GEOTECHNICAL ASPECTS OF BIOREACTOR LANDFILLS

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ABSTRACT: Currently, there are more than three thousand landfills in the United States in which approximately 55% of the municipal solid waste (MSW) generated is being disposed. The majority of these landfills are designed on the premise that liquid generation should be minimized through the design of liner, leachate collection and removal, and final cover systems. Recently, “bioreactor” landfills are being designed on the contrasting premise that leachate recycling, water addition, and other operating strategies should induce an enhanced environment for biochemical degradation of MSW. Bioreactor landfills are receiving a great deal of attention from environmental professionals because they offer a sustainable way to achieve increased waste degradation along with benefits such as reduction in leachate pollution potential and rapid increase in landfill volumetric capacity. They also offer significant reductions in post-closure management as a result of a reduced period for landfill leachate and gas generation and improved potential for more rapid land reuse for a recreational facility or industrial park. The design of bioreactor landfills requires a careful assessment of several engineering issues such as leachate/moisture distribution, waste degradation and gas generation, waste settlement, and stability of waste slopes. This paper first discusses these issues and then describes the selected historic and current bioreactor demonstration projects. Finally, this paper outlines additional research needed to design and operate bioreactor landfills for effective stabilization of MSW.

1. INTRODUCTION

A bioreactor landfill is a municipal solid waste (MSW) landfill that uses enhanced biochemical processes to transform and stabilize the decomposable organic waste within short time (typically 5 to 10 years) as compared to long time (typically 30 to 100 years) for conventional ("dry tomb" or “Subtitle D”) landfills. Bioreactor landfills are gaining popularity in the United States and worldwide and they are being demonstrated at various landfill sites.

A bioreactor landfill can be classified as anaerobic, aerobic, or hybrid. In an anaerobic bioreactor landfill, moisture is added to the waste using recirculated leachate and nonindigenous liquids to obtain optimal moisture levels. Biodegradation occurs in the absence of oxygen and enhances rates of methane production as a biogas fuel. An aerobic bioreactor landfill involves addition of moisture through recirculation of leachate that has been collected from the leachate collection and removal system. Air is also injected into the landfill through vertical or horizontal wells to help promote aerobic activity and waste stabilization. The hybrid technique utilizes both aerobic and anaerobic methods to accelerate waste degradation.

Compared to conventional “dry tomb” landfills, a bioreactor rapidly stabilizes MSW into a form where potential contaminant leaching is minimized and environmental effects are reduced. The material that remains in the landfill after stabilization consists of non-biodegradable waste (metal, plastic, glass) as well as residual biodegradable materials. During the process of landfill stabilization, waste mass is lost through the production of landfill gas. The resulting landfill mass will settle, decreasing volume of the placed material.

The operation of MSW landfills as bioreactors has been initiated at several locations in the United States and other countries. Many of these operations are under intensive study to optimize design and operation methods. These facilities are designed to perform leachate recirculation and instrumented to monitor leachate distribution and leachate head on the liner. Monitoring data from these facilities demonstrate that the waste is biodegraded rapidly by the leachate recirculation, and the dynamics of leachate distribution controls the extent and rate of waste degradation. The dynamic moisture/leachate distribution will also influence the hydraulic and mechanical properties of the waste spatially and temporally. Such changes in the properties should be taken into consideration in design and analysis of bioreactor landfills. In particular, the settlement and stability of waste will be affected by the changed waste properties; thus the design and analysis should account for transient changes in waste properties.

This paper presents an overview of the following important aspects of bioreactor landfills:

- Leachate/moisture distribution,
- Waste degradation and gas generation,
- Engineering properties of waste,
- Waste settlement analysis, and
- Slope stability analysis.

This overview is followed by a description of the selected historic and current bioreactor demonstration projects. Finally, an outline of additional research needed for the safe and effective operation of bioreactor landfills is provided.

2. LEACHATE/MOISTURE DISTRIBUTION

The most critical aspect of a bioreactor landfill is leachate addition and management. The amount of leachate within the waste influences other chemical, biological, physical, and economic factors. For example, if properly implemented and managed, the increased moisture content will enhance chemical and biological transformations of both organic and inorganic constituents within the landfill airspace. Leachate recirculation will increase the rate at which waste decomposes, which will also enhance landfill gas (LFG) generation rates.

One of the greatest challenges to effective leachate recirculation is the difficulty of distributing moisture evenly throughout the landfill. The efficiency of leachate distribution varies with the method of application. These methods differ in leachate recirculation capacity, volume reduction, and compatibility with active and closed phases of landfill operation. Different methods that have been used for leachate/moisture application at bioreactor sites are:

- Spray Irrigation
- Infiltration Ponds
- Subsurface Trenches or Wells
- Direct Application to Working Face.

2.1 Spray Irrigation

This method involves spraying leachate over a large surface area. Although this method allows for the distribution of leachate over a larger portion of landfill, loss of leachate volume through evaporation, odors, and wind conditions can be of concern.

2.2 Infiltration Ponds

This method recirculates leachate through surface infiltration ponds. The ponds are constructed using an area that is isolated with soil berms or developed in excavated waste.

2.3 Subsurface Trenches or Wells

This method uses either horizontal trenches or vertical wells, and it is the most common method for distributing leachate. The horizontal trenches are placed into the waste and filled with granular soils or permeable waste materials such as tire chips. The leachate is either pumped through perforated piping by gravity or pressure injected. Horizontal trenches are usually spaced about 100 to 200 feet horizontally and 40 feet vertically. The advantages of horizontal trenches are leachate distribution is maximized, injection rates can be high, and injection ports can be located away from operating and traffic areas. The main disadvantage to horizontal trenches is that insufficient spacing of trenches or over-pumping can result in vertical leachate seeps and possible artesian conditions.

On the other hand, the vertical wells are carefully placed throughout the landfill to ensure no interference with one another or with waste placement and compaction. Vertical wells are usually spaced 100 to 200 feet apart. The main advantage to using vertical wells is the low cost; however, the vertical wells may not uniformly distribute leachate laterally. Both of these application methods can be used during active and closed phases of operation.

2.4 Direct Application to Working Face

In this method, leachate is added directly to the waste as it is being deposited into the landfill using tank trucks or by manual spraying. This method requires a leachate storage facility for occasions when the leachate cannot be applied due to high winds, rainfall, and times when the landfill is closed.

The generation and distribution of leachate in bioreactor landfills is being investigated through laboratory studies and through field monitoring at several bioreactor landfill sites under different operating conditions. A field monitoring database is gradually developing to help assess the effects of the method of injection on leachate routing within the waste and to determine the impacts of other parameters such as the phase and age of the landfill.

