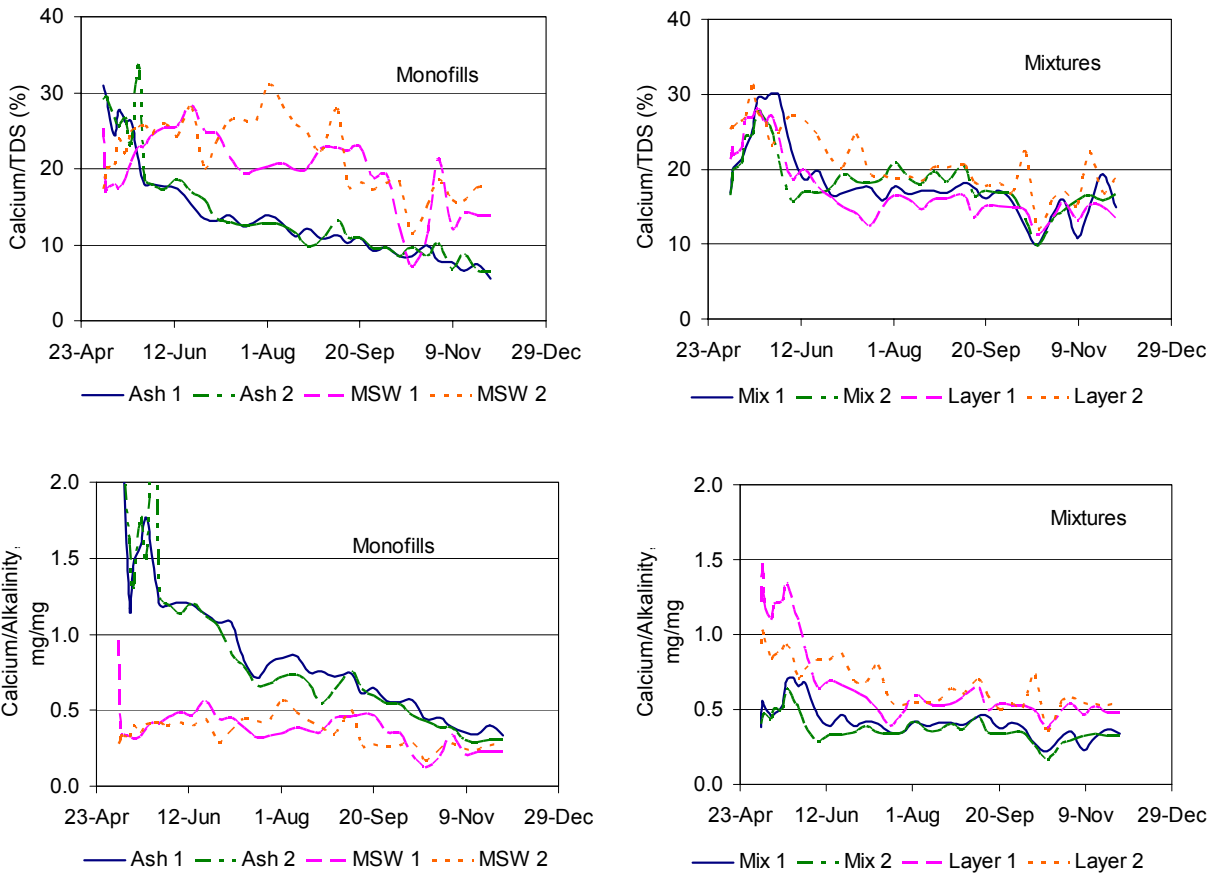
Figure 23. Comparison of the ratios of calcium to total dissolved solids (TDS) and alkalinity in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

Comparison of nitrogen and phosphorus levels in lysimeter leachates

Comparisons of nitrogen and phosphorus levels associated with lysimeter leachates are presented in Figure 24. As shown, nitrogen levels tended to be higher in leachates from the MSW dominated lysimeters (monofill and mixtures) than the ash dominated lysimeters. The highest levels of phosphorus were associated with leachates from the MSW monofills. The lower levels of phosphorus in the mixtures are most likely due to phosphorus complexation and co-precipitation with the calcium released from co-mingling of the ash and treatment plant residuals with the phosphorus mobilized from the MSW.
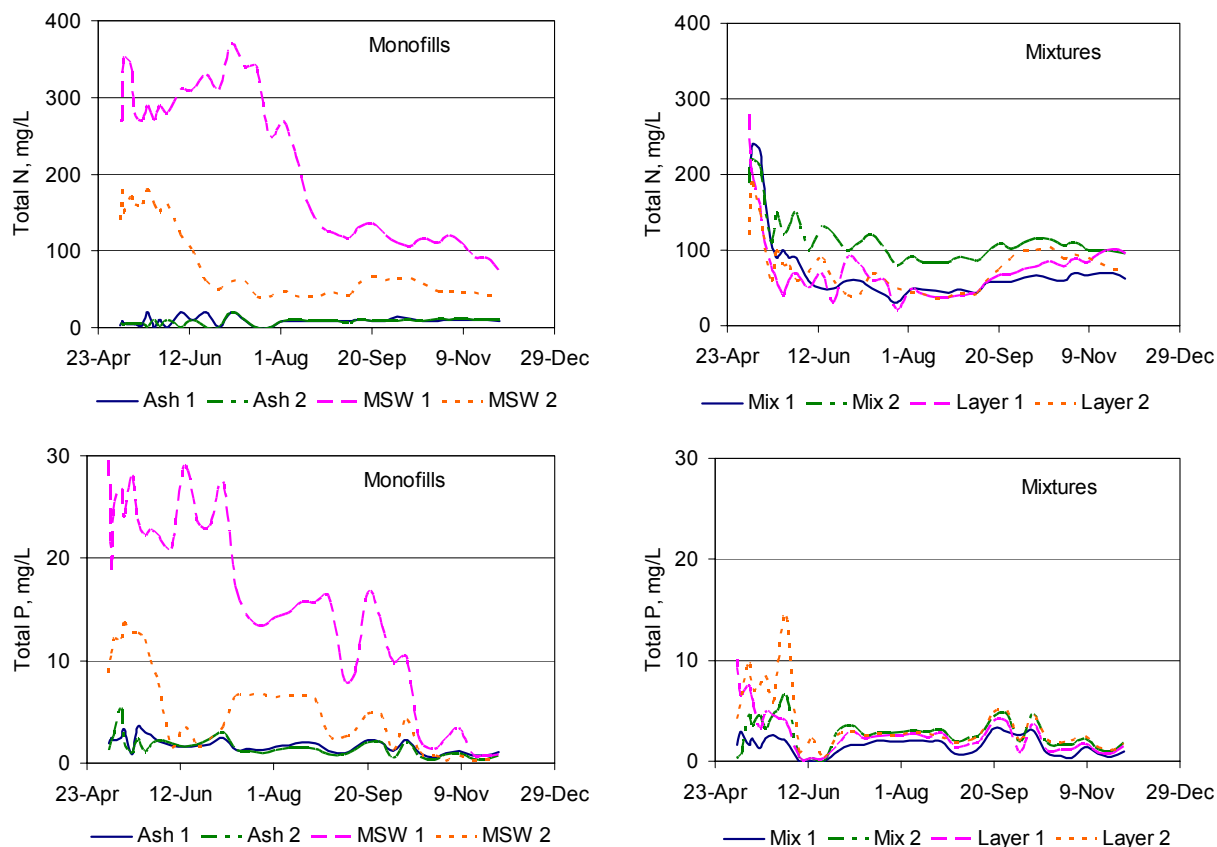
Figure 24. Comparison of the nitrogen and phosphorus levels in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals).

Comparison of concentrations of chloride, sodium, and potassium in lysimeter leachates

Concentrations of dissolved chloride, sodium, and potassium in lysimeter leachates are compared in Figure 25. As shown, chloride, sodium, and potassium are dominant constituents of the TDS in the ash dominated leachates with levels ranging from 500 to over 7,500 mg/L. Significantly lower levels of these minerals are associated with leachates from the MSW dominated lysimeters. It is interesting to note that the concentrations of potassium in leachates from the ash dominated 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.
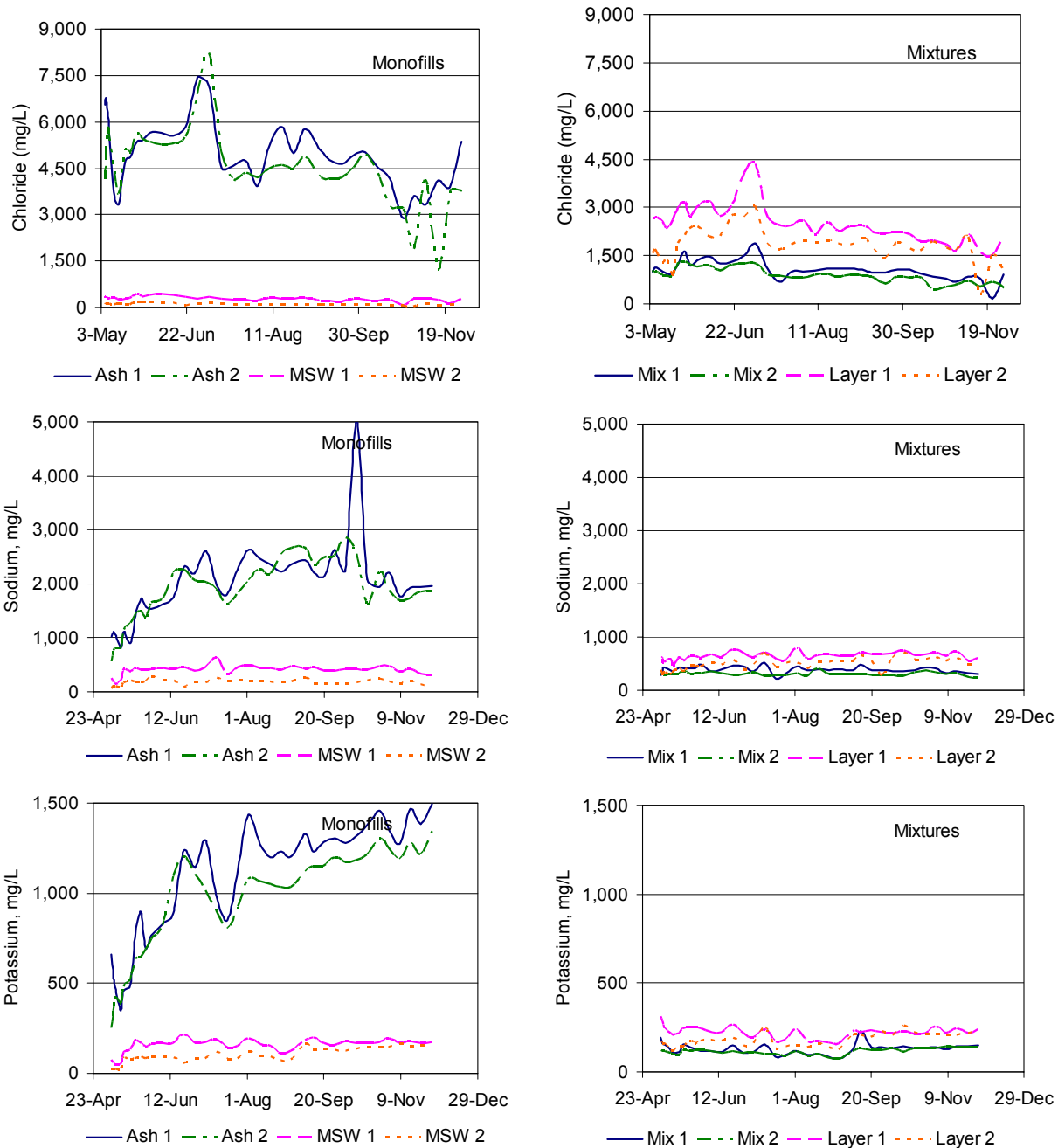
Figure 25. Comparison of the chloride, sodium, and potassium levels in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

Comparison of dissolved silica in lysimeter leachates

A comparison of the dissolved silica levels in lysimeter leachates is presented in Figure 26. In general, silica levels were fairly low in leachates from the ash dominated lysimeters as compared to the MSW dominated lysimeters with no apparent differences observed due to the different types of drainage materials. Leachates from one of the MSW monofill lysimeters (MSW 1) tended to be higher in silica content, perhaps due to differences in the material comprising the MSW.
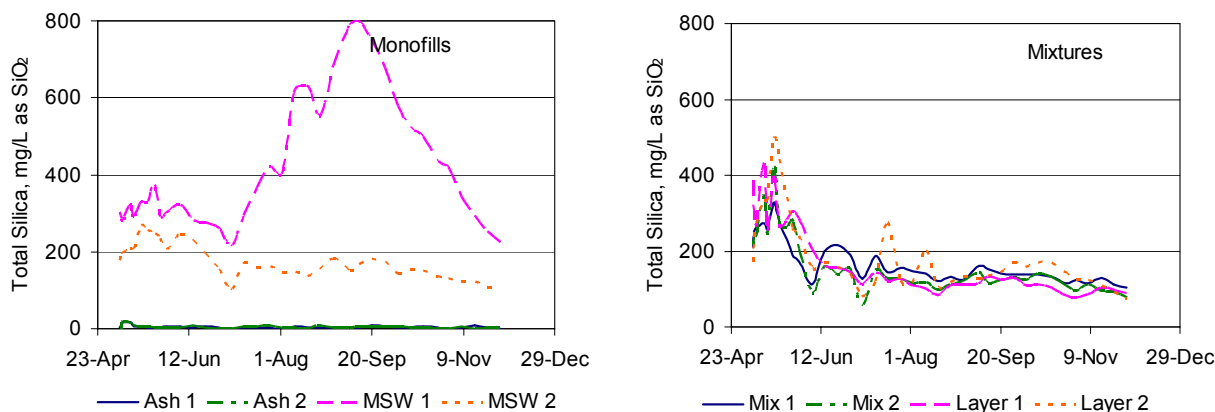
Figure 26. Comparison of the silica levels in leachates from lysimeters containing monofills (ash or MSW) or mixtures (ash, MSW, treatment plant residuals). Lysimeter descriptions are given in Table 5.

