Solid Waste Degradation, Compaction and Water Holding Capacity

By

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ABSTRACT

Bioreactor landfills offer a sustainable way to achieve increased waste degradation along with benefits such as enhanced landfill gas (LFG) recovery, reduction in leachate pollution potential and rapid increase in landfill volumetric capacity. It also offers significant reduction in post closure management activities as leachate treatment, LFG impact on the environment and improves the potential for land reuse. The regulatory 30 year post-closure period is believed to account for attenuation of organics, metals and trace pollutants of adverse environmental consequences. Methodologies to improve the degradation rate and process are refuse shredding, nutrient addition, pH buffering, and temperature control along with moisture enhancement. Municipal Solid Waste (MSW) settlement and field capacity are of significant beneficial interest to achieve maximum utility of landfill volume and compute water requirements for rapid degradation using bioreactor concepts.

Physical and biochemical Municipal Solid Waste (MSW) characteristics were investigated with specific emphasis on the Bio-Chemical methane potential (BMP) test. The impact of waste characteristics on its compressibility and moisture retention capacity was evaluated on a laboratory scale, and a test suited for this evaluation was determined. Traditional in-situ waste compression models from literature were used to compare with the obtained laboratory data. Moisture retained in the waste after 5 days with an imposed static load of 40 lbs was in the range of 24-35 % and 33-54 % expressed as wet and dry weight of waste respectively. The results correlate well with refuse physiochemical characteristics. The hyperbolic model is found to best fit the refuse settlement for the test and provides an estimate of primary consolidation in MSW.

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CHAPTER I: INTRODUCTION

Land filling as a primary means of end disposal of municipal solid waste [MSW] is commonly used in the United States (CRC Press Inc., 1990). In 2000, approximately 232 million tons of municipal solid waste (MSW) was generated in the U.S. (USEPA, 2002), of which 14.884 million tons was from Virginia (DEQ VA, 2002). Waste trends, as generation rates and management practices in the United States, are displayed in Figure 1-1 and 1-2 respectively below.

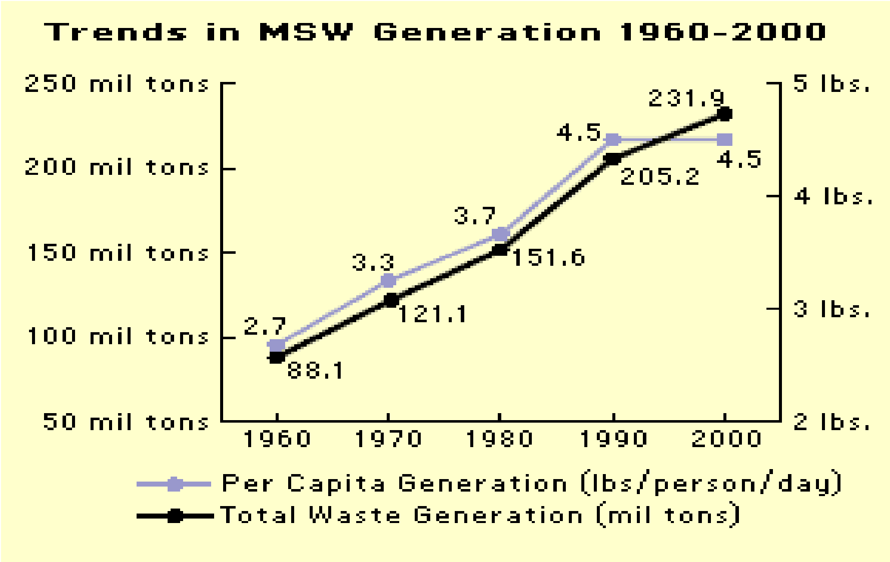
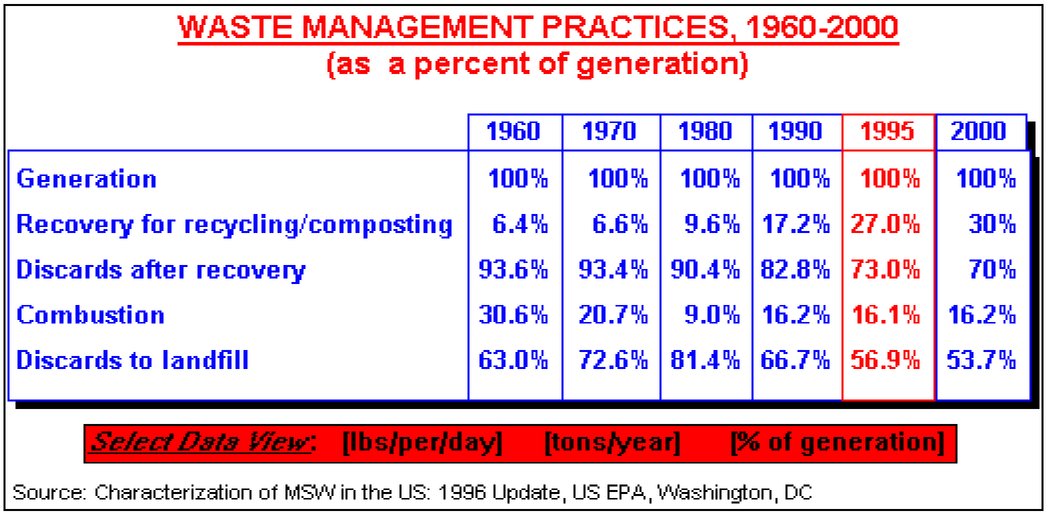


FIGURE 1-1 – Waste generation rates (USEPA, 2002)