Bogner and Spokas (1995) and Bogner et al. (2001) performed a comprehensive laboratory experimental program to investigate increases in moisture content of waste during optimized decomposition. A standardized synthetic waste was prepared with three degradable components (paper, grass and food) and two soils (sand or clay). All experiments were conducted *in vitro* in 125 mL glass serum bottles at three different initial moisture contents of 80%, 350% and 750% by weight, under leachate recycle or leachate drainage regimes. The two higher moisture contents simulated high-solids or low-solids anaerobic digestion in small batch systems, allowing examination of end points under optimal decomposition. The test results clearly revealed that the increase in moisture content can be as high as three times the initial moisture content under optimized decomposition. Such large and dynamic increases in moisture content must be accounted in the assessment of performance of bioreactor landfills.

Shearer et al. (2000) analyzed the variation of moisture in a bioreactor landfill in relation with time by using a series of columns. Three different moisture conditions were set up at 25, 35 and 45% by weight. The columns were filled with MSW from a landfill, aerated for ten hours every day, leached with recirculation by using a submersible pump, and fed with biosolids. The results showed that after 300 days, the moisture contents were 23, 29 and 45%, indicating a relatively low variation from the beginning of the experiments. However, this study revealed that the increased moisture enhanced waste degradation based on the measured volatile solids (VS) and cellulose. The optimum moisture content was determined to be above 45%.

Waste characteristics, most notably large pore volumes and heterogeneity, will lead to rapid vertical flow of leachate along preferential flow paths, causing incomplete use of moisture storage. Zeiss and Uguccioni (1997) conducted a laboratory study to evaluate the effects of channeled flow on effective storage and field capacity, which are important input variables to the water balance analysis. The water balance analysis was conducted for two separate periods, namely the pre-capping phase and the post-capping phase and determined the amount of water that was drained from a saturated zone at the base of the control section. From the water balance modeling and actual leachate measurement, it was estimated less than 50% of field capacity at the Trail Road Landfill in Ontario, Canada, was utilized after seven years of recirculation (Warith et al. 1999).

Based on field observations, the moisture content in waste could be in excess of the ambient levels of 10 to 20 percent to promote full bioreactor activity (anaerobic or aerobic) (Yuen, 1999). Based on previous data, the ideal moisture condition is reported to be about 45%. The efficiency and area of influence of the various available recirculation systems must be evaluated for the optimal moisture reintroduction effort. The timing and phasing of moisture influx and its effect on the bioreactor process are also important considerations.

Mathematical models are also being used to understand the role of different system parameters on leachate distribution in bioreactor landfills. Reinhart and Basel (1996) performed mathematical modeling to assess the impact of critical parameters that effect the leachate distribution within the waste during the leachate recirculation operations in typical bioreactor landfills. A saturated-unsaturated flow and transport model, known as SUTRA developed by the United States Geologic Survey (USGS), was utilized. This model is capable of analyzing the relationships among saturation, capillary pressure, and permeability under unsaturated flow conditions. Through modeling, the effects of using horizontal trenches, the presence of waste heterogeneities and daily cover, and the leachate application rate and frequency on the leachate distribution were investigated. The waste permeability was found to be a critical parameter that impinges on leachate routing within a bioreactor landfill. As permeability of waste decreases, lateral migration of leachate decreases, but instead upward leachate seeps may be possible to occur. It was also determined that leachate applications rates must be lowered when applied to low permeable waste to avoid surface seeps. According to the findings, lowering the leachate application rate will decrease the lateral area impacted.

Daily cover is another parameter that affects leachate flow in the landfill. Daily cover material varies from clay, sand, shredded tires, and foams to removable geotextiles or tarps. These materials differ in thickness and permeability and depending on where they are located, can seriously affect leachate routing. The mathematical modeling study of Reinhart and Basel (1996) also examined the effects of a low permeability cover versus a high permeability cover, intermittent leachate application versus continuous application rate, and tears/breaches in cover materials versus number of breaches. It was determined that the location of breaches seriously altered and directed leachate routing. In addition, a low permeability cover increased lateral movement and decreased vertical movement. Waste heterogeneities altered leachate routing in a similar manner as waste permeability. Waste is extremely heterogeneous, and its characteristics change with time. The model results showed that leachate distribution in heterogeneous waste resulted in highly saturated zones and dry zones. The lack of uniformity with permeability was determined to increase lateral leachate movement. As a result, careful placement of low permeability materials within the landfill must be considered as well as homogenizing the waste in order to obtain optimal and uniform saturation of waste.

3. WASTE DEGRADATION AND GAS GENERATION

When solid waste is buried in a landfill, the biodegradable fractions decompose via a complex series of microbial reactions under anaerobic conditions. These fractions include readily degradable food waste, more slowly degradable paper (cellulosic) wastes, and garden or commercial wastes containing slow to rapidly degradable components. Major intermediate products during decomposition include acetic acid (CH_3COOH), other carboxylic acids, carbon dioxide (CO_2), and hydrogen (H_2). The terminal reaction is the production of methane (CH_4) by methanogenic microorganisms. In developing countries, most solid waste disposal occurs at non-engineered sites without soil cover where a large fraction of the DOC may decompose aerobically to CO_2 rather than degrade anaerobically to CH_4. However, empirical evidence confirms that CH_4 generation does occur at such sites after older waste is buried with younger waste.

Classical modeling of gas generation in landfills involves 4-5 phases (Farquahar and Rovers, 1973; Young, 1986; Rees, 1990) wherein phase I (aerobic) involves initial aerobic degradation until available oxygen is depleted; phase II (initial anaerobic/acidogenic) involves the activity of hydrolytic and fermentative microorganisms with the generation of CO_2, H_2, and carboxylic acids; phase III (acetogenic) involves acetate generation (CH_3COOH) from precursor carboxylic acids; and phase IV (methanogenic) involves steady methane generation from acetate cleavage or the reduction of CO_2 with H_2. As a result of these two pathways, landfill gas typical consists of 50-60 % CH_4 (v/v) with the remainder primarily CO_2 (Bogner et al., 1996). An optional phase V involves the slow onset of secondary aerobic conditions after 2-3 decades. Barlaz et al. (1989) quantified the dynamic microbial populations and the changing chemistries of solid, liquid, and gas phases through detailed laboratory studies wherein the entire decomposition cycle was completed in 180 days via high moisture contents and leachate recirculation, the major strategies being evaluated for bioreactor landfills. Leachate was also neutralized in this study to prevent initial accumulations of carboxylic acids from retarding methanogenic activity, which is optimized at near-neutral pH.