Summary of lysimeter leachate characteristics

Based on operation of laboratory lysimeters for a period of 8 months, several trends were observed. Ash dominated leachates tended to have higher pH levels and higher concentrations of TDS, calcium, sodium, potassium, and chloride than MSW dominated leachates. MSW dominated leachates tended to contain higher concentrations of microorganisms, alkalinity, volatile solids, TOC, turbidity, nitrogen, phosphorus, and silica than ash dominated leachates. The concentration of calcium decreased over time and the concentration of potassium increased over time in the ash dominated leachates. Mixtures containing ashes, MSW, and treatment plant residuals tended to have higher concentrations of magnesium and lower concentrations of phosphorus than would be expected based on relative contributions of MSW and ashes.

Development of solid deposits in leachate collection system

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. No deposits developed in the ash dominated lysimeters. The tubing was replaced and the elemental composition of the deposits was analyzed. A comparison of the physical features of the deposits is shown in Figure 27 - 29. Deposits in the MSW monofill tubing tended to contain more biomass and a lower density of granular material than did the deposits from the lysimeters containing mixtures of MSW, ash, and treatment plant residuals.
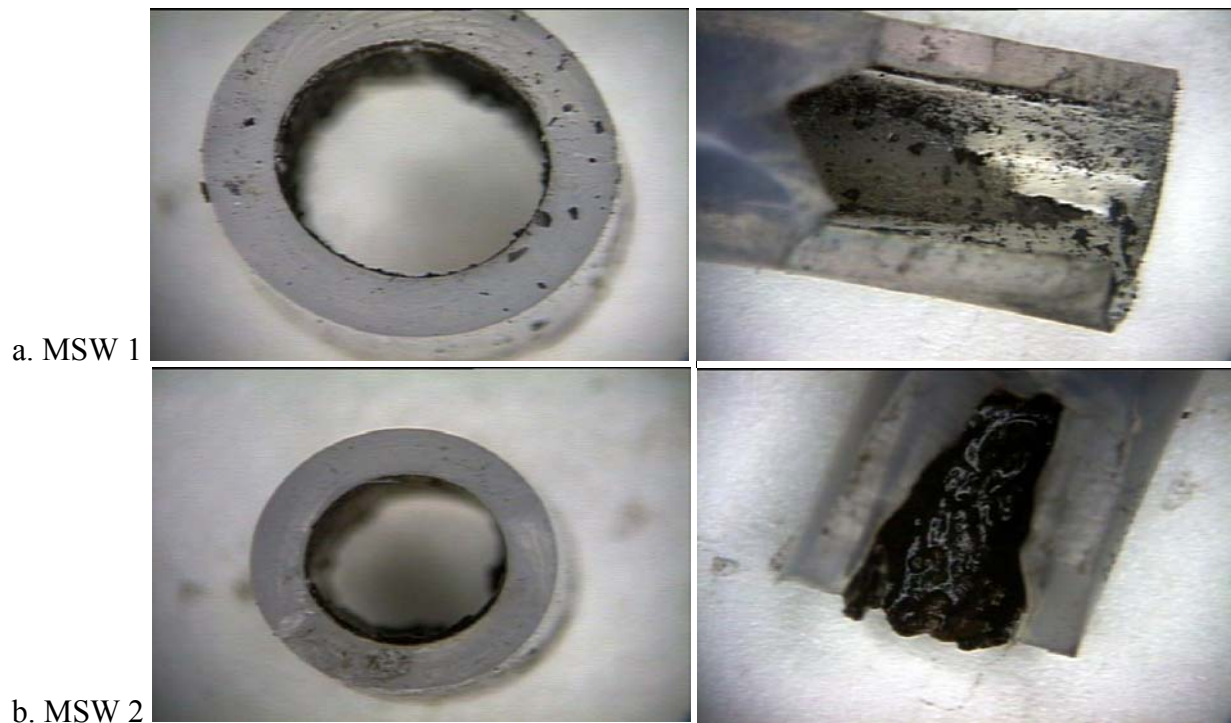
Figure 27. Photograph of deposits in leachate collection tubing from a.) MSW 1 and b.) MSW 2. The tubing has an ID of 8 mm and OD of 10 mm.

Figure 28. Photograph of deposits in leachate collection tubing from a.) Mix 1 and b.) Mix 2. The tubing has an ID of 8 mm and OD of 10 mm.
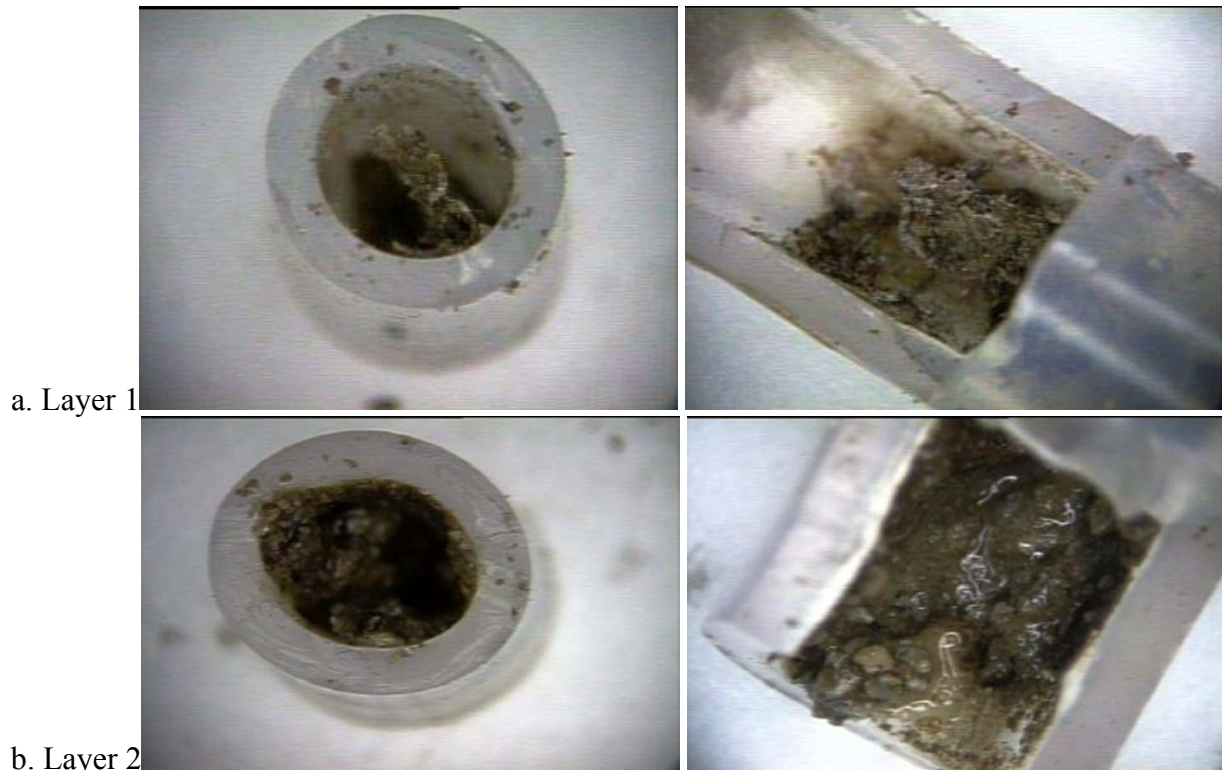
a. Layer 1

b. Layer 2

Figure 29. Photograph of deposits in leachate collection tubing from a.) Layer 1 and b.) Layer 2. The tubing has an ID of 8 mm and OD of 10 mm.

To provide additional insight into the characteristics of the lysimeter clogging material, SEM/EDS was used to analyze the surface characteristics of the deposits. Samples were preserved using formaldehyde, dehydrated, and sputter coated with carbon to allow for visualization of microorganisms and elemental analysis.

Example electron micrographs and distributions of dominant elements associated with the deposits are shown in Figure 30 for deposits from MSW monofills, Figure 31 for deposits from mixtures of MSW, ash, and treatment plant residuals, and Figure 32 for layers of MSW, ash, and treatment plant residuals. As shown, the dominant elements associated with the deposits include calcium, silica, phosphors, 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 is evidence of bacteria in all of the deposits suggesting that microorganisms play a role in the deposition process.