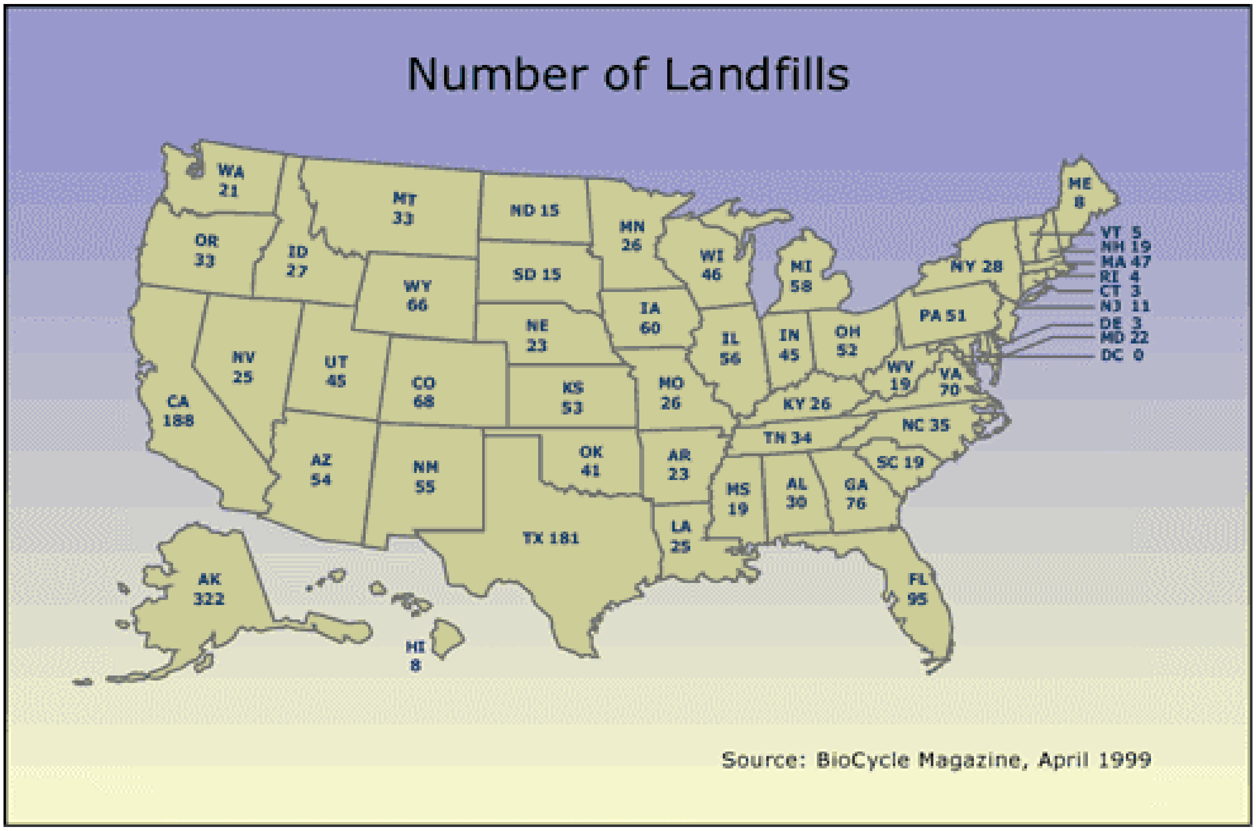
WASTE MANAGEMENT PRACTICES, 1960-2000
(as a percent of generation)

	1960	1970	1980	1990	1995	2000
Generation	100%	100%	100%	100%	100%	100%
Recovery for recycling/composting	6.4%	6.6%	9.6%	17.2%	27.0%	30%
Discards after recovery	93.6%	93.4%	90.4%	82.8%	73.0%	70%
Combustion	30.6%	20.7%	9.0%	16.2%	16.1%	16.2%
Discards to landfill	63.0%	72.6%	81.4%	66.7%	56.9%	53.7%

Source: Characterization of MSW in the US: 1996 Update, US EPA, Washington, DC

FIGURE 1-2 – Waste management practices (USEPA)

The disposal in landfills has been reduced from 66.7 % to about 53.7 % in the decade from 1990 to 2000 and on a gross basis it has declined from 131.6 to 119.1 million tons/yr. The number of MSW landfills in the United States for year 1999 is displayed below in Figure 1-3.



Source: BioCycle Magazine, April 1999

FIGURE 1-3 Existing number of MSW landfills in United States 1999 (USEPA, 2002)

In 1991, the U.S. EPA promulgated regulations governing the disposal of MSW in landfills. The regulations, Subtitle D of Resource Conservation and Recovery Act define a number of aspects of landfill design and operations, site closure and post-closure monitoring. Typical regulations for most agencies specify that a monitoring period of 30 years after a site is closed is mandatory unless extended by the governing agency on a site-specific basis. Post-closure involves monitoring, collection and treatment of leachate, and prevention of landfill gas [LFG] migration out of the site.

Water leaching out from the bottom of a landfill is severely contaminated with organics, metals, and solids and is called as leachate. It has been observed that increasing the moisture content of a waste fill, up to a site specific maximum optimum enhances hydrolysis of waste organics and also accelerates the rate of breakdown of MSW. In older landfills this was achieved with leachate recirculation, i.e. application of the derived leachate back on the top of landfill with its subsequent movement down the waste. Landfills that add external moisture in addition to the recirculated leachate, are able to achieve the optimum moisture content in the waste, which enables them to achieve rapid and more efficient hydrolysis along with the associated degradation, and are termed as bioreactor landfills. A higher moisture content promotes faster microbial decay and hence leachate recirculating and bioreactor landfills have grown to be popular. Potential benefits of biologically active landfills include more efficient energy generation from landfill gas and a more effective usage of landfill volume. Emerging trends for developed countries, due to higher per capita generation of refuse, are increasing paper and plastic content and greater carbon to nitrogen, i.e. C: N ratio, which limits microbial nitrogen fixation at landfill [LF] sites. Waste analysis to evaluate stability of refuse includes determination of density, moisture, volatile solids, settlement, biochemical methane potential, cellulose, lignin, pH and inorganic nutrients as metals. Leachate analyses include COD, forms of nitrogen, inorganic nutrients, pH, and phosphorus. Gas monitoring includes landfill gas and non-methane organics (NMOCs), which comprise of some volatile organic compounds (VOC's) along with surface emissions for methane.

The objective of this study is to develop a laboratory scale methodology to evaluate waste moisture retention potential i.e. field capacity and its associated compression characteristics. Waste from various sources at different decomposition stages was used and the waste compressive strain was analyzed to determine if traditional waste compression models would fit the observed behavior. The research objective to evaluate laboratory scale field capacity coupled with associated best-fit settlement model would enhance an understanding of field parameters in a short duration and thus help achieve realistic landfill volumetric usage estimation.