If decomposition reactions proceed at optimized rates, then the mass of CH_4 produced depends directly on the mass of degradable organic carbon landfilled, i.e., the waste composition. Bingemer and Crutzen (1987), in the first global estimate of landfill CH_4 emissions, assumed that 0.77 of the degradable organic carbon landfilled was anaerobically converted to biogas carbon (CH_4 and CO_2). This was based upon a temperature-dependent equation for optimized low-solids anaerobic decomposition and, using a typical waste composition for developed countries, was equivalent to a CH_4 yield of 0.10 kg $CH_4 \cdot kg^{-1}$ (dry) solid waste. The theoretical maximum CH_4 yield, based upon an empirical equation for U.S. solid waste composition, is approximately 0.18 kg CH_4 (dry) kg^{-1} solid waste (Halvadakis et al., 1983). In contrast, optimized laboratory studies of solid waste decomposition from the U.S., Germany, and Italy have shown that the fraction of organic carbon converted to biogas carbon ranges from negligible to a maximum of 0.25 – 0.47 (Table 4, Bogner and Spokas, 1993), which is equivalent to maximum yields of 0.04 – 0.08 kg $CH_4 \cdot kg^{-1}$ (dry) solid waste. Methane yields in field settings are lower because landfills do not function as efficiently as anaerobic digesters or laboratory systems. Indeed, Richards (1989) assumed a yield of 0.036 kg $CH_4 \cdot kg^{-1}$ (dry) solid waste, based on commercial landfill CH_4 recovery data. Some recent literature has proposed CH_4 yields ranging from 0.07 – 0.13 kg $CH_4 \cdot kg^{-1}$ (dry) solid waste (Kura and Lee, 1995; Li et al., 1999).

At conventional landfills not being operated as bioreactors, empirical evidence suggests that phases I-IV are concurrent rather than sequential, depending on localized moisture contents within the waste. Laboratory studies have clearly demonstrated the importance of moisture content for accelerated biodegradation (Barlaz et al., 1989; Bogner et al., 1990). In general, localized rates of CH_4 generation and the time to achieve a substantial portion of theoretical CH_4 yield from waste in a particular landfill cell are highly variable. Some current bioreactor projects are demonstrating extremely high CH_4 generation rates; for example, the Yolo County with rates of 0.11 scf CH_4/dry lb refuse.
(www.epa.gov/projectxl/yolo/index.html).

4. ENGINEERING PROPERTIES OF WASTE

Similar to soils, the important engineering properties of waste are particle size distribution, moisture content, porosity, unit weight, field capacity, hydraulic conductivity, compressibility, and shear strength. These properties affect the waste degradation, leachate generation and distribution, and the overall geotechnical stability of bioreactor landfills. The properties of MSW in conventional landfills are presented in Sharma and Reddy (2004). Although the same methods can be used to determine the properties of MSW in bioreactors, very limited effort has been made to date to characterize the properties of MSW in bioreactor landfills. The **size distribution of waste components** controls the overall engineering properties such as hydraulic conductivity, compressibility, and shear strength. As the waste is biodegraded, the particle size distribution is expected to vary with time, resulting in change in the engineering properties.

Moisture content (w) defines the amount of mass of water within the waste. The moisture content is defined in three different ways: (a) the ratio of mass of water to the dry mass of waste, (b) the ratio of mass of water to the wet mass of the waste, or (c) the ratio of volume of water to the volume of waste. Previous experience and research indicates that the control of waste moisture content is the single most important factor in enhancing waste decomposition in landfills (Pohland, 1975). Enhancement of methanogenesis, nutrient transport, and microbial degradation are stimulated with increased moisture content of the waste. Leachate recirculation has been found to be the most practical approach to moisture content control; therefore, full-scale bioenhancement efforts tend to focus on this technique. The type of leachate recirculation system utilized and the method of operation are selected after appropriate consideration of project goals related to moisture distribution, minimizing environmental impact, and regulatory compliance. As discussed in previous section, several laboratory, field and monitoring studies are being conducted to evaluate the moisture generation and distribution in bioreactor landfills.

Porosity (n) can be related to the **void ratio (e)** by the relationship: $n = e/(1+ e)$. Porosity is defined as the ratio of volume of voids to total volume. The porosity of the waste is reduced by a number of factors, mainly due to: (a) biofouling- as the leachate is recirculated through the waste and leachate drainage materials such as geotextile and sand (Koerner and Koerner, 1990), and (b) large compression of the waste that reduces the pore volume.

The porosity changes affect the unit weight of the waste. **Unit weight** is the weight per unit volume, whereas the density is the mass per unit volume. Waste density in landfills is difficult to determine because it is dependent upon the waste type, water content, daily cover, and time since placement. The waste at the bottom of deep landfills compacts immediately upon placement as well as over time as waste filling progresses vertically. This results in greater density of the waste at the bottom of the landfill as compared to the top. In bioreactor landfills, organic waste is stabilized by the use of leachate (moisture) recirculation. The process of adding this moisture to waste also affects its density until the waste reaches an optimum moisture content. Hater (2000) measured unit weight of the wastes at four landfills where leachate recirculation was used. Based on these measurements, the average in-place unit weight was found to be 112 lb/ft^3 (pcf) or about 66% more dense than for conditions without leachate circulation which had the average unit weight of 67 pcf. The increase in unit weight depends on the initial moisture content of the waste, leachate generation or recirculation amounts, waste field capacity, and void ratio available for liquids. As MSW degrades chemically and biologically, the void space in a unit volume is expected to decrease, leading to further increase in the unit weight. Boda (2000) evaluated factors related to density increase in bioreactor landfills due to the added moisture (leachate) and the enhanced decomposition of waste. The added moisture makes waste compact physically more than dry waste, and the enhanced decomposition reduces waste particle size and creates a more dense structure. Based on a full-scale landfill study, dry density was found to increase with decrease in VS, cellulose, and lignin contents. Typically, one expects a relative percent increase in lignin during degradation; therefore, cellulose/lignin ratio is used as an index of degradation since lignin is recalcitrant.

The infiltration or flow of leachate through the waste depends on **field capacity** and **hydraulic conductivity** of waste. Field capacity is the total amount of moisture which can be retained in the waste. It is an important property because it determines the maximum absorption capacity beyond which excess free leachate will form. The field capacity varies with the height of waste, state of compaction, and state of decomposition. Typically, the field capacity of uncompacted waste from residential and commercial sources varies from 50 to 60%. The hydraulic conductivity of compacted waste is an important physical property because it governs the movement of liquids and gases in a landfill. Permeability depends on the other properties of the solid material in the waste including pore size distribution, surface area, and porosity. Saturated hydraulic conductivity of waste typically varies from 1×10^{-3} to 4×10^{-1} cm/s (Landva and Clark, 1990). As waste density increases with increased depth (compression), drainable porosity and vertical hydraulic conductivity will decrease, suggesting that liquid movement may be restricted in deep landfills, limiting leachate flushing. In deep landfills, the heavily compressed waste may have a hydraulic conductivity approaching that of "impermeable" liner materials. Also the increased rates of gas production or gas accumulation can reduce hydraulic conductivity.

Compressibility of waste is an important consideration in settlement analysis and often a compressibility index is defined, similar to soils, to characterize the compressibility of waste. The compressibility of the waste also depends on the leachate head, moisture content, density, composition, and biodegradation. The variations in these properties together with the heterogeneous, anisotropic and unsaturated nature of waste in most landfills limit the use of classical soil mechanics approaches to predict landfill settlements. Based on observations made at several bioreactor landfills, settlement during the bioreactor landfill operations varies significantly, both spatial and temporally. A comprehensive model for settlement analysis of bioreactor landfill waste should take into consideration of the decrease in void ratio due to solid to gas conversion, the changes in degree of saturation, as well as the physical changes in particle sizes and distribution. As the solid mass is converted to landfill gas in bioreactor landfills, the void ratio decreases, hydraulic conductivity decreases, and the degree of saturation increases, which all lead to increased compressibility.