The deposits formed in the laboratory lysimeters are similar in composition to the clog material obtained from the southeast Florida leachate collection system. The sample preparation process for the lysimeter deposits included a preservation step to assess the microbial content. Samples from the landfill were obtained in a dry form and therefore it was not possible to determine the presence or absence of bacteria within the deposits. However, it is likely that similar mechanisms were responsible for the development of solid material in each situation.
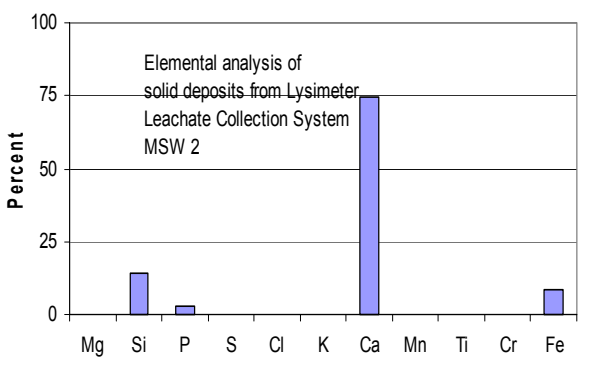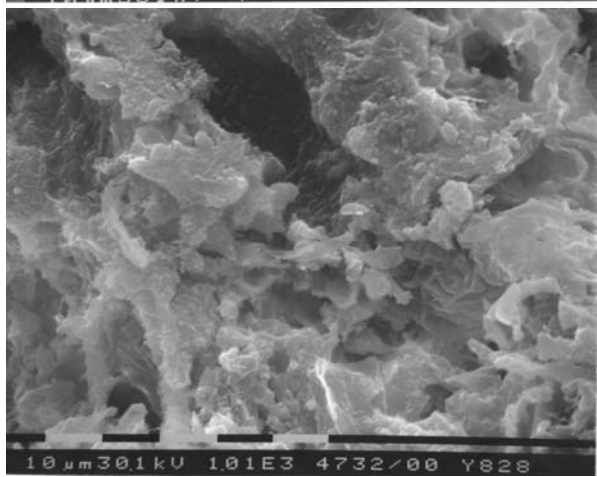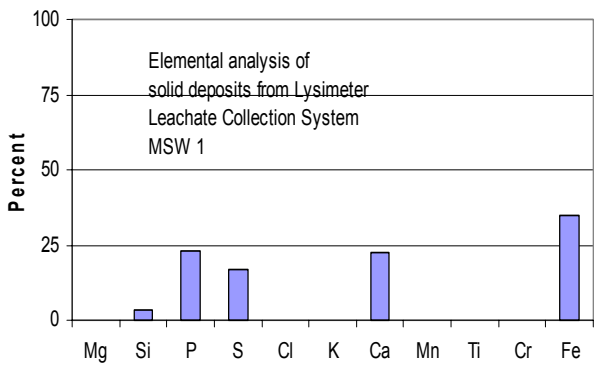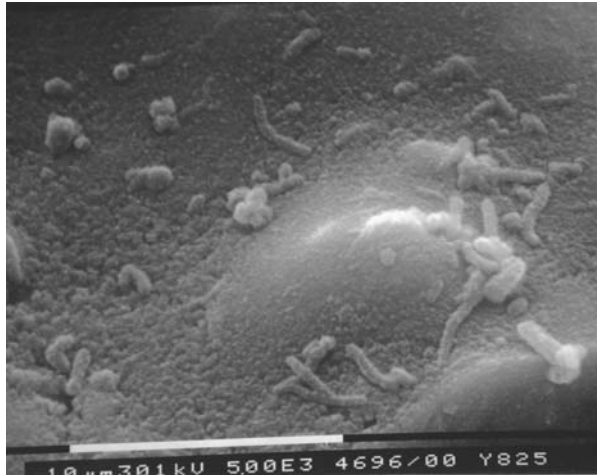
Figure 30. Scanning electron micrograph of deposits from MSW 1 and MSW 2 leachate collection tubing.
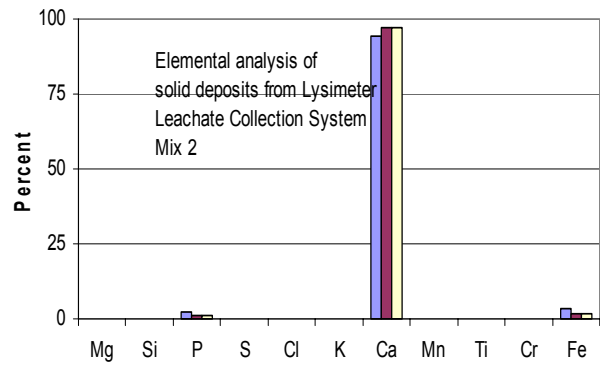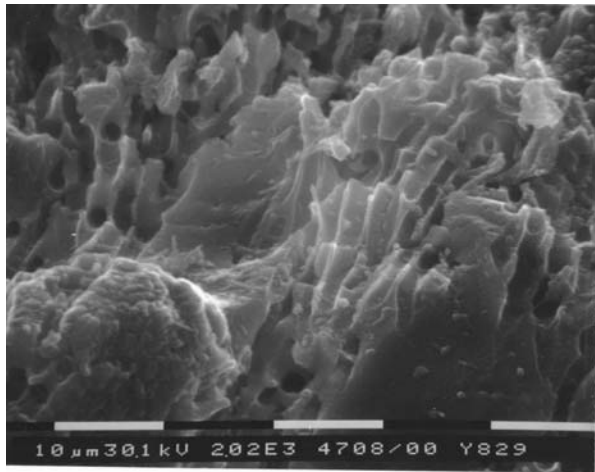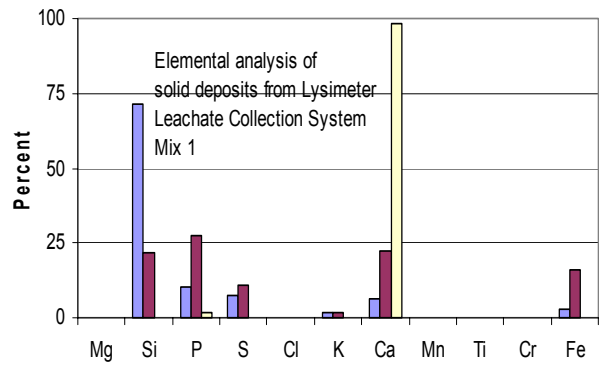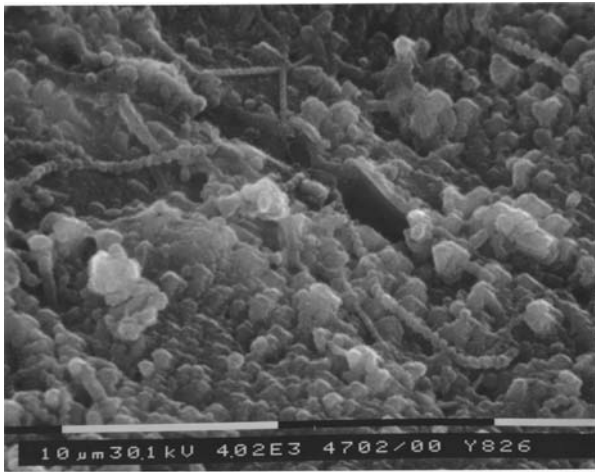
Figure 31. Scanning Electron Micrographs and dominant elements in deposits in tubing from lysimeters containing a mixture of ash, MSW, and treatment plant residuals.
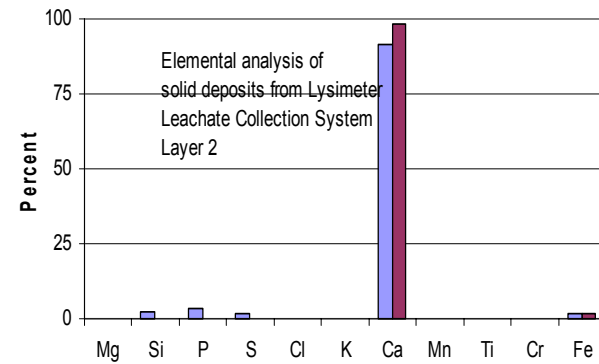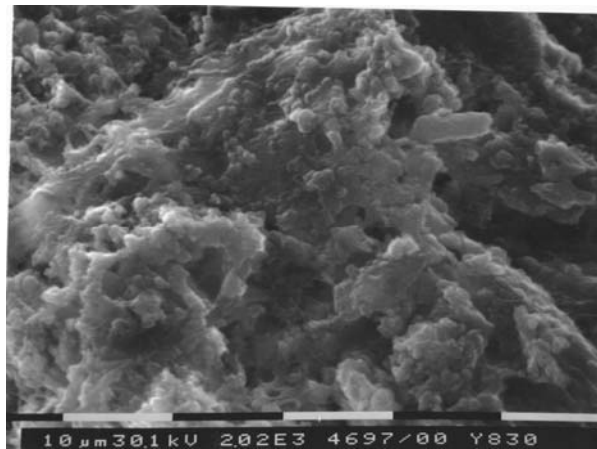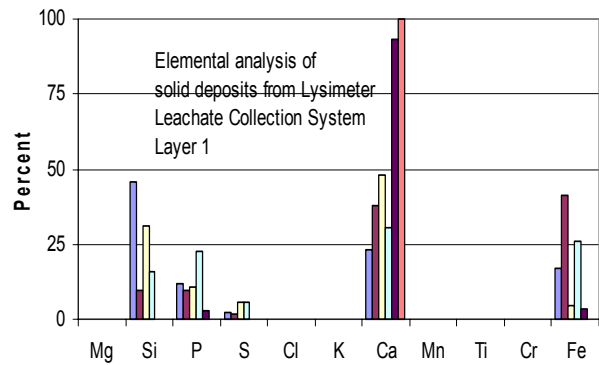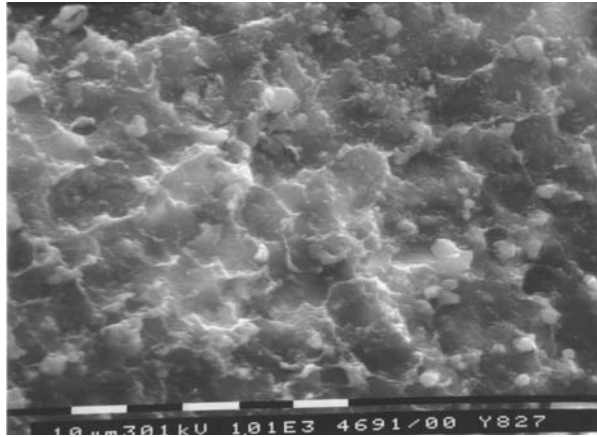
Figure 32. Scanning Electron Micrographs and dominant elements in deposits in tubing from lysimeters containing layers of ash, MSW, and treatment plant residuals.

Microbiological community structure associated with different phases of lysimeter operation

Based on the changes in leachate chemistry, development of deposits within lysimeter tubing, and microbiological data, the lysimeter operation was divided into five phases: initial phase, early phase, peak phase, pre-clogging, and post-clogging. The degree of microbial species diversity associated with each phase was analyzed based on the results of DGGE analysis. An example DGGE output is shown in Figure 33. Each of the horizontal layers represents an individual gel from a specific sample of DNA isolated from a specific lysimeter at a specific time. The vertical bands in the gels represent individual microbial communities that have a unique DNA pattern. The pattern of bands in the gels provides a signature of the diversity associated with each sample event. Further characterization of each band can be conducted by sequencing the DNA and identifying the microbial species. In this project, the goal was to determine if it was possible to ascertain differences among the lysimeters. Follow-up studies are planned to allow for DNA sequencing, however that is beyond the scope of the current project. Differences exist between the population patterns observed in the pre- and post-clogging gels; however, based on the analyses conducted to date, no individual band has been identified as the dominant contributor to the clogging process. Future research should be conducted on this question.
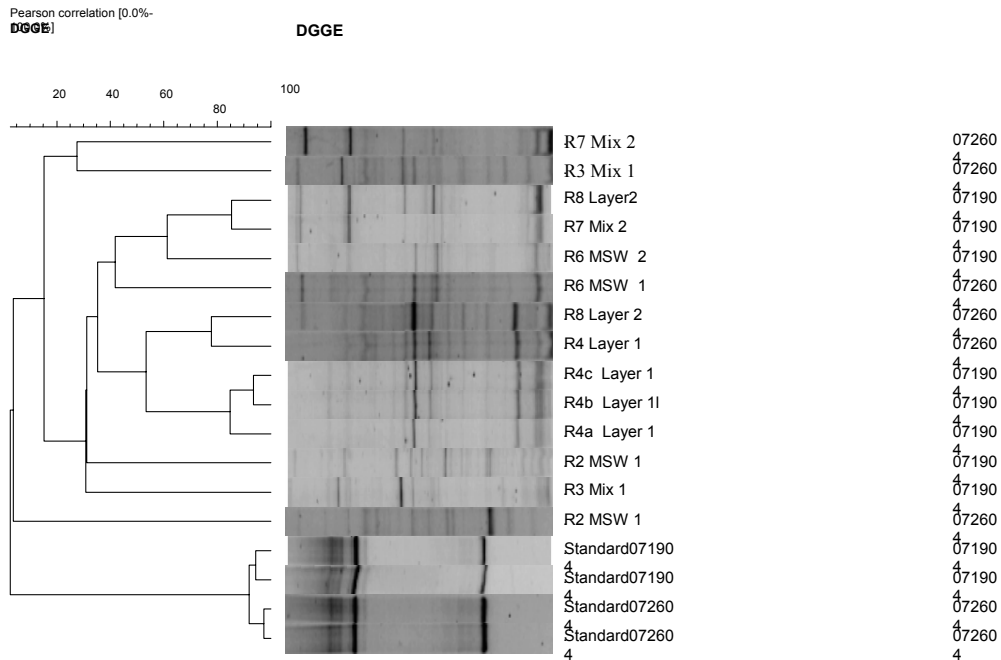
Figure 33. DGGE comparison of microbial community structure before and after the onset of clogging in the lysimeters.

A comparison of the relative species diversity associated with each phase of lysimeter operation is shown in Table 12 in terms of the number of bands separated on DGGE gels. During the initial phase of lysimeter operation, 19-29 bands were observed, with higher numbers associated with the layers, perhaps due to inputs from the wastewater biosolids. As time progressed, the number of bands decreased for all lysimeters and post-clogging there were about 12-18 bands identified. Follow-up testing is needed to identify the bacterial species associated with each band.

Table 12. Comparison of the number of bands observed on DGGE gels during each phase of lysimeter activity.

Lysimeter	Initial Phase	Early Phase	Peak Phase	Pre-clogging	Post-clogging
MSW 1	23	17	17	18	16
MSW 2	22	18	11	13	16
Mix 1	19	17	16	9	18
Mix 2	26	13	18	13	12
Layer l	28	16	8	12	15
Layer 2	27	22	13	12	14

USE OF BATCH LEACHING TESTS TO PREDICT LEACHATE COMPOSITION ASSOCIATED WITH COMBUSTION RESIDUES

Typically, combustion residues are disposed either in monofills or in combination with other waste materials. Based on the results of the lysimeter studies, it is evident that the co-disposal of MSW and combustion residues can result in the production of leachates supersaturated in calcium and carbonate. To gain further insight into the role of combustion resides in the leaching process, batch tests were conducted on combustion residues from different facilities. Distilled water was used as a leachant to mimic the chemical composition of rainwater. The relationship of the batch tests, lysimeter tests, and field tests is shown in Figure 34.
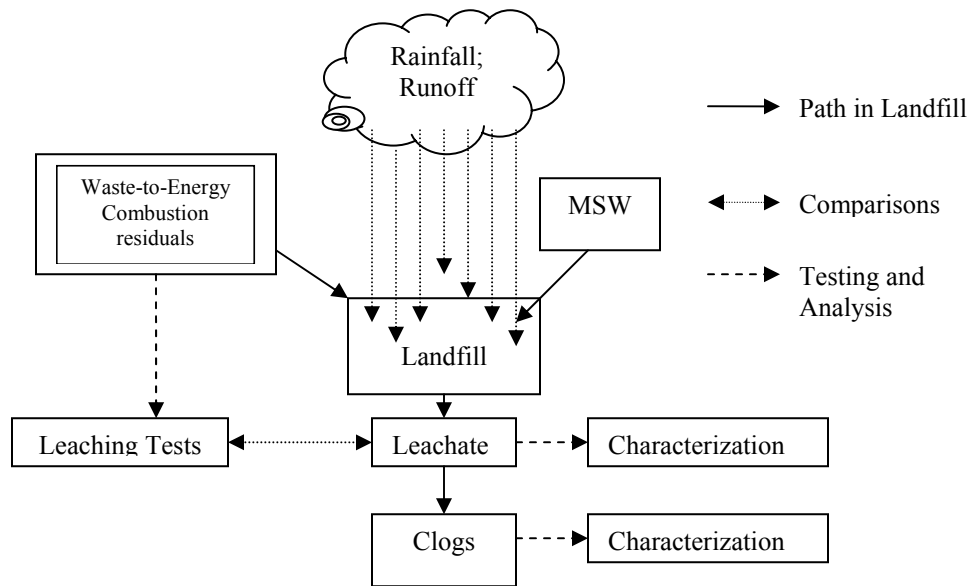
Figure 34. Overview of the interactions between combustion residues, MSW, and the production of leachate in landfills, lysimeters, and batch tests (from Rhea, 2004).