CHAPTER II LITERATURE REVIEW

The reduction in number of Municipal Solid Waste (MSW) landfill facilities along with increase in their size has made it imperative to achieve maximum utility of landfill volume. Water requirement computations are necessary to apply bioreactor concepts to MSW landfills and achieve rapid waste degradation and volumetric reduction. The costs incurred for this water requirement and associated benefit by increasing the available storage space is an attractive incentive for applying bioreactor concepts. The settlement of landfills is caused by waste decomposition and compression and has been modeled using Terzaghi's soil consolidation theory, which includes consolidation rate parameters and secondary compression terms. The objective of this study was to evaluate feasibility of the adopted biochemical tests for MSW. The laboratory scale compression and dewatering characteristics of MSW were studied. These can be correlated with the waste strength to yield preliminary estimates of refuse compressibility and field capacity.

Landfill Ecology:

Landfills are by nature heterogeneous systems due to variable refuse characteristics. Furthermore placement methodology, hydrological conditions and compaction along with seasonal variations make the system more complex and difficult to predict. Stratification of refuse can occur in lifts and localized volumes. Key parameters controlling degradation are refuse composition, moisture content, temperature, redox conditions viz. Eh and pH, hydraulic gradients, xentiobiotics, metals and oxic-anoxic interfaces.

Christensen and Kjeldsen (1989) observed rapid depletion of oxygen in landfills and report complete depletion in a time frame of a week after which nitrate is consumed rapidly. With depletion of oxygen the anaerobic environment enables dominance of facultative and then obligates anaerobes. Numerous interacting microbial species use a variety of substrates and intermediates as nitrate, sulphate, and carbon dioxide theoretically in sequence of available energy from species selective electron donors. Hence bacterial populations can be a good indicator of the degree of degradation in a particular lift. Redox conditions dictate availability of electron donors and often the species deriving maximum energy gains a kinetic advantage over the others. However, mixed cultures coexist due to complex transport phenomenon in a landfill matrix. Commonly reported species are Clostridium butyricum, C. pectinovorum and C. fulsincum for pectin dissimilation, C. thermocellum and C. cellobiopavum, and C. cellulosaedisslovens for cellulose degradation (CRC Press Inc., 1990).

Study of anaerobic bacterial counts indicates that total anaerobes ranged from 103 cells per dry gram in cover soil to 109 in grass, food waste and fresh refuse. Hemicellulolytics ranged from 160 cells per dry gram in cover soil to 109 in grass. The highest cellulolytic population was measured on branches 316 cells per dry gram, while the maximum acetogenic population was measured on leaves 104. The highest methanogen populations were measured on leaves 103 and one of two fresh refuse samples as 105. (Qian and Barlaz, 1996)

A generalized reaction for anaerobic digestion can be written as:-

$$C_xH_yO_z + (4x-y-2z)/4H_2O \longrightarrow (4x-y+2z)/8CO_2 + (4x+y-2z)/8CH_4$$

The average energy release upon oxidation of organic compounds is 3.3 kcal/gm COD whereas that from anaerobic digestion is about 0.3 kcal/gm COD with the remaining 3.0 kcal/gm COD being left out in the methane produced (Haandel et al., 1994). The waste characteristics associated with the decomposition phases in a landfill are as below: (Tchobanoglous, et al., 1993)

Phase I: (Aerobic) After initial placement of waste carbon dioxide and heat produced, temperature rises to approximately 30 degrees Fahrenheit, carbon dioxide generated equals oxygen used (timeframe months/up to 1 year).

Phase II-III: (Transition-Acid) After onset of anaerobic conditions the carbon dioxide dissolves and results in acidic leachate, numerous organic acids are produced. (1-2 years). The buffering capacity and the available moisture in the waste mass influences the redox conditions and the metals are solubilized by low pH. Hydrogen consumption by anaerobes begins to start and the equilibrium depends on redox conditions, nutrients, temperature and substrate competition between various species. (1 year to 3 years) .In various studies on leachate recirculating and bioreactor landfills (Barlaz et. al., Bookter and Ham 1982, Wall and Zeiss 1995, Reinhart and Al-Yousfi 1995, Reinhart 1996, Edil et al. 1990, Pohland and Kim 1999, Leckie et al. 1979, Mehta et al. 2002, Warith 2002, Onay 1998, Pacey et. al

1996, Pohland & Al-Yousfi 1994) it is found that this acid formation phase is enhanced and attained rapidly without a reduction in pH exceeding the natural buffering capacity of MSW. The hydrolysis of waste by such enhancements is observed in a matter of month's up to one year along with the benefits in reduction in immediate leachate strength and post closure treatment.

Phase IV: (methane Fermentation) The methanogens consume hydrogen at nearly constant rate and produce methane and carbon dioxide. (Up to 30 years). methane potential depends on available substrate. In bioreactor landfills rapid reduction in waste strength is achieved by elevated rate of methane formation and early onset of methanogenesis. Monitoring time frame can be reduced from 30 years to about 3-5 years.

Phase V: (Maturation) After all the readily bio-degradable waste converted to CH4 and CO2 LFG production drops off and is negligible. Typical phases in anaerobic degradation for a MSW landfill are depicted in Figure 2-1 below