Hossain (2002) attributed the total *settlement* of waste in bioreactor landfills to the following three components: (1) compressibility of waste caused by the own weight; (2) compressibility of waste caused by physicochemical processes originating in waste and its consequent variability of components arrangement; and (3) compressibility of waste enhanced by gas production and the corresponding decrease in void space. On the basis of laboratory one-dimensional consolidation experiments, Hossain (2002) reported that the compressibility of waste increases with time when the conversion of solid matter to gas phase is enhanced by decomposition and leachate recycling. The compressibility parameter (C_c), similar to the compression index defined for soils, was correlated to biodegradation factors such as the ratio of (cellulose+hemicellulose)/lignin or (C+H)/L. For decreasing ratios of (C+H)/L, C_c values are found to increase. For similar ratios, however, the creep index ($C_{\square}$), defined similar to the coefficient of secondary compression for soils, showed a certain independency to the degree of decomposition. A biological index (C_b) was defined to determine the compression as a result of biodegradation and it was found to vary depending on the state of degradation.

Data on the **shear strength** of MSW in bioreactor landfills is very limited, but the shear strength of waste in conventional drier landfills has been investigated by several researchers (Landva and Clark, 1986; Sharma and Lewis, 1994; Valero, 1995; Sharma and Reddy, 2004). The friction angle values were found to vary from 38^0 to 42^0, and the cohesion values were found to vary from 16 to 19 KPa. In the case of bioreactor landfills, initially the waste conditions are similar to that of a conventional landfill; therefore, the drained shear strength of undegraded waste in bioreactor landfills is the same as that of waste in the conventional landfills. However, as liquids are injected in bioreactor landfills, the waste is fully saturated and the degraded waste may have relatively low permeability, and under such conditions, undrained shear strength of degraded waste is of engineering significance. The increased moisture content leading to waste saturation can lead to positive internal pore pressure and reduced angle of friction. The impact of waste decomposition on shear strength is also of critical concern. Some field investigations reported mud-like conditions at the bottom of wet, deep landfills, indicating a low shear strength of degraded waste.

At some deep landfills in the U.S., an alternation of highly decomposed waste above buried intermediate soil cover layers with undecomposed waste below has been observed. The decomposed layers were semi-solid to liquid and were characterized by high moisture content, uniform gray color, low volatile solids, and the absence of recognizable refuse components.

Gabr and Hossain (2002) conducted laboratory direct shear tests on waste samples that have undergone various stages of degradation under simulated bioreactor conditions. The various features of this testing program are as follows:

- Samples were prepared in eight 4-litre reactors
- Various stages of degradation were considered. Decomposition was represented by gas generation rates and cellulose to lignin ratio.
- Twelve direct shear tests on biodegraded waste were conducted. Samples ranged from fresh to well-decomposed waste.
- Nine direct shear tests were conducted on different MSW main components especially plastics and paper in order to relate the results to the specific displacement observed in biodegraded waste.

Overall, this study revealed that shear strength decreases during decomposition and the shear strength parameters are dependent on the magnitude of the displacement.

5. WASTE SETTLEMENT ANALYSIS

In general, the settlement of waste is attributed to:

- Mechanical properties
- Raveling
- Physicochemical reactions
- Biochemical decay
- Interactions among the above mechanisms.

After waste is landfilled, waste particles bend, crush, and relocate themselves to better accommodate their new stress situation. Due to the wide range of particle sizes, small particles will tend to move into the void space between larger ones (raveling), causing additional settlement, especially during compaction immediately after placement. Physicochemical changes (e.g., corrosion, oxidation) and biochemical decay which cause a decrease in waste mass will lead to additional vertical settlement. Landfill settlement generally follows a nonuniform pattern because of variations in waste composition, causing differential settlement. The occurrence of differential settlements is even more critical than total settlement because excessive local settlement can lead to structural failure in the final cover and damage to the surface-water drainage system, gas and leachate pipes, and underground utilities. The amount of settlement at a specific location depends on the nature of landfill materials at that location. In areas where highly decomposable and compressible materials exist, larger amounts of settlement can be expected. Other contributing factors to differential settlements include changes in the manner in which waste is placed or compacted. Operational and maintenance practices (e.g., sorting, pretreatment, uniform compaction, etc.) can minimize problems associated with both total and differential settlements (Sowers, 1968). In bioreactor landfills, enhanced biodegradation of organic material in waste occurs and causes reduction in the volume of waste, leading to a higher rate and total magnitude of settlement.

Currently, the settlement analysis methods developed for analyzing conventional landfills are being applied to analyze bioreactor landfills as well. These methods are predominantly empirical and usually based on measured laboratory and field parameters. Most models developed to date can be grouped into four categories:

- Soil mechanics based models,
- Rheological models,
- Empirical models, and
- Models accounting for the waste degradation.

5.1 Soil Mechanics Based Models

Several models developed to estimate waste settlement are based on conventional geotechnical theory (Morris 1990; Oweis and Khera, 1986; Rao 1977; Sowers 1973; El-Fadel and Khoury, 2000). Traditionally, settlement models in the literature have relied on a form of Terzaghi's (1925) theory of consolidation including secondary compression terms. The compression indices for both primary and secondary compression are a function of the initial void ratio. The primary compression index was estimated to range between 0.15 and 0.55 times the initial void ratio (the lower value is for fills low in organic matter), while the secondary compression ratio ranged between 0.03 and 0.09 times the initial void ratio (the lower value is for conditions unfavorable to decay). However, these relations were obtained based on measurements up to 15 months only. The application of this theory to landfills has been questioned for landfills that are not saturated, have large void spaces and particles, experience large deformations and creep, have compressible solids and pore fluid, undergo solids loss due to biodegradation, and have changing material properties over time (Chen, 1974).

5.2 Rheological Models

Rheological (stress-strain-time) models evaluate the mechanical behavior of materials which are considered to be continuous, and homogeneous. Even though the material may consist of various phases, only statistical averages of its microscopic behavior are considered. The Gibson and Low model and the Power Creep Law model are the two rheological models used commonly to assess the transient creep behavior of many engineering materials and the same are used to assess the waste settlement. The model estimates the rate and magnitude of settlement as a function of time and the initial refuse thickness. Zimmerman (1972) and Franklin et al. (1981) developed a rheological model based on the micropore concept to describe the time settlement behavior of milled urban refuse. The model consists of two partial differential equations, one of which is non-linear. The equations include the effects of finite strains, biological and chemical decay, variations in saturation and large amounts of creep. Edil et al. (1990) simulated refuse settlement at four different sites using the Gibson and Lo rheological model and the Power Creep Law model. The sites that violated the assumption of constant stress change could not be analyzed with these models. Overall, the Power Creep Law better – matched the field data in 65% of the cases, while in the remaining cases the models were comparable to each other. EI-Fadel et al (1999) used the Gibson and Lo, Power Creep and one-dimensional consolidation models to simulate laboratory and field settlement data. The Gibson and Lo model rapidly reached constant settlements, and exhibited limitations if settlements persist at a significant level. In contrast, the Power Creep Model did not allow the determination of a time at which settlement rate stabilizes. The one-dimensional model had a greater application potential as it allowed for a second stage of consolidation to describe secondary long-term settlement. In general, it provided a better representation of laboratory and field measurements than other models. A major drawback in the rheological models lies in the fact that the parameters largely depend on applied stress, and extrapolations to other fills must be exercised with care, even when waste composition is similar. A more comprehensive set of data from other landfills in different decomposition stages is needed in order to develop a better dataset of ranges for the empirical parameters.