Batch tests are widely used to evaluate the leaching potential of wastes from the perspective of releasing potentially toxic constituents (USEPA, 1996). 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). The feasibility of applying batch tests as a screening procedure for combustion residues was evaluated in this project.

Two different types of batch tests were developed to characterize the leaching potential associated with combustion residues: contact time tests and sequential extraction tests. The contact time test provides an estimate of the time necessary to mobilize minerals from solid wastes and the sequence of dissolution. The sequential extraction test provides a dynamic view of the material's behavior as it encounters fresh leachant at regular time intervals. To assess the feasibility of using batch tests to predict leachate characteristics and the potential for clogging of leachate collection systems, batch test results were compared to leachates from laboratory

lysimeters containing combustion residues and to landfill leachates. The sources of the combustion residues and leachates tested in this project are listed in Table 13.

Table 13. Sources of Combustion Residues used in batch tests and sources of leachates compared to batch test results.

Source	Material	Code	Processing Method	Tests Run
West Palm Beach County	Bottom Ash	BA	RDF Facility	Contact Time, Sequential Extraction
	Fly Ash	FA	RDF Facility	Contact Time, Sequential Extraction
	Leachate	PBL	Landfill cell- Co-disposal of bottom ash, fly ash, MSW, and treatment plant residuals	Analysis of inorganic constituents
	Clogging material from leachate collection system	C	Landfill cell- Co-disposal of bottom ash, fly ash, MSW, and treatment plant residuals	Elemental Analysis of solid phase
	Laboratory lysimeter	RA	80% bottom ash 20% fly ash	Analysis of inorganic constituents
Pasco County	Mixed Ash	P	Mass Burn	Contact Time, Sequential Extraction
	Leachate	PL	Landfill cell- Ash monofill	Analysis of inorganic constituents
Hillsborough County	Mixed Ash	H	Mass Burn	Contact Time, Sequential Extraction

Batch testing methodology

Protocols for the batch tests conducted in this project were adapted from the Method for Accelerated Leaching of Solidified Waste (U.S Department of Nuclear Energy, 1990). All tests were conducted using Nalgene amber high-density polyethylene (HDPE) wide mouth bottles. The HDPE bottles are non-reactive with the leachant and leachate, and do not absorb the released ions (U.S. Department of Nuclear Energy, 1990). To ensure a uniform environment, in which the temperature does not change by ±1 °C and to simulate the higher temperatures found in landfills, the containers were placed in a 35 °C incubator for the reaction period.

A diagram of the batch-test protocol is given in Figure 35 for the contact time tests and in Figure 36 for the sequential extraction tests. The initial set-up for all batch tests was identical. In each case, 125 mL amber HDPE bottles were pre-cleaned by soaking in an acid bath of 1% nitric acid for 24 hours. The bottles were then rinsed five times with Nanopure™ water and allowed to air dry for two to three days. Once completely dried, the bottles were placed on an analytical balance, tared, and approximately 13.5 grams of combustion residue was added to each bottle. The exact mass was recorded and sufficient distilled water was added to achieve a liquid to solid mass ratio of 10.

```
┌─────────────────────────────────┐
│   Weigh sample into tared HDPE  │
│   bottle; Record mass of sample │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│ Add distilled water to achieve an L/S ratio of 10, │
│   using 1g/mL as the density of water              │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│  Place bottles with sample and water on │
│      the orbital shaker for 20 minutes  │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│  Place bottles in a 35°C incubator for the │
│  selected length of time as shown in Table 4 │
└─────────────────────────────────┘
                 │
                 ▼
┌─────────────────────────────────┐
│  Remove sample by filtration, run time │
│   sensitive tests and preserve for future │
│                analysis                    │
└─────────────────────────────────┘
```

Figure 35. Overview of Contact Time Batch Tests (from Rhea, 2004).

The contact time batch test was conducted for 21 days with three replicates per time interval. At the end of each time interval, the three bottles were removed from the incubator and the leachate was removed by filtration. The leachate was divided into three volumes, one for immediate testing and the other two were preserved for chemical characterization.

The sequential extraction batch tests were conducted for about three months with replacement of the liquid occurring every 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 liquid to solid ratio, which increased with each subsequent extraction. The protocol used for the sequential extraction batch test is shown in Figure 36 and a photograph of the containers used for the test is shown in Figure 37.
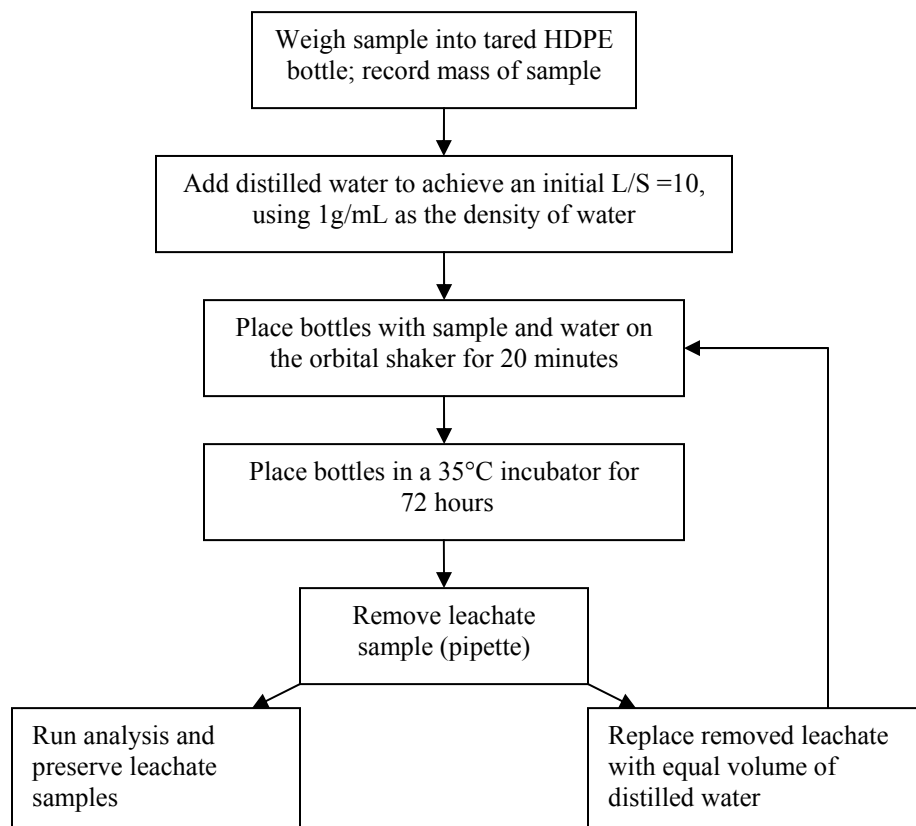
Figure 36. Overview of Sequential Extraction Tests (from Rhea, 2004).

Figure 37. Sequential Extraction HDPE Reaction Containers in incubator at 35 °C.

Results of batch leaching tests

The batch leaching tests allowed for a side-by-side comparison of combustion residues from different types of facilities. A comparison of the concentrations of TDS and pH in the batch leachates from the different samples is shown in Figure 38. As shown, the fly ash yielded about a three folds higher concentration of TDS than did the mixed combustion residues. All batch leachates had fairly high levels of pH, similar to the levels observed in the ash monofill lysimeters, but higher than the levels observed in the ash monofill leachate.
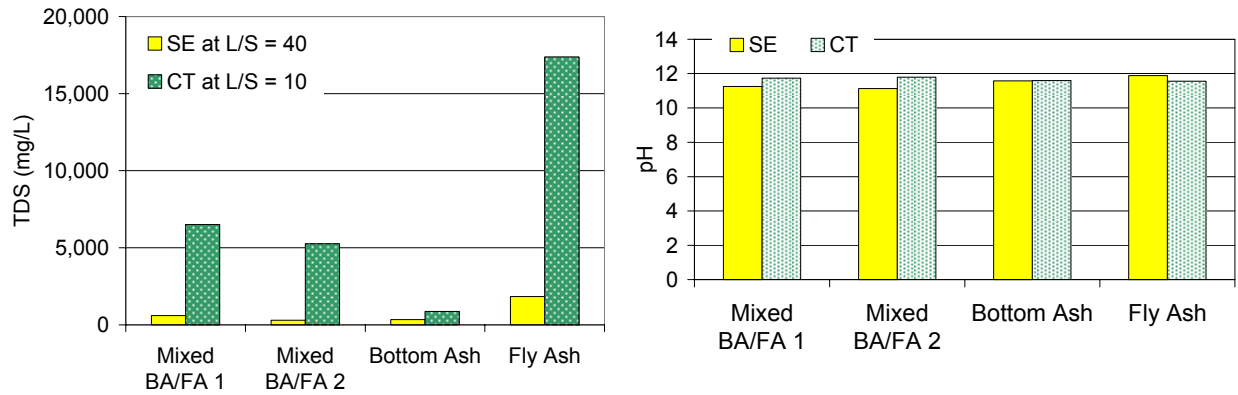
Figure 38. Comparison of TDS and pH levels in batch leaching tests conducted on combustion residues from three facilities: BA/FA and BA/FA 2 are mixtures of bottom ash and fly ash.

Based on analysis of clogged materials from leachate collection systems, calcium appears to play an important role in the overall process. A comparison of calcium levels observed in the contact time and sequential extraction tests is shown in Figure 39. Calcium concentrations in the two mixed combustion residues were about half of the levels associated with fly ash leachants, whereas negligible calcium leached from the bottom ash, most likely due to its partitioning into the fly ash. Interesting trends were observed from the sequential extraction test. Once the liquid:solid mass ratio was over about 30, there was minimal difference in the extent of calcium leaching that occurs from any of the residues. Calcium concentrations observed in landfill leachates are similar to liquid to solid ratios below 10, suggesting that the leaching of minerals is limited by the availability of moisture.
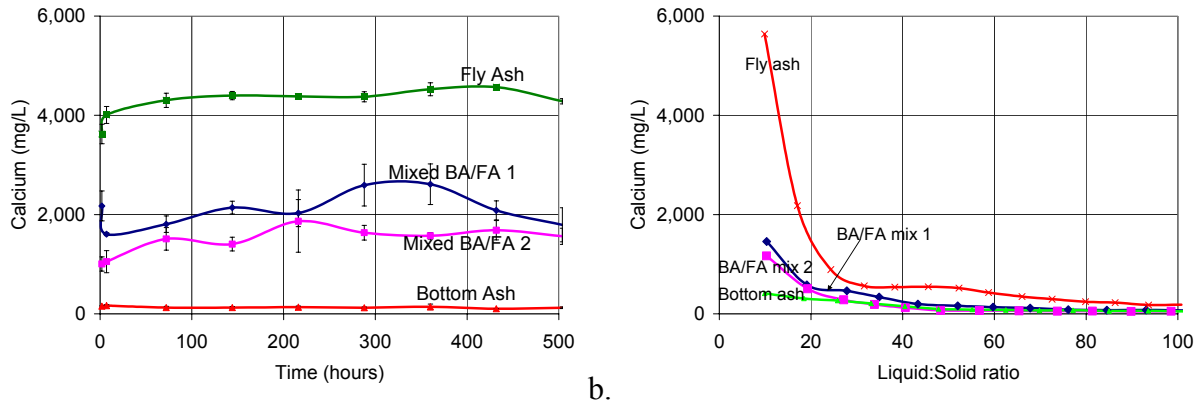
Figure 39. Comparison of calcium levels leached from combustion residues in batch tests: a.) contact time tests and b.) sequential extraction tests.