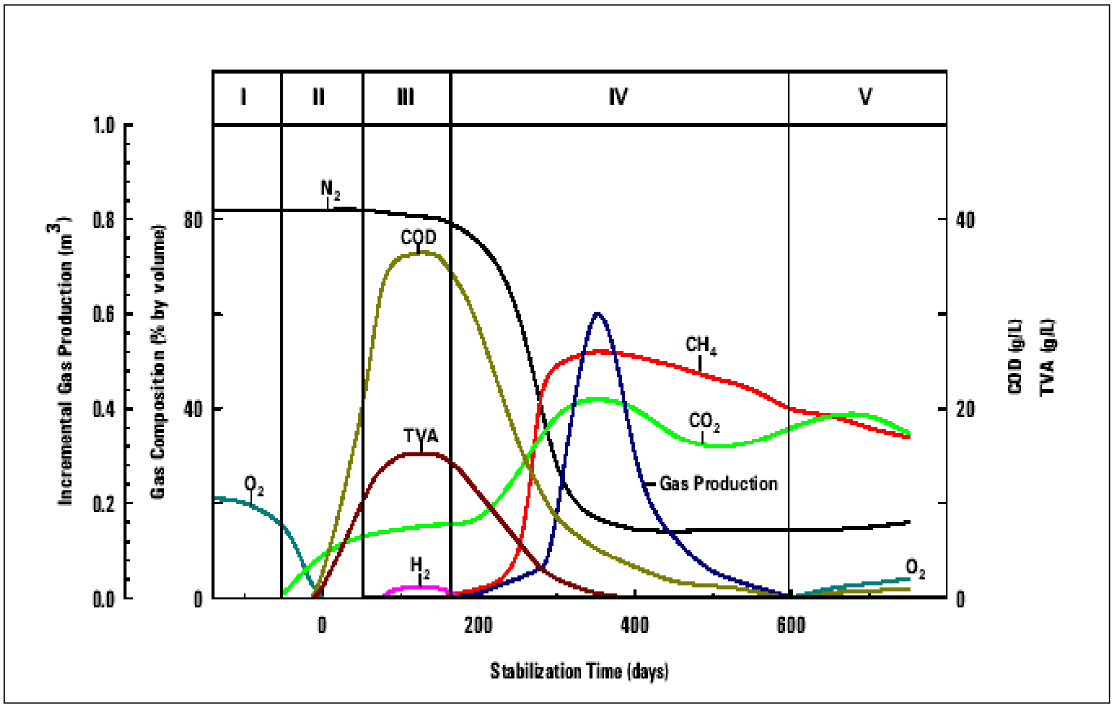


FIGURE 2-1 Phases of degradation in a typical landfill (WMI 2000)

Bioreactor landfill considerations:

Development of a Bioreactor Landfill with methane recovery is an attractive incentive for rapid and managed waste degradation since the landfill gas has a heating value of about 500 Btu/scf. In leachate recirculating landfills both acid formation and methane fermentation phases are reduced in duration and stabilization is sped up (Pohland and Kim, 1999). The impact of recirculation also results in either rapid formation of VFA's, which tend to be retained more than those in conventional fills or more gas recovery with more stable leachate subsequently. The optimal recirculation of leachate implies that the landfill be divided into cells such that leachate from fresh cells having high organic load can be recirculated into old stabilized cells, where methanogenic conditions prevail and the LFG extracted from old cells. Leachate management from process control consideration implies storage of leachate during the acid formation phase to avoid inhibition of fermentation, facilitate pH control and its subsequent release in the waste during methanogenesis. Studies indicate that about 60% of the total solids are cellulose and hemicellulose and they generate about 90% of methane in a landfill (Barlaz et. al.).

In conventional landfills, metal removal is by washout and chemical precipitation. For leachate recirculating landfills, the primary metal removal mechanism appears as precipitation in form of sulfides and hydroxides. (Reinhart and Al-Yousfi, 1995). In general, metal solubility is higher at low pH during acid formation phase restricted by ligands both organic and inorganic. The solubility drops during fermentative phase due to rise in pH and formation of insoluble precipitates.

In older stabilized fills moderate to high molecular weight humic-like substances are formed from waste organic which tend to form strong complexes with heavy metals. Potentially remobilization of precipitated metals can occur from such complexation once the organic content has been stabilized, and oxic conditions get re-established.

Reinhart (1996) suggests a storage volume in excess of 700m3/ha to manage leachate. Figure 2-2 below depicts the effect of leachate recirculation on leachate generation. It is evident from the Figure that leachate generated exceeds leachate recirculated thus implying leachate holding/treatment facility during some stage before closure of landfill.