5.3 Empirical Models

Given the difficulty with applying soil mechanics theory to waste consolidation, empirical models have been proposed. These models attempt to simulate the settlement of landfilled waste by a mathematical function involving empirical parameters which are site specific. Common mathematical functions employed include the Logarithmic Function, Power Function, Hyperbolic Function, and the Multiple Linear Regression Function.

5.4 Models Accounting for the Waste Degradation

The contribution of biodegradation to settlement accounts for a large portion of the total settlement. The assumption is that the amount of settlement is directly proportional to the amount of solids solubilized. Bioconsolidation models require determination of bacterial degradation expressions with their respective kinetic coefficients. More reliable expressions incorporate hydrolysis reactions for different types of bacteria and different types of waste components. However, the determination of the kinetic coefficients or the hydrolysis constants and the modeling their variation with environmental conditions are difficult tasks.

Edgers et al. (1992) identified two stages of delayed compression, the first stage being dominated by mechanical interactions with an average compression coefficient of 0.04, and the second stage by biological processes with an average compression coefficient of 0.1. Primary consolidation is represented by the three-parameter rate process equation, while the secondary compression is represented by the growth rate of bacteria in the exponential growth phase. A major drawback is that the landfill contains a complex microbial ecosystem, yet the model can only incorporate the growth kinetics of the methanogens. The superposition of the two expressions fitted field data well, particularly in landfills undergoing substantial decomposition. Determination of empirical parameters remains a difficult task, especially the lag time after which strain rates start to increase due to decomposition. Additional work was suggested to relate model parameters to waste composition, density, moisture content, and applied stress. Wall and Zeiss (1995) applied this model to activated (enhanced) cells to assess settlement and other parameters affecting settlement such as gas composition, volume, leachate, and total organic carbon.

Park and Lee (1997) defined the concept of settlement that occurs due to decomposition of biodegradable refuse. Long-term settlement was divided into two parts: one associated with mechanical compression, the other with decomposition. The first part was estimated using classical theory, and the second using first-order kinetics. The decay process was related to the solubilization of biodegradable refuse solid. The model was applied to an old refuse site, and it was found that biological strain would be completed in 3 to 5 years. The model lacks field validation. More research is required to account for the effects of leachate and gas production on the decomposition process.

Intense efforts are underway to monitor settlement of waste in bioreactor landfills and develop a workable settlement analysis methodology for bioreactor landfills. Yen and Scanlon (1975) plotted settlement against the logarithm of the median time for three landfills with depths varying from 6 to 31 meters, and construction times varying from 1 to 7 years. The survey periods ranged up to 9 years after completion of the fills. It was assumed that the settlement rates decrease linearly with the logarithm of the median fill age; however, the median age has a limiting value after which settlement rates become negligible. Rao et al. (1977) presented an expression that determines the settlement of any representative layer in a sequential loading process. This expression incorporates the concept of relative height in the conventional Terzaghi model. Laboratory and field tests were conducted on household refuse to determine model parameters. Laboratory data showed that settlement depends on stress history, initial density, load increment ratio, and magnitude of pressure. Field data underlined the importance of environmental factors (rainfall and temperature) on the rate and magnitude of settlement. It was recommended that parameters be obtained from field rather than laboratory data. Dodt et al. (1987) monitored settlement to evaluate the behavior of an old clay cover during vertical expansion of a landfill. The old refuse behaved like cohesive soils. Long-term settlement decreased linearly with logarithm of time. No efforts were made to simulate the observed settlement. Wall (1992) conducted a laboratory experiment to test the effects of biodegradation on settlement. Results showed that secondary settlement is linear with the logarithm of time. The one-dimensional consolidation theory was found to simulate settlement better than the Gibson and Lo and the Power Creep Law models. Warith et al. (1995) monitored settlements at an actual landfill site, and settlement predictions were made using the Gibson and Lo model to estimate the percentage of the ultimate settlement that different portions of the landfill had undergone. Boutwell and Fiore (1995) conducted a field test program to evaluate the need for a temporary surcharge to reduce post-construction settlements to less than a certain value. Conventional soil mechanics theory was used to size the test fills whose settlement was almost that of a wide area load. EI-Fadel (1998) reported several field scale experiments conducted to evaluate biodegradation and associated refuse settlement rates with different operational management practices, including leachate recirculation, addition of water, buffer, and microbial seed.

6. SLOPE STABILITY ANALYSIS

Injection of leachate and other liquids in a bioreactor landfill can endanger the stability of slopes due to the following reasons (Kavazanjian et al., 2001):

- Increased driving force due to the increase in unit weight of the waste mass following liquid injection,
- Decreased strength due to decreases in the effective ("intragranular") stress corresponding to the increase in pore pressure that result from liquid injection (both leachate head build-up and localized decreases in effective stress), and
- Decreased strength due to transformation of waste mass by the biological and chemical processes that enhance degradation, turning the waste into an inherently weaker material.

Overly aggressive leachate recirculation (compounded by the use of an impermeable cover soil) has been cited as contributing factor to the catastrophic slope failure of landfill (Maier, 1998). Therefore, to minimize such risk, one needs to better define the shear strength of stabilized waste and to provide appropriate input to accurately assess the bioreactor landfill stability.

The important geotechnical property needed for stability analysis is the shear strength of the waste. Because of the low degree of saturation and relatively high permeability of MSW, drained shear strength of MSW is used in the analysis of waste mass stability in conventional landfills. In the case of bioreactor landfills, initially the waste conditions are similar to that of a conventional landfill; therefore, the *drained shear strength* of undegraded waste in bioreactor landfills is the same as that of waste in the conventional landfills. However, as the liquids are injected in bioreactor landfills and degradation occurs, the waste becomes fully saturated and may have relatively low permeability; under such conditions, the *undrained shear strength* of the degraded waste is of great engineering significance.

For stability analysis, both undrained and drained shear strengths of the degraded waste are required. Unfortunately, no data are available on the undrained shear strength of degraded MSW and such data are crucial in evaluating stability of bioreactor landfills, especially in regions with high potential for seismic activity. Information on the drained shear strength of degraded wastes is also very limited. Kavazanjian et al. (2001) obtained representative degraded waste samples from a bioreactor landfill and conducted direct shear tests under saturated drained conditions. For design purposes, the drained shear strength of degraded waste in bioreactor landfills is often assumed to be equal to the drained shear strength of waste in conventional landfills.