The relative amount of calcium, carbonate, and sulfate in leachates can impact the potential for formation of precipitates. A comparison of the molar concentrations of these constituents in batch test leachates, laboratory lysimeters, and landfill leachates is shown in Figure 40. If the molar ratio of calcium to either carbonate or sulfate is greater than one to one, the solution is supersaturated and has potential to form precipitates. As shown, all of the leachates are dominated by calcium, but the ratio of the anions differs depending on the source of the leachate. The batch tests (H-mix, P-mix, Fly ash, and Bottom ash) provide a reasonable prediction of the extent to which calcium leaches from the combustion residues.
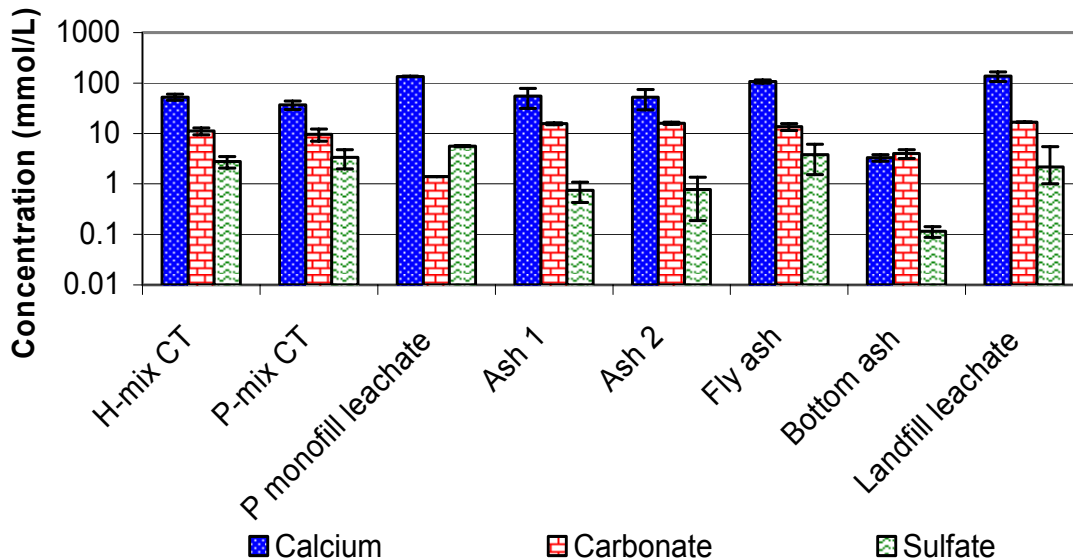
Figure 40. Comparison of calcium, carbonate, and sulfate levels in batch tests, leachates, and lysimeter tests from ash monofills. H-mix is a mixture of bottom ash and fly ash from a mass burn facility, P-mix is a mixture of bottom ash and fly ash from a different mass burn facility, Ash 1 and Ash 2 are from laboratory lysimeters containing 20% fly ash and 8-% bottom ash. The landfill leachate is from the southeast Florida landfill that co-disposes fly ash and bottom ash with MSW.

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Further insight into the predictive capability of the batch tests is shown in Figure 41 in terms of saturation indices for calcite and gypsum associated with each of the combustion residues. 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. It should be noted that typically bottom ash comprises 70-90% of the mass of combustion residues, with the remainder consisting of fly ash. The fly ash on a mass basis yields a higher degree of calcium and other constituents that contribute to the formation of deposits. These results suggest that further stabilization of fly ash or development of alternative disposal practices may help to reduce the extent of clogging associated with co-disposal of ashes and MSW.
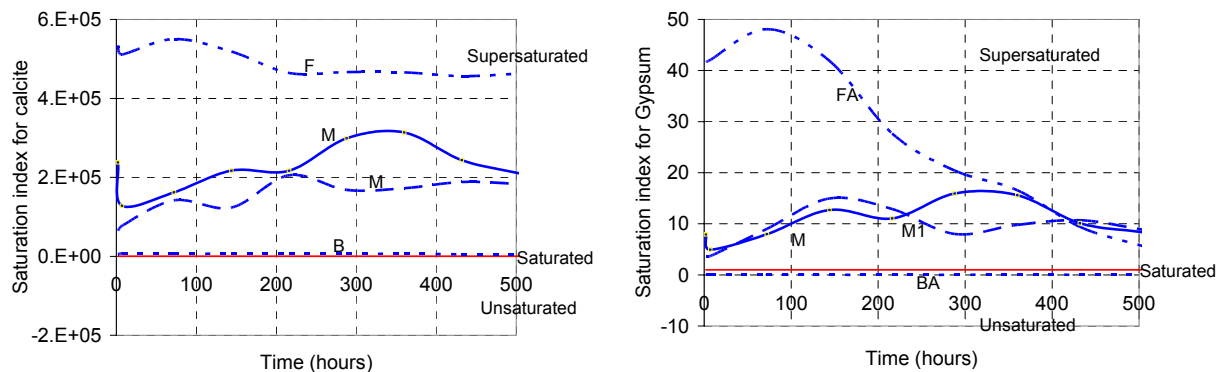
Figure 41. Comparison of saturation indices for a.) calcite and b.) gypsum from contact time batch tests. FA: fly ash; BA: bottom ash; M1 and M2 represent mixtures of bottom ash and fly ash from mass burn waste-to-energy facilities.

Applications to leachate management practices

While this project was focused on identifying the potential for formation of clogs in leachate collection system, some of the results can be extrapolated to leachate management practices. As discussed, leachates associated with different types of waste materials 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. An interesting consequence of the exposure of leachates to air and the addition of acid to ash dominated leachates was observed in this project. In this study, acid was added to samples from 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 42 for samples of bottom ash batch test leachates at a liquid to solid mass ratio of 10 and in Figure 43 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

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gypsum material that formed, other calcium and magnesium dominated precipitates formed, 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. In the fly ash sample, lead sulfate precipitated in addition to gypsum.
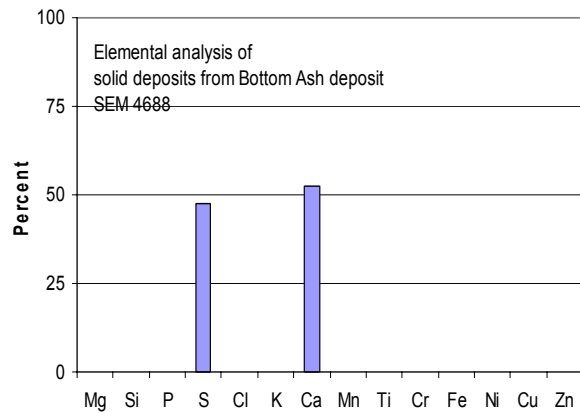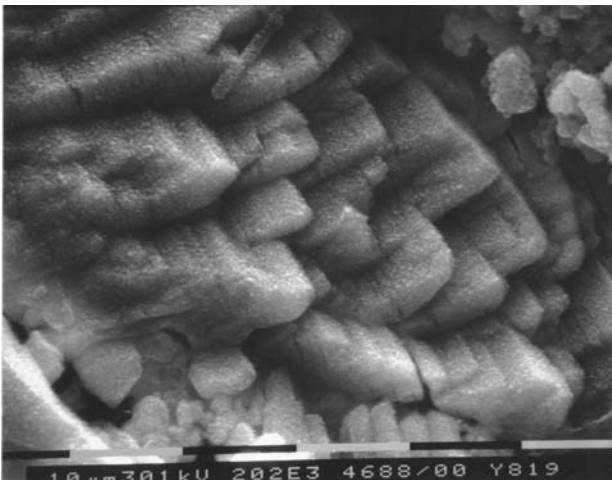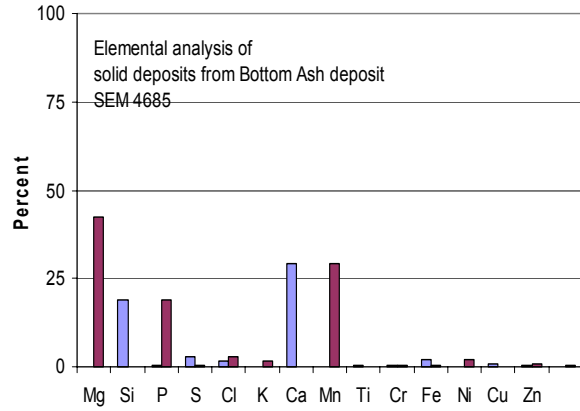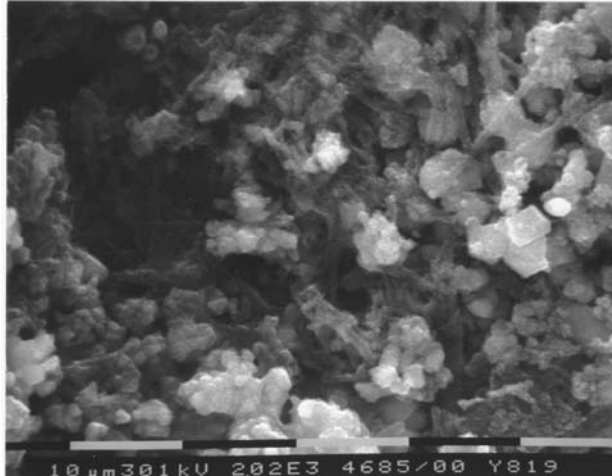
Figure 42. SEM/EDS analysis of precipitates formed from the addition of sulfuric acid to leachates formed from contact time batch leaching tests of bottom ash at a liquid to solid mass ratio of 10.
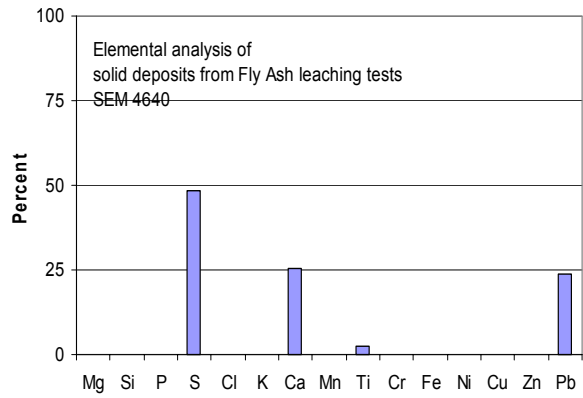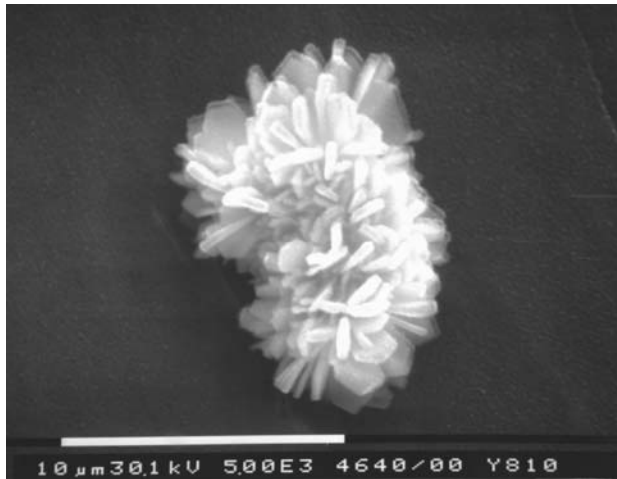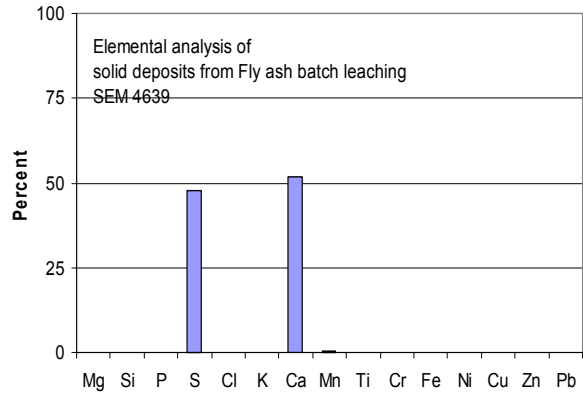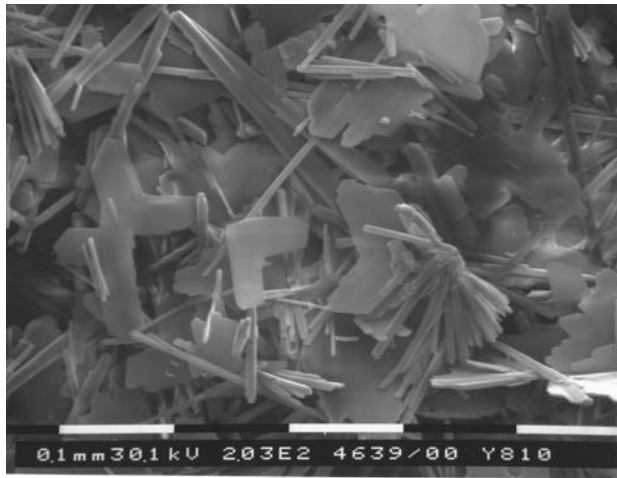
Figure 43. SEM/EDS analysis of precipitates formed from the addition of sulfuric acid to leachates formed from contact time batch leaching tests of fly ash at a liquid to solid mass ratio of 10.