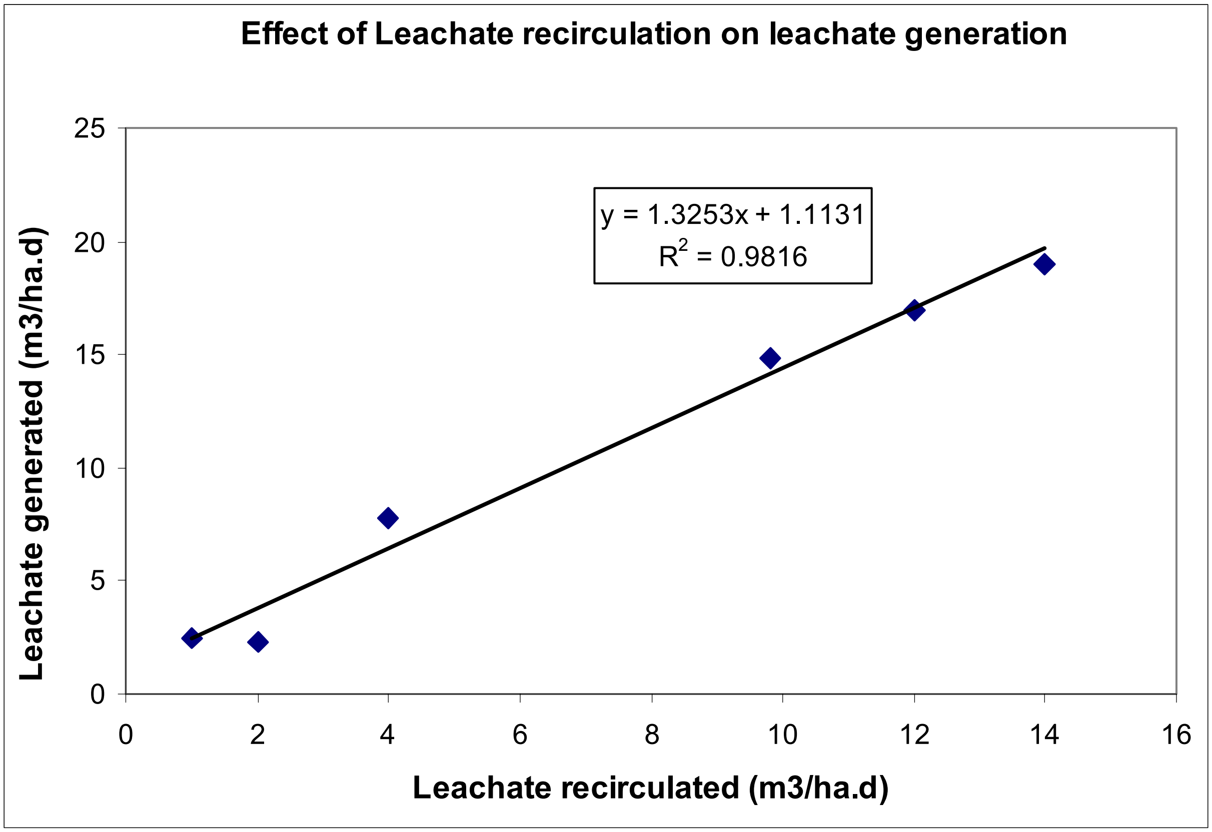


FIGURE 2-2 (reproduced from Reinhart 1996)

Doedens & Cord-Landwehr (1989) recommended storage volumes of 1500–2000m3 ha-1 in their investigations of German full-scale leachate recirculating landfills. The New York Department of Environmental Conservation requires storage for 3 months leachate generation.

Potential benefits of Bioreactor landfills are:

The gas yield is increased whereas greenhouse gas emissions are reduction due to more efficient degradation. Almost all of the rapid and moderately decomposable organic constituents are degraded within 5 to 10 years of closure. Bioreactor landfills also offer low cost partial treatment of leachate within the active life of a fill and improved leachate quality & stabilization within 3 to 10 years after closure along with subsequent reduced leachate disposal costs. The enhanced biodegradation enables rapid settlement, rapid volumetric reduction resulting in more disposals within the landfill volume, early landfill closure and subsequent land use. Other benefits include reduced operation and maintenance activities and reduced risk of gas migration. At landfills where leachate recirculation is practiced, leachate ammonia concentrations may accumulate to much higher levels than during conventional single pass leaching, thereby creating a leachate discharge problem (Onay, 1998).

Disposal of leachates high in nitrogenous constituents has damaging impacts due to a reduction in chlorine disinfection efficiency, an increase in the dissolved oxygen depletion in receiving waters, adverse public health effects, and a reduction in suitability for reuse (De Renzo, 1978).

Landfill leachate from old sites are usually highly contaminated with ammonia resulting from the hydrolysis and fermentation of nitrogen containing fractions of biodegradable refuse (Knox, 1985) and (Carley and Mavinic, 1991) and may contain 400 – 800 mg/l of ammonia nitrogen (Welander et. al, 1998). Another aspect is that the low refuse hydraulic conductivity at the bottom of the landfill interferes with movement of the leachate down to the leachate collection system (LCS), and potentially a leachate mound can form in the refuse above an operating LCS. A leachate mound has the potential to cause leachate side seeps and could interfere with the landfill gas collection system. However, a leachate mound within the refuse is not necessarily indicative of the head on the liner. Hence the strain due to settlement results in reduced refuse permeability and along with chemical precipitation and biological clogging significant reductions in refuse permeability may occur and in turn contribute to the formation of a leachate mound within the refuse. The increased water content of the refuse will lead to an increased rate of biodegradation and gas production. Additionally, the higher densities result in higher gas production per unit volume. Due to reduced refuse permeability, the gas hydraulic conductivity is reduced since void space is occupied by leachate, and gas collection apertures are reduced in magnitude due to submergence. This leads to a reduction in the radius of influence for gas collection wells and trenches and thus a decrease in the efficiency of the landfill gas recovery system (Bleiker, 1995). Other important factors to consider are the pathways to relieve the excess pore pressure. Leachate production is observed to follow precipitation and leachate recirculation events due to such preferential flow pathways in a refuse mould. Potential pathways are flow into gas collection devices, flow to the leachate collection system and migration through the liner due to increased head on the liner.

Economics of LFG utilization:

The LFG potential as found in a study (World Bank, 1999) indicated that for industrialized countries the in-situ LFG potential is of 370 Nm^3 of MSW. Due to heterogeneous and partial biodegradation a realistic value of 200 Nm^3 of LFG can be generated from 1 ton of landfilled MSW.

Factors influencing utilization of the generated LFG are:

- Atmospheric losses via surface or lateral gas migration.
- Partial anaerobic decomposition of the near-surface layer.
- Washout of organic carbon via leachate.
- Oxygen intrusion through leachate recirculating and gas recovery mechanisms reducing anaerobic zones in a fill.

The study (World Bank, 1999) indicates that most landfills recover a maximum of about 60% of the available LFG. Thus the LFG recovered is about 100 Nm3/tonne of waste in place over a period of about 15-20 years. Adopting the bioreactor landfill techniques the total LFG yield can be made within 5-10 years, and the average annual flow of LFG up to four times that of conventional landfill can be achieved. methane in concentrations of 5-12%, in atmospheric air is an explosive gas. Projects using current technologies for LFG utilization that are operational or planned for use in the U.S. are summarized below in table 2-1.

TABLE 2-1 LFG utilization facilities in United States (E.H. Pechan & Associates, Inc.)

Technology	Operational Facilities	Construction/ Advanced planning	Capacity range of installed Facilities (kW) or equivalent
Reciprocating engines	89	>30	80-12,300
Gas turbines	22	4	740-16,500
Combined cycle	-	2	113,600-20,500
Boiler/Steam turbines	5	1	7,000-50,000
Medium Btu Fuel	-	27	11,300-17,000
High Btu/Vehicle Fuel	5	5	800-19,000

The economics done in the study (World bank 1999) indicate a reduction from US$15-US $20/ton to US $8-US $13/ton of MSW i.e. reducing the total landfill costs by 35-47 %. Total land filling costs without LFG recovery range typically from US $21-US

$37 per ton of waste whereas with LFG recovery the total landfill costs will be reduced between US $18-US $35/tonne, i.e. reducing the total landfill costs by 17-27%. A cost saving of about $U.S.2500 acre (approximately $ U.S.6250 ha-1 year–1) is expected at leachate recirculating landfills due to reduced long-term care and liability and the potential for landfill mining and space recovery (Pohland and Yousfi, 1994).