To demonstrate the effects of higher moisture content on the reduction of waste shear strength, Bogner et al. (2001) analyzed a typical landfill design with respect to slope stability under various moisture conditions. The factors of safety for the waste and liner slopes were determined using the two-dimensional limit equilibrium stability analysis program STBL. The results showed that the factors of safety reduce proportionally to the reduction in shear strength, and a significant reduction in shear strength due to increased moisture can result in unstable slopes.

Lacking reliable data on shear strength of degraded waste, Isenberg et al. (2001) conducted sensitivity modeling using a typical landfill configuration to better understand how potential reduction in shear strength, coupled with increases in unit weight, will influence waste mass slope stability. They analyzed a landfill configuration that consisted of:

- Composite bottom liner (e.g., smooth geomembrane over compacted clay soil) sloping at 2% slope toward a perimeter leachate collection pipe,
- 3(H):1(V) final side slopes with benches at 40 feet vertical intervals,
- 5% minimum final cover top slope, and
- Maximum waste depth 140 feet- separated into three horizontal waste layers (upper, middle and lower).

Four different bioreactor types were assumed as designated below:

- Type O: Baseline condition; no liquids recirculation practiced (conventional Subtitle D landfill)
- Type I: Limited and/or intermittent liquid recirculation and application practiced
- Type II: Moderate and well-controlled liquid recirculation practiced; below field capacity
- Type III: Heavy liquids recirculation and application; maximum lateral and vertical extent; approaches field capacity or beyond.

The unit weights were assumed to increase with depth and the values applied to the baseline case (Type O) were 45 pcf, 55 pcf, and 65 pcf for Layer 1 (upper), Layer 2 (middle), and Layer 3 (lower), respectively. To model the combined influence of higher moisture content and waste settlement, unit weight values for Type I, II and III bioreactors were represented by increases of 25%, 50% and 75%, respectively, over the baseline layer densities. Initially, the shear strengths were assumed to be the same for all landfill types. The friction angle values were assumed to be 26, 30, and 34 degrees (upper, middle and lower layers, respectively) and the cohesion values were assumed to be 200, 250 and 300 psf (upper, middle and lower layers, respectively). It was assumed that the waste would not be saturated under controlled recirculation, and no pore pressure build-up would occur. Slope stability analyses were performed with circular and block modes of failure using the PCSTABL computer model. Circular failure planes were assumed through the waste mass and block failure was assumed to occur along the bottom smooth geomembrane interface with interface friction angle of 8 to 10 degrees. The block failure mode indicated that the low shear strength of waste combined with the low interface of the friction angle on top of the bottom liner system has significant impact on the stability of the landfill. Sensitivity analyses were conducted to investigate the effects of reduced shear strength and leachate head build-up, and the results of these analyses showed that:

- By comparison to shear strength, unit weight of waste is not as critical a parameter for slope stability.
- Depending on the landfill configuration, block failure modes are likely to be more critical than circular failure modes within the waste mass
- A build-up of liquids on the bottom liner system (leachate heads) of 1, 5 and 10 feet reduced the FS value slightly, although the values for block failure were already less than 1.5.
- It is recommended that variations of unit weight and shear strength with depth should be modeled with multi-layers rather than using a single layer with average values.

Slope stability analyses for bioreactor landfills need to consider site-specific conditions and bioreactor management strategies in order to make reasonable judgments for slope stability. The analysis methods used to date for bioreactor landfills have been limited to limit equilibrium methods. Unfortunately, these methods do not account for the spatial and temporal variation in the properties of waste and operational conditions. Finite element based analysis methods, such as that used by Reddy et al. (1996), take into account of the staged disposal of waste as well as the spatial variation in waste properties and provide a better understanding of shear displacement behavior of slopes. Reddy et al. (1996) analyzed a typical landfill under operational conditions and showed that reduced stiffness of waste can increase shear stress and displacement in the base liner system. The stiffness of the waste will change during leachate recirculation and the effects of such changes should be accounted in the analysis and design of bioreactor landfill slopes.

7. SELECTED HISTORIC AND CURRENT BIOREACTOR DEMONSTRATION PROJECTS

Several historic bioreactor test cell projects have been completed in the U.S., and a number of current landfills are being operated as bioreactors with intensive monitoring to collect adequate data towards the development of rational design guidelines for bioreactor landfills. Some significant projects in the U.S. are discussed in this section. It should be mentioned that there have also been large multi-year field scale tests of accelerated landfill biodegradation in Europe, notably the Brogborough project in the U.K. and the coordinated Swedish test cell projects.

7.1 Mountain View Controlled Landfill Project

The Mountain View Controlled Landfill Project was undertaken in response to a need to optimize energy recovery from landfills, accelerate stabilization, and control gas migration and explosion hazards in the vicinity of landfills (EMCON, 1982-1986; Halvadakis et al. 1988). The test site was constructed within the Mountain View Landfill located approximately 15 miles Northwest of San Jose, California. The field experiment included the design and construction of six landfill cells considered as representative of actual landfills:

Cell A with leachate recirculation
Cell B with addition of sludge and buffer
Cell C with addition of sludge and buffer
Cell D with addition of sludge and water
Cell E with addition of sludge and water
Cell F control cell

Each cell was 30 m by 30 m and 15 m deep, and the waste was deposited in fifteen layers. A 1.5 m-thick compacted clay liner formed the base of the cells to prevent downward movement of liquids and gases from the cells as well as isolate them from groundwater intrusion. Each cell was contained within 3 to 4.5 m wide clay side walls to avoid lateral gas and leachate movement from one cell to the other. The six experimental cells were filled with approximately equal amounts of municipal refuse from San Francisco which was placed in all cells at the same time. The surface was covered with an impermeable plastic consisting of a 30 mil thick nylon-reinforced chlorosulfonated polyethylene membrane (Hypalon) installed as a single piece for maximum integrity of cell top cover. The monitoring spanned over a period of approximately four years. There were some issues with maintaining the integrity of the Hypalon membrane over the entire period of the experiment. Settlement in each cell was monitored using nine concrete block monuments installed in a diagonal pattern over the cell surface. Cell settlement data were normalized by dividing the raw data by cell average depth at the completion of construction. Some cells exhibited an uneven settlement distribution which typically is translated into differential settlement under any structure that might be erected on the cells.

7.2 Lycoming County Landfill Project

Lycoming County Landfill is located 9.5 miles South of Williamsport, Pennsylvania and is a 130-acre landfill facility. The landfill operations began in June 1978, and the site is projected to be active through 2013, based on current landfilling rates. The landfill consists of six cells lined with PVC, with the newer cells having thicker and improved liner systems. Leachate recirculation was investigated over a seven-year period.