COMPARISON OF LEACHATES FROM LYSIMETERS AND LANDFILL LEACHATES

Laboratory lysimeters were operated for a period of eight months using fly ash, bottom ash, MSW, and treatment plant residuals obtained from a southeast Florida landfill. The purpose of operating the lysimeters was to gain an understanding of the characteristics of leachate produced from different waste materials and to determine the potential for formation of clogs in leachate collection systems. It is important to evaluate the degree to which the lysimeter leachates simulate leachates produced in field settings.

A comparison of results of field monitoring conducted at the southeast Florida landfill and lysimeter results is provided in this section. In addition to differences in the amount of moisture available for waste degradation and the age of the landfill, another qualitative difference between the lysimeter leachates and the landfill leachates was temperature. Typical temperatures associated with landfill leachates ranged from 56 to 101 ^{o}F with average temperatures ranging from 87 to 91 ^{o}F. Laboratory lysimeters were operated at room temperature with typical leachate temperatures ranging from 70 to 85 ^{o}F. Temperature variations can impact mineral solubility, biological growth rates, and reaction kinetics.

A comparison of the total dissolved solids, alkalinity, and calcium levels in the landfill leachates and the lysimeter leachates is shown in Figure 44 in a boxplot format. As shown, the landfill leachates had three to five fold higher TDS levels, reflecting higher ionic strength. Alkalinity and calcium levels were variable in both cases, with higher levels of alkalinity associated with leachates from the MSW dominated lysimeters. With the exception of leachates from cells 1, 5, 6, and 8, calcium levels in the lysimeter leachates were of similar magnitude to those observed in the landfill leachates.

A comparison of the ratio of calcium to total dissolved solids and to alkalinity for the leachates from the landfill and leachates from the eight lysimeters is shown in Figure 45. The calcium to alkalinity ratios tended to be similar for the layered lysimeters and cells 2, 3, 4, and 7; whereas cells 1, 5, 6, and 8 had much higher ratios of calcium to alkalinity   The percent of the TDS that consists of calcium was much higher in the lysimeters than the landfill leachates and did not seem to be significantly different for the ash dominated lysimeters as compared to the MSW dominated lysimeters.
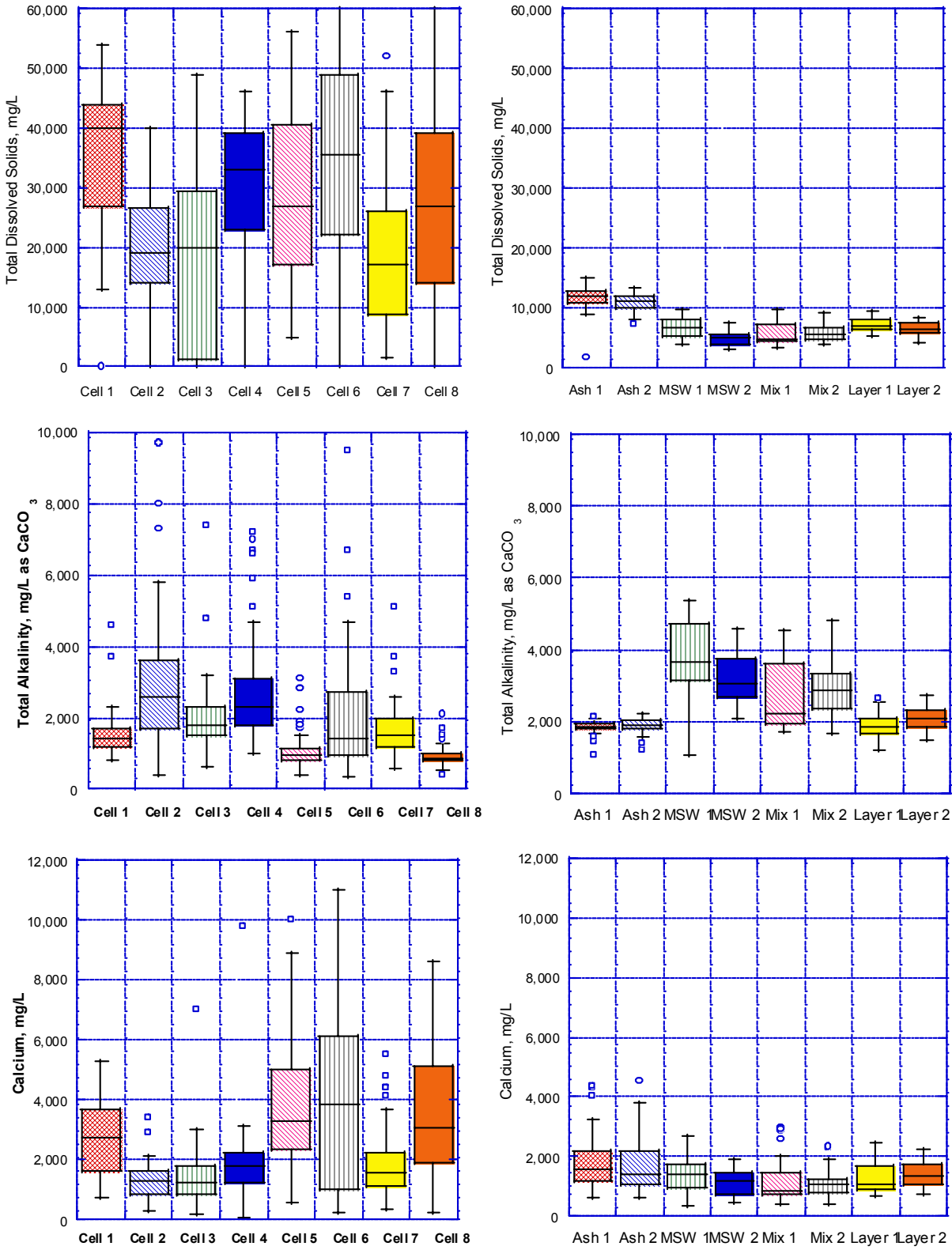
Figure 44. Comparison of total dissolved solids, alkalinity, and calcium levels in leachates from the southeast Florida landfill and laboratory lysimeters operated with waste materials from the same landfill.
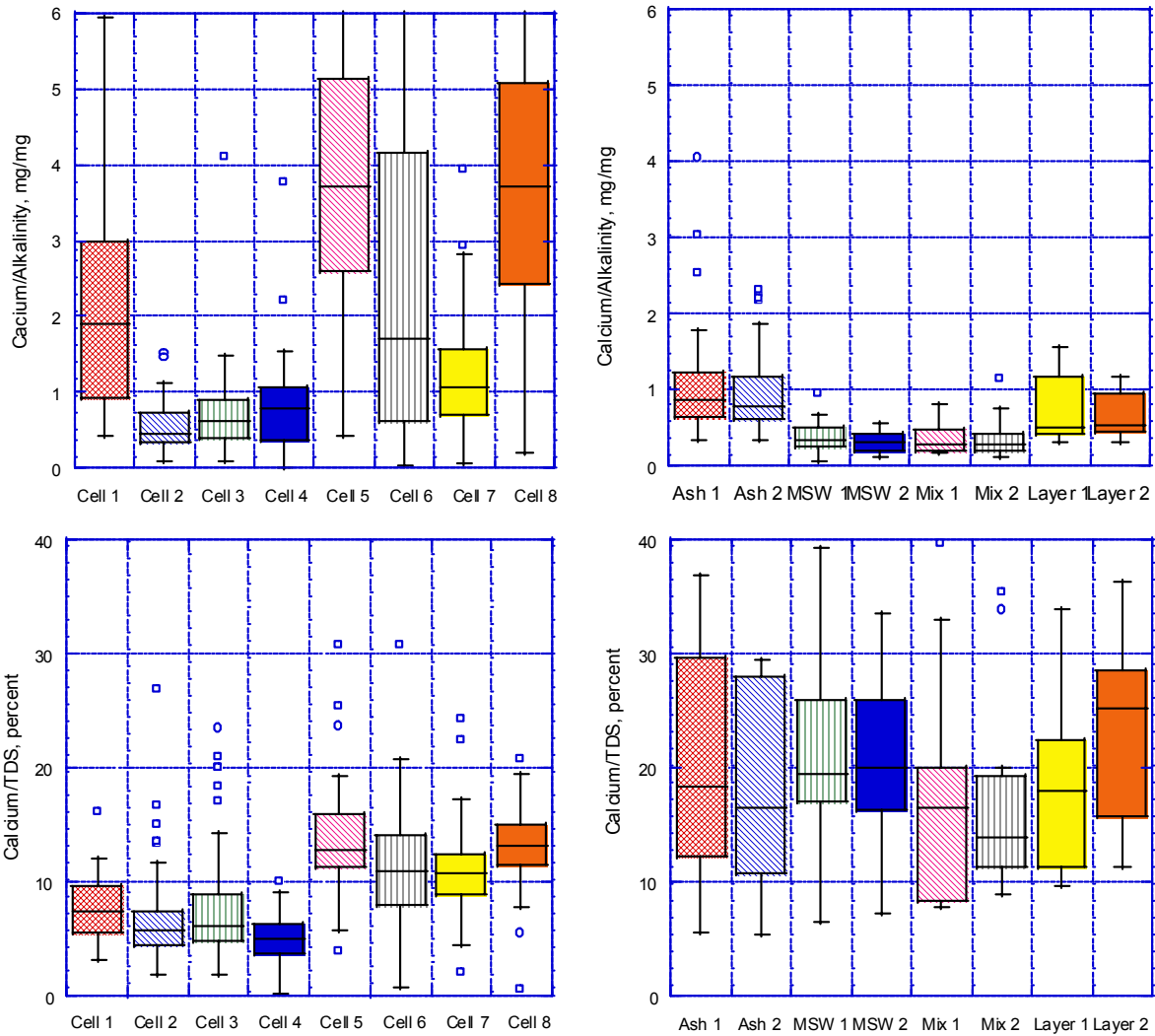
Figure 45. Comparison of the ratio of calcium to alkalinity and calcium to TDS for landfill leachates and laboratory lysimeter leachates.

Characteristics of leachates tested in this project are similar to those reported in other studies (Abbas et al. 2003, Albrechtsen and Christensen 1994, Barlaz et al. 1989, Blight et al. 1999, Fielding et al. 1988, Kjeldsen et al. 2002, Levine and Kroemer, 1989, Mostbauer 2003, Wilfred et al. 2001). The relative concentrations of insoluble minerals and dissolved anions from microbiological activity can create transient conditions that promote the formation of mineral deposits. Temperature, microbial activity, and ionic strength all impact the rate and extent of mineral precipitation.

CONCLUSIONS

This study has provided an opportunity to investigate relationships between waste characteristics, leachate composition, and the potential for clogging. Several conclusions can be drawn from this study:

1. Leachates from ash monofills are dominated by high concentrations of dissolved calcium and high pH levels, but contain relatively low levels of carbonate species.

2. Leachates from lysimeters containing MSW have higher levels of microbial activity and bicarbonate, but contain lower levels of calcium species than do ash dominated lysimeters.

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.

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

5. Microbial activity as evidenced by volatile acids and monitoring of microbial concentrations influenced the rate and extent of clogging that occurred in lysimeter tubing.

6. Data on microbial activity in landfill leachates would be helpful in developing a better understanding of the steps leading to the onset of clogging in leachate collection systems.

7. Landfills containing mixtures of combustion residues and MSW appear to be more susceptible to clogging due to the relative contributions of each waste stream. The combustion residues provide 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.

8. Dominant constituents in clogged materials from leachate collection systems include calcium, carbonate, sulfur, phosphorus, iron, and silica. Assessment of solubility indices for these materials in leachates could help to predict the likelihood of precipitate formation.

9. The use of contact time and sequential extraction batch leaching tests provide a tool that can be used to assess the degree of leaching that may occur from exposure of combustion residues and other waste materials to landfill environments. This procedure was adapted from leaching tests that are widely employed for assessment of toxicity associated with waste materials. The use of this test to screen ash stabilization methods may help to reduce the incidence of clogging in leachate collection systems associated with Class I landfills.

RECOMMENDATIONS

This study has provided an initial evaluation of the chemical and microbiological factors that may impact the formation of clogs in leachate collection systems. It is important to develop tools for preventing and correcting problems associated with leachate clogging. Recommendations for further study are:

1. 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 clogging.

2. Methods for control of leachate clogging such as the use of chemical amendments should be evaluated in the context of leachate characteristics. Detailed testing of the impacts of chemical augmentation (acids, chelating agents, etc.) is needed to identify the optimum approach for controlling clogging.

3. Methods for assessment of microbial community structure have been developed through this project. It would be valuable to apply these methods to field samples to obtain a better understanding of the relative role of microbial growth in the genesis of solid precipitates.

4. 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 of the leachate collection system.

5. The impacts of current combustion technologies and ash handling protocols on the leaching characteristics of residues from combustion facilities may help to develop protocols for stabilization of residues prior to landfilling.