Typical leachate composition is displayed in Table 2-2 below.

Table 2-2 Typical Leachate Composition (Pohland and Kim, 1999)

Parameter	Unit	Acidic Phase (6 months to 2 years)	Methanogenic phase (2 to 100+ years)
pH		5-6.5	7.5-9
COD	mg/l	20,000-30,000	1,500-2,000
BOD	mg/l	10,000-25,000	500-1,000
Iron	mg/l	5-20	<5
Zinc	mg/l	1-5	0.03-1
Cadmium	mg/l	<30	6
Ammonia	mg/l	900-1,500	900-1,500
Chloride	mg/l	1,200-3,000	1,000-3,000

Typical oxidation half reactions are displayed in Table 2-3 below.

Table 2-3 (Pohland and Kim, 1999) (At pH 7, 1 atm. and 1 kg/mol activity, 25 ^{o}C)

Oxidation reactions	ΔG^{o} (KJ)

Caproate → Propionate	$CH_3(CH_2)_4COO^- + 2\,H_2O \rightarrow 2CH_3CH_2COO^- + H^+ + 2.5H_2$	+ 48.3
Caproate → Acetate	$CH_3(CH_2)_4COO^- + 4\,H_2O \rightarrow 3CH_3COO^- + H^+ + 4H_2 + 2H$	+96.7
Caproate → Butyrate +Acetate	$CH_3(CH_2)_4COO^- + 2\,H_2O \rightarrow CH_3(CH_2)_2COO^- + CH_3COO^- + H^+ + 2.5H_2$	+48.4
Propionate → Acetate	$CH_3CH_2COO^- + 3\,H_2O \rightarrow CH_3COO^- + HCO_3 + H^+ + 3H_2$	+76.1
Butyrate → Acetate	$CH_3CH_2\,CH_2COO^- + 2\,H_2O \rightarrow 2CH_3COO^- + H^+ + 2H_2$	+48.1
Ethanol → Acetate	$CH_3CH_2OH^- + H_2O \rightarrow CH_3COO^- + H^+ + 2H_2$	+9.6
Lactate→ Acetate	$CH_3CHOHCOO^- + 2\,H_2O \rightarrow CH_3COO^- + HCO_3 + H^+ + 2H_2$	-4.2
Acetate → methane	$CH_3COO^- + H_2O \rightarrow HCO_3 + CH_4$	-31.0

Typical reduction half reactions are displayed in Table 2-4 below.

Table 2-4 (Pohland and Kim, 1999) (At pH 7, 1 atm. and 1 kg/mol activity, 25 °C)

Reduction reactions		ΔG^o (KJ)
HCO_3 → Acetate	$2\,HCO_3 + H^+ + 4H_2 \rightarrow CH_3COO^- + 4\,H_2O$	-104.6
HCO_3 → methane	$HCO_3 + H^+ + 4H_2 \rightarrow CH_4 + 3\,H_2O$	-135.6
Sulfate → Sulfide	$SO_4 + H^+ + 4H_2 \rightarrow HS^- + 4\,H_2O$	-151.9
	$CH_3COO^- + SO_4 + H^+ \rightarrow 2\,HCO_3 + H_2S$	-59.9
Nitrate →Ammonia	$NO_3 + 2H^+ + 4H_2 \rightarrow NH_4^+ + 3\,H_2O$	-599.6
	$CH_3COO^- + NO_3 + H^+ + H_2O \rightarrow 2\,HCO_3 + NH_4^+$	-511.4
Nitrate →N_2 gas	$2NO_3 + 2H^+ + 5H_2 \rightarrow N_2 + 6\,H_2O$	-1120.5

Degradation aspects:

Traditionally anaerobic degradation is a two-stage process viz-anaerobic respiration and fermentation. Anaerobic breakdown of MSW results in formation of volatile fatty acids [VFA's], ethanol, lactate, succinate and gases as hydrogen, carbon dioxide. Fermentation is favored by a low hydrogen ion (H^+) concentration. Propionic bacteria i.e. acid degrading bacteria constitute a vital species for H^+ consumption. Acetogens can be classified into 2 groups; hydrogen producers, which consume alcohols and organic acids and form acetic acid and hydrogen gas while the other group hydrogen consumers utilize carbohydrates, hydrogen, carbon dioxide and produce acetic acid. Hydrogen producers grow only at a low partial pressure of $H_2 < 10^{-4}$ atmospheres (CRC Press Inc., 1990). At greater concentration of H_2 VFA's tend to accumulate and inhibit methanogenesis. In solid state fermentation lack of nitrate and sulfate results in the dominance of carbon dioxide utilizing methanogens which direct the electron flow to a more reduced product i.e. methane to yield maximum energy. Essential nutrients include iron, cobalt, nickel and inorganic sulfur many of these being vital in enzymatic structures of the bacteria. In the initial acid formation phase metals are mobilized and complex as VFA's and subsequently precipitate as hydroxides, sulfides and carbonates when the pH rises.

Since cellulose is the primary constituent that undergoes decay in a landfill, pathways for its metabolism are vital to be understood under field conditions. Cellulose is a linear homopolymer of anhydrous units linked by beta-D-1,4 glucosidic bonds (Tsao, 1984) with degree of polymerization from 1000 to 10,000 and is resistant to hydrolysis. The intra and inter molecular Hydrogen bonds are primary responsible for offering resistance to hydrolytic cleavage i.e. require higher activation energy to break H+ bonds. In landfills it is uptaken after enzymatic hydrolysis. It is also believed to be hydrolyzed in part by the acidic phase of anaerobic digestion. Cellulose and hemi celluloses have been reported to be anaerobically biodegradable in pure forms (Magee and Kosaric, 1985). Hemicellulose is a mixed branched polymer of pentoses and hexoses (Grethlein, 1984). Chief pentoses are xylose and arbinose and hexoses are mannose, galactose and glucose. Lignin is a branched polymer of cyclic carbon compounds of which only a small fraction is acid soluble the amount increasing with temperature. Due to the structural encapsulation of cellulose by lignin the diffusion of bacterial enzymes is slow (Bisaria and Ghose, 1981) and also some phenolic groups in lignin may be inhibitory to bacterial enzymes, which limit the rate of cellulose decay. Cellulose in well-decomposed landfills was found from 8-30 % by Bookter and Ham (1982). A high degree of synergism and interspecies interactions is involved in anaerobic bio degradation, which is brought out in steps by acetogenic and hydrolytic bacterial and the methanogens.