The original leachate management included collection, storage, recirculation, and offsite hauling. The liner system rests on compacted glacial till over low permeability bedrock and consists of:

- A l-foot thick sand layer containing the under-drainage collection system,
- A PVC membrane liner (single 20-mil liner for cells1 and2; a 30-mil liner for cell4; and a 30 and 50-mil liner for cell 5),
- A 0.5-foot sand layer containing the leachate collection system piping, and
- A l-foot clay layer.

Various techniques for leachate recirculation were tried to achieve effective distribution of leachate. Originally, it was planned to spray leachate on the operating face and other areas using spray headers. Spraying directly on the working face using a spray nozzle was also tried; this allowed for flexibility in operation but was labor intensive, cumbersome, and caused odor problems. The next technique consisted of excavating small pits in the waste and filling them with leachate using a spray header. Due to the shallow depth of the landfill, the waste had limited absorption capacity, so the technique was abandoned. To increase recirculation volumes, a trenching technique was also tried. Trenches were excavated on top of completed sections of the landfill and filled with leachate. The absorption capacity of the trenches varied and resulted in leachate outbreaks on some side slopes which coincided with periods of peak infiltration and recirculation. The trench method was modified by filling the trench with auto-shredder waste or baled fiberglass wastes. These materials acted as wicks and transferred leachate to a larger area of the refuse, thereby increasing the allowable recirculation volumes and permitting longer use of trenches. A combination of bale-filled areas and an auto waste -filled trench were also used where an. injection well was installed in the bale-filled area using perforated concrete well rings. However, the impact of both the auto shredding waste and fiberglass waste on leachate quality were not evaluated.

The leachate generation quantities were estimated using a water balance method and compared with quantities derived from the lagoon balance for cell 1 for 1982. The water balance method estimate of 2 million gallons compared well with 1.8 million gallons derived from a lagoon balance and 2.2 million gallons of measured inflow into the lagoon. It was estimated that the moisture storage capacity of the solid waste was not fully utilized, and this was verified by excavations that revealed dry cells previously considered to be at field capacity. There was no measurable settlement at the landfill. The excavations and backfilling activities, relatively shallow depth of the landfill (maximum 69 feet), large amount of daily cover (limiting the settlement, stockpiling of cover materials, and absence of settlement plates may have obscured settlement detection. Settlement would extend the life of the landfill because the final site development is limited by permitted elevation and not by volume or quantity.

Based on the performance evaluation of the Lycoming County Landfill, it was concluded that:

(1) Waste degradation and rates of methane generation were improved as a result of leachate recirculation; (2) Quality of leachate stabilized more rapidly than landfills without leachate recirculation; (3) Stabilization rates close to pilot-scale studies (with low recirculation rates and minimum daily cover) can be achieved; (4) Clayey cover soil, high recirculation rates, and certain industrial residuals may inhibit the vertical flow of leachate resulting in incomplete use of moisture storage capacity as well as causing ponding on top of the landfill; (5) The design and operation of leachate recirculation measures were adequate but their effectiveness could be improved; (6) Because of an inability to isolate storm water drainage from the leachate collection system, some areas generated significant quantities liquids for future recirculation; and (7) Aerated leachate storage lagoons provided effective pretreatment of raw leachate.

Leachate should be recirculated in a manner to fully utilize moisture storage capacity rather than periodically saturating the top of the landfill, leading to leachate outbreaks on side slopes.

7.3 Sonoma County Landfill Project

A pilot-scale landfill project was started in 1972 in Sonoma County, California, to study the effect of moisture addition on refuse stabilization and on leachate quantity and quality. Five large-scale field test cells, each 49 ft by 49 ft by 10 ft, were constructed, filled with municipal solid waste compacted to 1000 Ib/yd^3, and subjected to different operating conditions (moisture regimes). Each cell served a specific purpose. The cells were monitored for 900 days to evaluate leachate quality, gas composition, and settlement.

Cell A was the control cell, Cell B was initially brought to field capacity, Cell C received water at a rate of 1000 gal/day, Cell D was subjected to leachate recirculation, and Cell E was initially inoculated with septic tank pumping. After construction, Cells A, B, and E received moisture only from infiltrating rainwater. The rate of leachate recirculation in Cell D varied from 500 to 5000 gal/day.

Leachate recirculation significantly increased the rate of establishment of an anaerobic microbial population (as suggested by gas quality) and increased the rate of biological stabilization of the organic fraction of the refuse (as evidenced by reductions in BOD, COD, and TVA in leachate). Settlement was enhanced by liquid flow and the accelerated microbial activity associated with leachate recirculation (20 percent reduction in height for leachate recirculating cell vs. 7.6 percent for remaining cells). However, although the continual flow-through of water increased the rate of stabilization, there were also large volumes of leachate requiring ex-situ treatment.

The addition of septic tank pumping wastes accelerated acid fermentation and was not beneficial in the absence of pH control and leachate recirculation. In the presence of leachate recirculation, the landfill acted as an anaerobic digester in treating leachate and therefore was found to be the most feasible and beneficial management strategy utilized in the study.

7.4 Yolo County Landfill Project

The Yolo County Landfill Bioreactor Project consists of two demonstration cells, roughly 100 ft^2 and 40 ft deep, at the Yolo County Central Landfill, Davis, California. The first cell, the control cell, is setup in the same manner as a conventional MSW landfill, with a bottom liner and surface liner in place to prevent liquid infiltration or leakage. The second cell, the enhanced cell, is setup as a bioreactor landfill. Both cells were built using a Subtitle D composite liner system, consisting of compacted soil and a HDPE geomembrane liner. Because of the liquid addition, the enhanced cell was required to have a second liner system placed below the primary liner. A liquid detection and collection system was placed between these liners to detect any possible leakage from the primary liner. Each cell was filled with about 9000 tons of MSW from April through October, 1995. The waste was placed in five-foot lifts, with one foot of shredded greenwaste as daily cover. Large bulky items such as couches and mattresses were excluded from the cells. Several monitoring instruments were installed into both cells during their construction including pressure, temperature and moisture sensors. Liquid dispersion in the enhanced cell is accomplished with 14 infiltration trenches dug into the surface of the cell. The specific objectives of the project are:

- Demonstrate substantially accelerated landfill gas generation and biological stabilization while maximizing gas capture
- Estimate the landfill life extension that can be realized through rapid waste decomposition
- Demonstrate that the recirculation of leachate is an effective leachate treatment strategy
- Provide regulatory agencies with information to develop guidelines for the application of this technology
- Better understand the movement of moisture through landfills
- Disseminate information resulting from the continued monitoring of the project
- Monitor the biological conditions within the landfill cells
- Assess the performance of shredded tires as a medium, for the transfer of landfill gas to collection pipes

Both cells were highly instrumented to monitor conditions within the waste. These systems collect, measure and record data independently from each other. Moisture and temperature sensors were placed throughout the waste in each cell. Data from these sensors is automatically recorded and sent to the Yolo County office via a remote telemetry unit. The landfill gas generated in the cells is collected using vertical collection wells. Some of these wells employ a conventional medium of gravel, and others use shredded tires. Each cell also has a horizontal gas collection system, consisting of a layer of shredded tires over the cell's surface. Landfill gas not captured by the vertical wells is collected in this horizontal system thereby preventing surface emissions. The use of shredded tires is demonstrating their possible effectiveness as a gas extraction medium. The leachate monitoring system uses manholes that allow personnel to monitor leachate quantity and quality.