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APPENDIX A:

SUMMARY OF LEACHATE CHARACTERISTICS FROM

LABORATORY LYSIMETER TESTS CONDUCTED FROM APRIL

THROUGH DECEMBER 2004

Summary of laboratory lysimeter monitoring results from May 5 to November 29, 2004

Table A-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	1,189.83	314.07	59.35	1.34	1.35	98,640.24	28
Total Alkalinity (mg/L as CaCO$_3$)	1,872.2	1,866.7	1,064	2133.3	160.95	18.97	-1.85	8.32	25,904.25	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
Hardness (mg/L as CaCO$_3$)	4,556.10	3,882.79	1,593.7	10,880.3	2,442.49	407.08	1.23	-1.35	6E+06	36
Total Solids (mg/L)	13,118.7	12,863.3	11,626.7	17,826.7	1,303.45	217.24	2.40	6.52	1.7E+06	36
Volatile Solids (mg/L)	1,367.28	916.65	726.7	4,873.3	932.34	155.39	2.23	5.19	869,253.4	36
Estimated TDS (mg/L)	11,973.65	11,999.57	8,803.46	14,975.13	1,547.71	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	2,800.49	33
Chloride (mg/L)	5,148.72	4,988.99	3,325.62	7,431.25	964.30	167.86	0.49	0.21	929,882.6	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)	1,826.03	1,556.2	638.7	4,360.8	978.91	163.15	1.23	1.14	958,265.1	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)	1,065.74	1,217.5	350.4	1,494	335.63	55.94	-0.691	-0.818	112,650.5	36
Sodium (mg/L)	1,984.47	1,973.75	808	502	730.23	121.71	1.785	7.74	533,240.7	36
Aluminum (mg/L)	0.099	0.055	< 0.002	0.65	0.121	0.020	2.950	11.627	0.015	36

Table A-2. Lysimeter leachate monitoring summary. MSW 1: 100% MSW.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	5.93	5.56	5.22	7.07	0.56	0.06	0.59	-1.35	0.31	99
Conductivity (µS/cm)	6.85	6.83	1.92	9.87	2.69	0.27	-0.47	-1.16	7.24	99
Temperature (°C)	22.2	22.1	19.3	24.5	1.41	0.16	-0.31	-0.73	1.99	77
ORP (mV)	-39.75	-54	-189	140	89.58	10.21	0.05	-1.36	8,024.93	77
Turbidity (NTU)	266.08	232	41.6	589	135.38	13.61	0.62	-0.72	18,326.81	99
Ammonia (mg/L NH_3)	1,791.67	99.03	1.87	15,610.59	3,438.84	649.88	2.82	9.25	1.2E+07	28
Total Alkalinity (mg/L as $CaCO_3$)	3,768.55	3,650	1,064	5,366.7	907.26	106.92	-0.17	-0.37	823,124.8	72
Volatile Acids (mg/L as Acetic Acid)	864.21	950	33.3	1,950	631.58	90.23	-0.04	-1.31	398,900.1	49
Hardness (mg/L as $CaCO_3$)	3,837.74	3,952.14	1,555.36	7,205.59	1,542.14	257.02	0.25	-0.63	2.4E+07	36
Total Solids (mg/L)	10,176.5	10,726.6	4,026.7	15,033.3	3,393.67	565.61	-0.54	-0.73	1.1E+07	36
Volatile Solids (mg/L)	5,536.48	5,923.35	1840	9,166.7	2,093.40	348.90	-0.43	-0.61	4.4E+06	36
Estimated TDS (mg/L)	6,810.4	6,830.63	3,998.85	9,778.64	1,761.46	293.58	-0.10	-1.04	3.1E+06	36
Total Nitrogen (mg/L as N)	217	260	72	370	97.30	16.22	-0.05	-1.69	9,467.54	36
Total Phosphorus (mg/L as PO_4)	48.52	49.1	2.4	98	28.04	4.67	-0.25	-0.97	786.39	36
Silica (mg/L as SiO_2)	416.92	336.5	214	798	170.52	28.42	0.97	-0.29	29,078.59	36
Bromide (mg/L)	8.94	3.13	0.08	46.18	12.89	3.33	2.19	4.69	166.27	15
Chloride (mg/L)	290.66	289.85	100.29	449.2	71.63	12.47	0.15	1.01	5,131.28	36
Fluoride (mg/L)	5.85	6.01	0.02	12.09	3.13	0.65	-0.03	-0.40	9.78	23
Phosphate (mg/L)	383.71	489	15.8	820.27	312.72	80.75	-0.14	-1.81	97,797.19	15
Sulfate (mg/L)	162.08	52.34	9.74	595	212.82	54.95	1.44	0.54	45,290.18	15
Calcium (mg/L)	1,394.87	1,431.5	346.2	2,706.8	606.79	101.13	0.21	-0.56	368,197.3	36
Magnesium (mg/L)	86.91	89.95	53.4	186.1	22.46	3.74	2.30	10.22	504.25	36
Copper (mg/L)	0.070	0.075	< 0.01	0.241	0.053	0.009	1.030	2.538	0.003	36
Iron (mg/L)	52.420	34.747	4.741	174.13	47.596	7.933	1.190	0.418	2,265.42	36
Manganese (mg/L)	5.792	6.092	< 0.01	11.643	4.082	0.680	-0.143	-1.392	16.66	36
Zinc (mg/L)	0.466	0.147	0.006	4.219	1.080	0.180	3.138	8.396	1.166	36
Potassium (mg/L)	154.71	167.3	46.8	216.2	40.983	6.831	-1.403	1.567	1,679.62	36
Sodium (mg/L)	402.02	417.25	149	635	91.525	15.254	-0.867	2.283	8,376.82	36
Aluminum (mg/L)	1.033	1.085	0.31	1.43	0.260	0.043	-1.104	0.877	0.068	36

Table A-3. Lysimeter leachate monitoring summary. Mix 1: 60% MSW, 24% Bottom Ash, 6% Fly Ash5% Water Treatment Residuals, 5% Wastewater 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/L NH$_3$)	2,995.88	75.56	3.06	17,296.14	4,913.34	928.53	1.84	2.90	2.4E+07	28
Total Alkalinity (mg/L as CaCO$_3$)	2,670.59	2,250	1,733.3	4,533.3	842.46	99.28	0.61	-1.18	709,734.7	72
Volatile Acids (mg/L as Acetic Acid)	132.69	33.3	16.7	875	189.86	27.12	1.93	3.88	36,047.63	49
Hardness (mg/L as CaCO$_3$)	3,731.32	2,884.41	1,678.31	8,312.79	1,834.61	305.77	1.44	1.16	3.4E+06	36
Total Solids (mg/L)	7,719.75	5,520	4,526.7	14,940	3,390.09	565.02	0.98	-0.36	1.1E+07	36
Volatile Solids (mg/L)	3,306.94	2,210	1,720	7,593.3	1,739.44	289.91	1.11	0.03	3E+06	36
Estimated TDS (mg/L)	5,916.33	4,870.26	3,457.89	9,835.55	1,845.32	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	3,110.92	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	3,323.16	36
Bromide (mg/L)	39.18	27.985	10.09	172.05	32.48	5.93	2.80	9.21	1,054.86	30
Chloride (mg/L)	1,084.40	1,052.28	243.86	1,890.06	291.12	50.68	0.17	2.60	84,748.24	36
Fluoride (mg/L)	8.46	8.32	7.42	10.08	0.98	0.44	1.36	2.85	0.97	5
Phosphate (mg/L)	744.86	659.25	16.13	1,705	665.99	200.81	0.11	-1.82	443,553.1	11
Sulfate (mg/L)	215.04	65.01	13.77	719	280.64	81.01	1.13	-0.50	78,758.43	12
Calcium (mg/L)	1,182.97	842.95	416.1	2,961.6	712.32	118.72	1.42	1.11	507,399.2	36
Magnesium (mg/L)	189.55	184.7	123.5	300.7	33.25	5.54	1.14	2.78	1,105.71	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)	11.105	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
Zinc (mg/L)	0.112	0.109	0.019	0.225	0.059	0.010	0.032	-0.949	0.003	36
Potassium (mg/L)	128.46	130.1	76.7	229.3	31.29	5.53	0.995	2.389	979.271	36
Sodium (mg/L)	389	377.15	219	520	58.15	9.97	-0.343	1.513	3,380.91	36
Aluminum (mg/L)	0.5	0.48	0.18	0.86	0.152	0.025	0.477	0.191	0.023	36

Table A-4. Lysimeter leachate monitoring summary. Layer 1: 60% MSW, 24% Bottom Ash, 6% Fly Ash, 5% Water Treatment Residuals, 5% Wastewater Residuals.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	6.34	6.38	5.7	6.74	0.23	0.02	-0.91	0.21	0.05	99
Conductivity (µS/cm)	9.29	10.45	1.96	13.58	3.65	0.37	-1.17	-0.14	13.33	99
Temperature (°C)	21.92	22	2.4	24.5	2.67	0.31	-5.22	37.58	7.15	77
ORP (mV)	-59.80	-56	-112	-11	22.51	2.57	-0.29	-0.38	506.63	77
Turbidity (NTU)	114.26	106	44.3	342	42.27	4.25	1.93	7.48	1,786.85	99
Ammonia (mg/L NH$_3$)	5,047.18	86.11	3.57	40,139.55	9,148.7	1,728.94	2.53	7.41	8.4E+08	28
Total Alkalinity (mg/L as CaCO$_3$)	1,880.4	1,833.3	1,200	2,633.3	277.0	32.65	0.62	0.61	76,729.33	72
Volatile Acids (mg/L as Acetic Acid)	93.35	16.7	16.7	575	144.05	20.58	2.05	3.32	20,751.41	49
Hardness (mg/L as CaCO$_3$)	4,468.32	3,989.31	2,874.25	7,312.84	1,277.18	212.86	0.98	0.02	1.6E+06	36
Total Solids (mg/L)	8,882.94	7,710	7,033.3	13,453.3	1,950.92	325.15	0.89	-0.43	3.8E+06	36
Volatile Solids (mg/L)	3,026.3	2,666.65	1,566.7	5,353.3	966.72	161.12	0.81	-0.12	934,547.9	36
Estimated TDS (mg/L)	7,246.67	6,936.26	5,358.81	9,503.79	1,165.14	194.19	0.35	-0.91	1.4E+06	36
Total Nitrogen (mg/L as N)	82.61	70	20	280	54.30	9.05	2.16	5.11	2,948.53	36
Total Phosphorus (mg/L as PO$_4$)	9.22	7.9	1	31	6.94	1.16	1.28	1.66	48.09	36
Silica (mg/L as SiO$_2$)	171.83	125	79	431	98.10	16.35	1.28	0.60	9,622.77	36
Bromide (mg/L)	94.33	84.7	18.9	262.28	41.45	7.22	2.22	8.18	1,717.79	36
Chloride (mg/L)	2,541.64	2,535	933.17	4,354.01	636.19	110.75	0.57	2.52	404,742.9	36
Phosphate (mg/L)	509.28	533	176	885.57	241.80	80.60	0.22	-0.82	58,465.85	9
Sulfate (mg/L)	130.17	60.36	12.91	439	150.39	38.83	1.28	0.12	22,618.26	15
Calcium (mg/L)	1,333.21	1,071.7	657.5	2,485.3	551.80	91.97	0.90	-0.39	304,485.4	36
Magnesium (mg/L)	277.58	290.35	142.6	377.5	51.84	8.64	-1.01	1.16	2,687.60	36
Copper (mg/L)	0.048	0.053	< 0.01	0.12	0.037	0.006	0.009	-1.03	0.001	36
Iron (mg/L)	3.987	1.307	0.241	19.32	5.169	0.862	1.607	1.860	26.723	36
Manganese (mg/L)	1.002	0.343	< 0.01	3.453	1.172	0.195	1.104	-0.493	1.373	36
Zinc (mg/L)	0.093	0.095	< 0.01	0.185	0.049	0.008	-0.372	-0.614	0.002	36
Potassium (mg/L)	224.76	224.5	161.5	307.9	32.29	5.38	-0.05	0.543	1,042.44	36
Sodium (mg/L)	646.22	644.3	453	809	72.26	12.04	-0.18	0.615	5,220.99	36
Aluminum (mg/L)	0.346	0.305	0.06	0.68	0.156	0.026	0.478	-0.733	0.024	36