Moisture content of MSW: The amount of moisture by weight or volumetric basis, expressed as percentage of MSW, (wet or dry) is the moisture content of refuse. Moisture added to refuse beyond its holding capacity constitutes the amount of leachate produced from the waste. The knowledge of moisture holding potential of refuse is important to estimate the amount of moisture to be added in a landfill before any leachate is produced and drained off through the bottom. This amount of moisture expressed on a weight or volumetric basis as percentage of total refuse mass or volume respectively is denoted as the field capacity of MSW. Typically reported field capacity for MSW landfills range from 14 to 44 % and are depicted below in Table 2-5.

TABLE 2-5 Typical Field capacity of MSW Landfills.

Reported Field capacity (v/v)	Reference
29	Remson et. al (1968)
29-42	Holmes (1980)
30-40	Straub and Lynch (1982)
20-30	Korfiatis et. al (1984)
20-30	Owens et. al (1990)
14	Zeiss and Major (1993)
29	Schroeder et. al (1994)
44	Bengtsson et. al (1994)

Refuse absorptive capacity has been estimated as 125 l/m^3 (Marriott, 1981) and as 1.62 inch/ft (Dilaj and Lenard, 1975). LF moisture can be visualized into 3 categories viz. gravitational, capillary and hygroscopic moisture. Knowledge of field capacity of the waste is essential to implement control over landfill moisture content and consequently affect its decay and settlement. Achieving field capacity in waste starting at 10 to 20 percent moisture requires between 40 and 80 gallons per cubic yard of waste (WMI 2000). Study from a pilot sized landfill (Rosqvist and Destouni, 2000) indicates that nearly 90% of the vertically flowing water in a landfill flows preferentially through 47% of the total water content. The observed difference between the preferential flow quantification of the landfill and that of the waste sample also were found to be more related to waste material properties than to the prevailing flow conditions i.e. the flow rate or degree of saturation. Hydrological study of a landfill (Bendz et. al 1997) indicates that initially the moisture in refuse is held by surface tension causing increasing volume of pools of water held against gravity. On subsequent increase in moisture content the capillary tension gives away abruptly and causes flow along preferential flow paths i.e. along paths having greater hydraulic conductivity.

The nominal angle of repose of MSW in landfills is about 1.5 to 1 (Tchobanoglous et al., 1993). Settlement occurs due to overburden pressure and waste degradation and is also affected by the moisture in the fill. Settlement also affects gas recovery mechanisms by rupturing and misaligning the strata and is not desired aesthetically on subsequent post closure usage. Typical overburden pressure is from 1750 to 2150 lbs/yd^3. Typically 90 % of the ultimate settlement is reported within 5 years (Tchobanoglous et al., 1993). Reliable indicators for ground water monitoring at landfill sites are reported as boron, iron, ammonia and total dissolved solids [TDS] (Nash and Khan, 1981)

Settlement in MSW landfills:

Edil *et al*. (1990) indicated the following mechanisms of refuse settlement:

(1) Mechanical—Distortion, bending, crushing and reorientation; similar to consolidation of organic soils.

(2) Ravelling—Movement of fines into large voids.

(3) Physico-chemical changes—Corrosion, oxidation and combustion.

(4) Bio-chemical decomposition—Fermentation and decay.

In a study (Spikula, 1997) of 5 conventional landfills, the average settlement was observed as 2.9 % vertical strain with a range of 0.6-4.8 % for about 1400 day post closure period. In actual pilot-scale landfill case study at the Sonoma County California the leachate recirculated cell settled by as much as 20% of its waste depth, while dry cells settled less than 8% (Leckie et al. 1979). Leachate recirculated cells at the trail road land site resulted in the recovery of 25% of landfill volume, which was utilized for additional waste placement. (Warith, 2002).

Wet cells at the Mountain View Landfill, California, settled approximately 13–15%, while control dry cells settled only 8–12% over a 4-year period (Buivid et al. 1981). Gandolla (1992) reported a rate of settlement decreasing to less than 5% per year after a period of approximately 5 years. A study at Yolo County Central Landfill (YCCL, 1997), California showed evidence of the potential of bioreactor landfills to gain additional space by increased settling.

TABLE 2-6 Summary of data for the (YCCL, 1997) Demonstration Project

Parameter	**Control Cell**	**Enhanced Cell**
Cumulative LFG Volume, 7/96-7/97 (10^6 scf)	9	12.2
Average methane content (%)	27	39
Average LFG flow rate (scfm)	50	53
Average Landfill settlement 5/96-5/97 (inches)	4.3	14

The settlement of landfills is caused by waste decomposition and compression and has been modeled using Terzaghi's soil consolidation theory, which includes terms for secondary compression, or on rate process theories such as the power creep model presented by Edil (1990) and Ling et al (1998). The settlement invokes problems associated for leachate and gas collection systems and the structural integrity of a landfill. Common problems due to vertical strain are rupture of conduits and fixtures used for leachate recirculation and gas collection, ground water pollution from washout and direct ingress. Secondary problems may arise from the rupture of cover soil/layer and expose the MSW to atmosphere and thereby create vector nuisance. Field scale experiments with leachate recirculation prove rapid biodegradation and settlement in MSW landfills (El-Fadel and Al-Rashed, 1998; Wall and Zeiss, 1995).