The monitoring data collected as of 1999 revealed the following:

- Air Quality- Based on air quality data, oxygen deficient conditions were found in landfills which results in anaerobic microbial activity. An important result of the microbial biodegradation activity is the production of landfill gas, which consists primarily of methane and carbon dioxide, both greenhouse gases. Air quality regulations exist to control landfill gas emissions from landfills that emit at a rate above a specific threshold. These regulations require the gas to be collected and destroyed. Although some surface cover systems have only a 60-90% efficiency in preventing gas loss to the atmosphere, new impermeable surface liners, similar to the one used in this project are becoming widely used and provide nearly 100% gas capture efficiency.
- Renewable Energy- As discussed previously, methane and carbon dioxide are two of the main landfill gases produced and both are greenhouse gases. Methane is 21 time more potent than carbon dioxide in its effects on the atmosphere. In a MSW landfill, the gas is commonly collected and destroyed by flaring. Flaring destroys the methane by burning. But methane is also a potential source of energy. Because the methane gas generation in a MSW landfill is far less than optimal, and even less predictable, it is not usually feasible to operate gas-to-energy conversion facilities at these landfills. Up to 50% of the gas generated from a traditional MSW landfill, occurs more than 30 years after its closure, which is also beyond the mandated gas collection time period.

A bioreactor landfill greatly improves the gas generation rate, decreasing the time frame for landfill gas generation from several decades to between 5 and 10 years. For this project, the enhanced cell has produced over 75% more landfill gas than the control cell since June 1996. Of the landfill gas, the percent methane in the enhanced cell has averaged 54%. The control cell was not significantly different in its concentration, averaging 52%, until March 1998 when it dropped to 30%. Monitoring continues to determine if this drop is a temporary condition. Because the quantity of landfill gas generation has been much higher in the enhanced cell, the total amount of methane generated has also been significantly larger. As of September 1998, the cumulative methane volume was 1.014 scf/ dry lb for the enhanced cell and 0.556 scf/dry lb for the control cell. Figure 25.5 shows the cumulative methane gas volumes for both cells.

Because the rate of methane generation is significantly higher, the feasibility of harnessing this renewable energy is greatly improved. This means that the energy market could increasingly depend on this type of renewable energy for the provision of electric generation rather than nonrenewable fossil fuels.

- Leachate- There are five distinctive phases of waste decomposition: initial, transition, acid, methane fermentation and mature phase. These phases occur sequentially and may be recognized in the leachate characteristics and composition. Leachate carries a high pollutant load during the initial phase of waste decomposition. These levels are reduced significantly once the methane fermentation phase of waste decomposition is underway. Most of the waste is stabilized and landfill gas generation is nearly complete during the maturation phase.

- In a bioreactor landfill, the methane fermentation phase is reached much faster and is completed in a shorter time frame, as discussed previously, leading to appreciably reduced pollutant levels early in the life of the landfill. By reducing the pollutant load early, the risk of groundwater contamination from seepage that could occur due to the age of the liner, defects, or other mishaps, is greatly reduced.
- Leachate treatment costs are directly tied to the pollutant load. Therefore, significant savings can be realized for the disposal of leachate that has been even partially decontaminated by microbial actions. Monitoring continues on this project in an effort to quantify the potential treatment effect.
- Landfill Life Extension- Waste decomposition results in landfill settlement, which creates a volume of space that could be reused for additional waste placement. Unfortunately, the majority of landfill settlement from conventional landfill practices occur after the 30-year post closure period, at which time it cannot be reduced. A bioreactor landfill accelerates the decomposition process to allow for additional waste placement during the life of the landfill. This reuse of space could potentially extend the life of the landfill by 20%. Settlement surveys for this project shown in Figure 25.6 exhibit that the settlement rate of the enhanced cell is nearly four times faster than the control cell. If the settlement rate continues, in less than four years the enhanced cell will have settled approximately 20%.

Subsequent to the demonstration project, Yolo County has proposed a full-scale 20-acre landfill module with both anaerobic and aerobic bioreactor areas (Yazdani et al., 2000). In the first phase of this project, a 12-acre module has been constructed. One 9.5-acre cell will be operated anaerobically and the other 2.5-acre cell aerobically. The liner system consists, from top to bottom, of an operations/drainage layer capable of maintaining less than one foot of head over the liner, a 60-mil HDPE geomembrane liner, and a 2 feet of compacted clay ($k \le 10^{-7}$ cm/sec). The liner and leachate collection system consists, from top to bottom, of a 2 foot thick chipped tires operations/drainage layer ($k > 1$ cm/sec) over 6 inches of pea gravel, a blanket geocomposite drainage layer, a 60-mil HDPE liner, 2 feet of compacted clay ($k \le 6 \times 10^{-9}$ cm/sec), 3 feet of compacted earth fill ($k \le 1 \times 10^{-8}$ cm/sec), and a 40-mil HDPE vapor barrier layer. The operation and monitoring data will help compare the performance of bioreactors operated under anaerobic and aerobic conditions.

8. RESEARCH NEEDS AND CONCLUSION

Currently, the management of MSW relies heavily on landfills which are designed and operated to minimize moisture infiltration. However, bioreactor landfill technology is being explored as a new approach to achieve accelerated stabilization of MSW. This technology involves injecting leachate or other supplemental liquids into the waste in order to accelerate or enhance the anaerobic biodegradation of waste. Injection of air for accelerated aerobic biodegradation or composite anaerobic/aerobic methods are also being investigated. Several research studies involving laboratory experiments, mathematical modeling and field monitoring are being conducted to understand the performance of bioreactor landfills and to develop more standardized performance specifications.

The most critical aspect of bioreactor landfills is the dynamic water balance. Increased moisture levels increase waste biodegradation and gas generation rates, and also influence the engineering properties of waste. To date, the dynamic water balance in bioreactor landfills has not been studied thoroughly. The temporal and spatial variation of waste geotechnical properties as biodegradation occurs is also unknown. Because of the transient and spatial variation in waste properties, the applicability of simple analysis methods, such as limit equilibrium slope stability analysis commonly used for conventional landfills, is questionable. Moisture distribution, settlement, and slope stability are all interrelated and such coupled responses should be accounted in the rational analysis and design of bioreactor landfills. Several on-going demonstration projects will be expected to yield valuable monitoring data that will help identify system parameters that influence the performance of the bioreactor landfills. In addition, the monitoring data will be useful to validate mathematical models dealing with moisture distribution, waste settlement and slope stability. Overall, the widespread acceptance of bioreactor landfill technology requires understanding of the waste degradation processes as well as development or use of workable analysis methods for settlement and slope stability.

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