Table A-5. 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)	-116.84	-122	-159	121	34.56	3.94	4.38	29.20	1,194.69	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	3,816.84	864.70	163.41	2.83	8.65	747,698.2	28
Total Alkalinity (mg/L as $CaCO_3$)	1,904.72	1,900	1,226.7	2,250	179.48	21.15	-0.69	2.13	32,211.2	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
Hardness (mg/L as $CaCO_3$)	4,310.02	3,444.03	1,598.05	11,293.4	2,366.70	394.45	1.14	0.96	5.6E+06	36
Total Solids (mg/L)	12,103.9	11,993.35	10,700	15,873.3	1,065.95	177.66	1.65	3.86	1.1E+06	36
Volatile Solids (mg/L)	1,313.34	963.35	633.3	3,346.7	777.17	129.53	1.79	2.05	603,991.1	36
Estimated TDS (mg/L)	10,921.9	11,268.24	7,295.51	13,425.69	1,249.74	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	162.69	43.1	777.08	111.42	18.57	4.59	25.21	12,414.74	36
Chloride (mg/L)	4,562.31	4,478.1	1,237.45	8,209.49	1,208.59	201.43	0.09	2.99	1.5E+06	36
Phosphate (mg/L)	229.3	214	195.2	294	44.16	22.08	1.72	3.19	1,949.69	4
Sulfate (mg/L)	96.57	57.96	24.49	460.24	108.07	26.21	2.63	8.19	11,679.02	17
Calcium (mg/L)	1,727.38	1,380.35	640.5	4,526.2	948.49	158.08	1.14	0.96	899,626.3	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)	944.50	1,057.1	254.2	1,340.7	308.38	51.40	-0.843	-0.486	95,099.44	36
Sodium (mg/L)	1,863.88	1,879.4	568	2,868.9	580.86	96.81	-0.467	-0.302	337,398.1	36
Aluminum (mg/L)	0.153	0.16	< 0.002	0.53	0.136	0.023	0.769	0.181	0.019	36

Table A-6. Lysimeter leachate monitoring summary. MSW 2: 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	7,359.93	99
Ammonia (mg/L NH_3)	1,029.22	78.2	0.51	8,715.56	1,984.19	374.98	2.74	8.24	4E+06	28
Total Alkalinity (mg/L as $CaCO_3$)	3,177.10	3,083.35	2,066.7	4,600	680.80	80.23	0.28	-0.85	463,493.3	72
Volatile Acids (mg/L as Acetic Acid)	307.16	100	16.7	1,025	314.52	44.93	0.63	-0.93	98,922.88	49
Hardness (mg/L as $CaCO_3$)	3,022.40	3,192.35	1,265.71	5,040.63	1,155.29	192.55	0.12	-1.28	1.3E+06	36
Total Solids (mg/L)	6,785.31	7,272.3	2,940	10,686.7	2,699.08	449.85	-0.05	-1.53	7.3E+06	36
Volatile Solids (mg/L)	3,527.17	4,292.2	1,160	6,080	1,661.80	276.97	-0.10	-1.59	2.8E+06	36
Estimated TDS (mg/L)	5,006.09	4,963.42	3,201.77	7,490.55	1,237.41	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	1,869.29	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	1,293.66	36
Fluoride (mg/L)	5.33	5.76	0.02	10.7	2.99	0.64	-0.33	-0.62	8.99	22
Phosphate (mg/L)	417.77	466	17.03	826.71	347.33	96.33	-0.16	-1.92	120,640.1	13
Sulfate (mg/L)	82.94	36.43	10.85	222	88.10	29.37	0.80	-1.48	7,761.99	9
Calcium (mg/L)	1,128.5	1,194.25	423.7	1,899.2	452.15	75.36	0.11	-1.26	204,436.9	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	13.155	0.829	49.085	13.842	2.307	0.602	-0.694	191.613	36
Manganese (mg/L)	2.996	3.116	0.086	7.656	2.520	0.420	0.375	-1.097	6.352	36
Zinc (mg/L)	0.101	0.099	0.001	0.2	0.047	0.008	-0.397	-0.102	0.002	36
Potassium (mg/L)	102.90	94.85	27.3	165.3	40.42	6.74	-0.24	-0.71	1,633.70	36
Sodium (mg/L)	177.61	178	60	279	49.53	8.26	-0.31	0.58	2,453.15	36
Aluminum (mg/L)	0.644	0.685	0.12	0.99	0.215	0.036	-0.451	-0.535	0.046	36

Table A-7. Lysimeter leachate monitoring summary. Mix 2: 60% MSW, 24% Bottom Ash, 6% Fly Ash, 5% 5% Water Treatment Residuals, 5% Wastewater 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	3,965.26	99
Ammonia (mg/L NH_3)	3,590.08	101.32	3.4	15,031.91	5,309.28	1,003.36	1.20	0.02	2.8E+07	28
Total Alkalinity (mg/L as $CaCO_3$)	2,895.97	2,866.65	1,666.7	4,800	690.29	81.35	0.45	-0.36	476,500.5	72
Volatile Acids (mg/L as Acetic Acid)	172.76	33.3	16.7	675	213.64	30.52	0.94	-0.73	45,640.02	49
Hardness (mg/L as $CaCO_3$)	3,441.21	3,307.87	1,654.66	6,574.11	1,282.82	213.80	1.17	0.97	1.6E+06	36
Total Solids (mg/L)	7,009.20	5,950	4,353.3	13,540	2,514.9	419.15	1.18	0.65	6.3E+06	36
Volatile Solids (mg/L)	2,829.26	2,313.35	1,853.3	5,453.3	1,023.61	170.60	1.02	0.02	1.1E+06	36
Estimated TDS (mg/L)	5,846.30	5,696.75	3,831.75	9,246.88	1,472.59	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	1,476.10	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	6,563.19	36
Bromide (mg/L)	30.92	25.025	12.83	82.58	18.43	3.07	2.36	4.31	339.51	36
Chloride (mg/L)	900.01	882.91	427.88	1,323.7	233.73	38.96	-0.02	-0.49	54,628.47	36
Phosphate (mg/L)	1,241.87	1,302	496.56	1,715.91	385.47	128.49	-0.78	0.44	148,584.4	9
Sulfate (mg/L)	165.71	39.70	12.22	449	194.19	68.66	0.71	-1.92	37,707.61	8
Calcium (mg/L)	1,120.52	1,065.65	396.4	2,326.9	497.73	82.96	1.16	0.95	247,734.9	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
Zinc (mg/L)	0.111	0.108	0.006	0.335	0.058	0.010	1.390	5.438	0.003	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	1,200.89	36
Aluminum (mg/L)	0.481	0.485	0.1	0.86	0.189	0.032	-0.180	-0.542	0.036	36

Table A-8. Lysimeter leachate monitoring summary. Layer 2: 60% MSW, 24% Bottom Ash, 6% Fly Ash, 5% Water Treatment Residuals, 5% Wastewater Residuals.

Parameter	Mean	Median	Minimum	Maximum	Standard Deviation	Standard Error	Skewness	Kurtosis	Sample Variance	n
pH	6.35	6.39	5.77	6.69	0.19	0.02	-1.01	1.08	0.04	99
Conductivity (µS/cm)	7.72	9.14	1.94	10.95	2.98	0.30	-1.08	-0.40	8.85	99
Temperature (°C)	22.22	22	19	24.6	1.45	0.17	-0.11	-0.92	2.11	77
ORP (mV)	-75.90	-75	-133	-34	22.15	2.52	-0.21	-0.61	490.65	77
Turbidity (NTU)	142.82	128	65.9	266	46.38	4.66	0.94	0.01	2,150.64	99
Ammonia (mg/L NH_3)	3,636.34	73.53	3.91	17,296.14	5,631.44	1,064.24	1.42	0.82	3.2E+07	28
Total Alkalinity (mg/L as $CaCO_3$)	2,091.23	2,100	1,466.7	2,733.3	304.91	35.93	-0.11	-0.68	92,969.75	72
Volatile Acids (mg/L as Acetic Acid)	184.58	17.3	16.7	675	248.12	35.45	1.03	-0.73	61,562.31	49
Hardness (mg/L as $CaCO_3$)	4,241.75	4,031.19	2,740.1	6,203.62	1,017.18	169.53	0.50	-0.97	1.0E+06	36
Total Solids (mg/L)	8,036.47	7,263.35	5,766.7	11,246.7	1,589.89	264.98	0.76	-0.73	2.5E+06	36
Volatile Solids (mg/L)	2,859.96	2,586.7	1,086.7	5,080	1,056.16	176.03	0.36	-0.92	1.1E+06	36
Estimated TDS (mg/L)	6,551.25	6,413.79	4,151.44	8,458.59	1,054.50	175.75	0.17	-0.32	1.1E+06	36
Total Nitrogen (mg/L as N)	80.06	75	36	190	36.41	6.07	1.25	1.80	1,325.83	36
Total Phosphorus (mg/L as PO_4)	12.16	8.2	1	44	9.32	1.55	1.66	2.86	86.87	36
Silica (mg/L as SiO_2)	187.86	156	76	498	99.51	16.58	1.56	2.15	9,901.32	36
Bromide (mg/L)	80.81	77.47	31.79	168.84	27.85	4.71	0.82	1.59	775.35	36
Chloride (mg/L)	1,822.52	1,852.31	298.91	3,002.24	501.67	83.61	-0.38	2.14	251,670.4	36
Phosphate (mg/L)	456.23	339.95	19.28	1,157.71	348.34	110.15	1.17	0.82	121,337.5	10
Sulfate (mg/L)	70.78	53.01	12.39	186	65.36	18.87	0.76	-0.80	4,272.40	12
Calcium (mg/L)	1,425.16	1,331.35	749	2,219.3	431.14	71.86	0.36	-1.06	185,878.9	36
Magnesium (mg/L)	166.74	178.65	65.4	235.5	43.63	7.27	-0.85	0.08	1,903.56	36
Copper (mg/L)	0.045	0.049	< 0.01	0.087	0.032	0.005	-0.376	-1.448	0.001	36
Iron (mg/L)	4.757	1.067	0.273	18.48	5.549	0.925	1.099	-0.034	30.795	36
Manganese (mg/L)	1.033	0.677	0.015	2.736	0.861	0.144	0.743	-0.805	0.742	36
Zinc (mg/L)	0.100	0.102	0.003	0.212	0.047	0.008	0.162	0.549	0.002	36
Potassium (mg/L)	179.60	174.6	118.4	261.5	37.84	6.31	0.343	-0.81	1,431.89	36
Sodium (mg/L)	494.19	506.7	281	720.8	110.63	18.44	-0.11	-0.42	12,238.91	36
Aluminum (mg/L)	0.451	0.455	< 0.002	0.73	0.154	0.026	-0.398	0.795	0.024	36

APPENDIX B:

SUMMARY OF STATISTICAL PARAMETERS

DESCRIPTION OF STATISTICAL PARAMETERS

Table B-1. Description of all of the statistical parameters used for lysimeters and field data analysis.

Parameter	Equation	Interpretation	Relevance to the project
Mean	$\mu = \Sigma X/n$	Average value.	Measures of central tendency.
Median	n odd: Median = $X_{(n+1)/2}$ n even: Median = $(X_{n/2} + X_{(n/2)+1})/2$	Value that divides data set into two equal parts.	
Minimum		Smallest score in a data set.	Calculation of the range, which is a measure of data variability.
Maximum		Largest score in a data set.	
Sample Variance	$S^2 = \dfrac{\Sigma (X - \mu)^2}{n - 1}$	Average of the squared deviations of the scores in a data set. Variability expressed in terms of the square of the original units.	Measures of data variability. How dispersed the data set is.
Standard Deviation	$S = [\Sigma (X - \mu)^2 / n - 1]^{1/2}$	Square root of variance. Variability in terms of the original units.	
Standard Error	$S_e = S/(n)^{1/2}$	Estimates the standard deviation of the sample mean based on the data set mean.	
Skewness	$Skew = \Sigma(X - \mu)^3 / S^3$	Skew = 0 Symmetric Skew > 0 It has a long tail in the positive direction. Skew < 0 It has a long tail in the negative direction.	Measure of distribution shape: degree of asymmetry in the distribution.
Kurtosis	$Kurt = \Sigma(X - \mu)^4 / S^4$	Kurt < 3 Platykurtic: flattened middle. Kurt = 3 Mesokurtic: normal distribution. Kurt > 3 Leptokurtic: sharp peak.	Measure of distribution shape: degree of peakedness of the distribution.

Table B-2 Statistical tests used for lysimeter and field data analysis.

Parameter	Results	Interpretation	Relevance to the project
ANOVA	P value, R square, and Confidence Intervals	Are means or medians significant different? P value $< 0.05 \longrightarrow$ Yes P value $\geq 0.05 \longrightarrow$ No	Statistical test for parameter heterogeneity by analysis of group ($\geq$3) variances.
t- test	P value and Confidence Intervals.	How big is the difference? 95% Confidence intervals.	Determines whether parameters from two groups differ from each other in a significant way.
Correlation	Correlation coefficient (r), r^2, and P value.	$r = \pm 1$ Perfect correlation. $r = 0$ No correlation. $0 > r > 1 =$ Increase or decrease together.	How well two variables vary together. Useful to find relationships between parameters.
Linear regression	Correlation coefficient (r)	$-1 < r < 0 =$ One increases as the other decreases. r^2 Fraction of the variance that is share. If p value is small, the idea of the correlation is due to random sampling can be rejected.	Determine the relationship between two parameter or variables.