MSW settlement is observed in 3 distinct stages, these are initial compression, primary compression and secondary compression (Morris and Woods, 1990). Initial compression occurs on application of a direct load or overburden in a landfill. This results in an immediate compaction of void space and causes particle deformation to some extent. Bowels (1998) proposed determination of modulus of elasticity of MSW as $Es = \Delta q\ H_0/S_i$,where Es is the modulus of elasticity, Δq is the imposed additional stress, H_0 is the initial waste height and S_i the height of waste at any time. Primary settlement occurs quickly to 4-5 weeks (Sowers 1973, Morris and Woods 1990, Edil et. al. 1990). Primary settlement is significant after load application for about a month, after which secondary compression effects become significant and approach that of primary settlement in magnitude. Secondary compression is a result of creep and biological decay but independent of the stress on the waste and can result settlement of 25 % of waste thickness of which biological decomposition is reported to account for 18-24 % of waste thickness (Coduto and Huitric, 1990). Figure 2-3 below displays the subsidence data for the sites from the quoted literature.

MSW constitutes typically of 40-50 % cellulose, 12 % hemicellulose, 10-15 % lignin and about 4 % of organics mainly proteins on a dry mass basis (Barlaz et al. 1990) and it is suggested by Barlaz et al.(1990) that cellulose and hemicellulose constitute up to 91 % of methane potential. In lysimeter studies (Barlaz et al. 1989), mineralization of 71 % of cellulose was observed in 111 days, which suggests a first order half-life of about 62 days. In the early stages of decomposition, the abundance of readily degradable hydrolysed substrate present in the refuse mass suggests that methanogenesis is the rate limiting step. Once solubilized, the substrate is also lost by leaching and washout. During later stages, the slow hydrolyzing organics and celluloses/hemicelluloses determine the process rate. MSW carbon source being chiefly in the insoluble form, this suggests that hydrolysis must be the rate-determining step for overall biodegradation and resulting settlement.

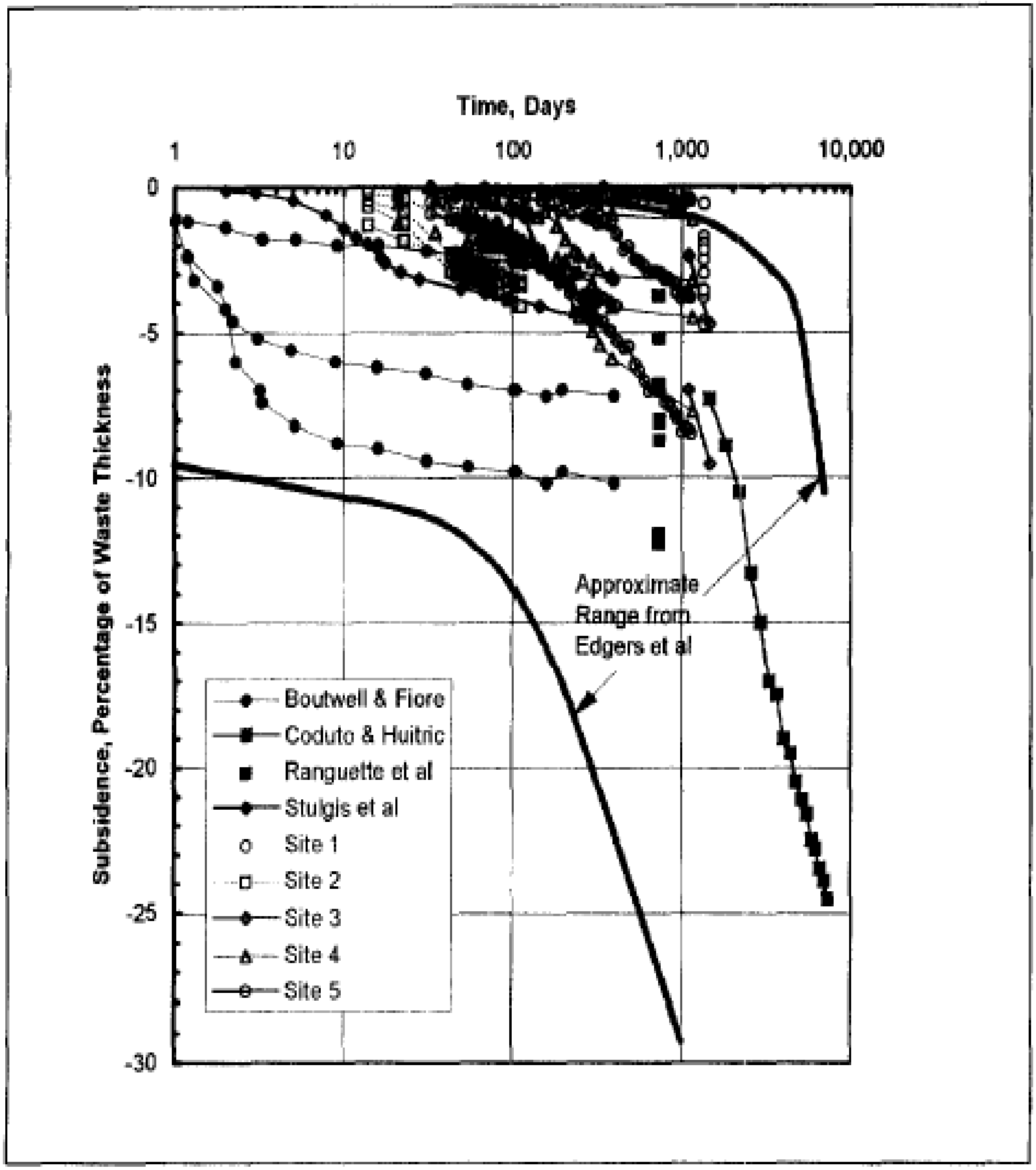


Figure 2-3 Percentage subsidence strain in various landfills

(Reproduced from Spikula, 1998)

Bioreactor landfills have been reported (WMI, 2000) to experience a total settlement of 30 % and possibly of 50 % in a span of 2-7 years, which implies a significant reduction in associated costs and simultaneous increase in landfill capacity. Leachate collected from most operating landfills provide 20-25 % of moisture content. To achieve the required moisture of up to 40 %, most landfills require external water addition in form of sludge, wastewater or storm runoff. Figure 2-4 depicts settlement for dry and wet cells of a typical landfill (Mehta et al., 2002).

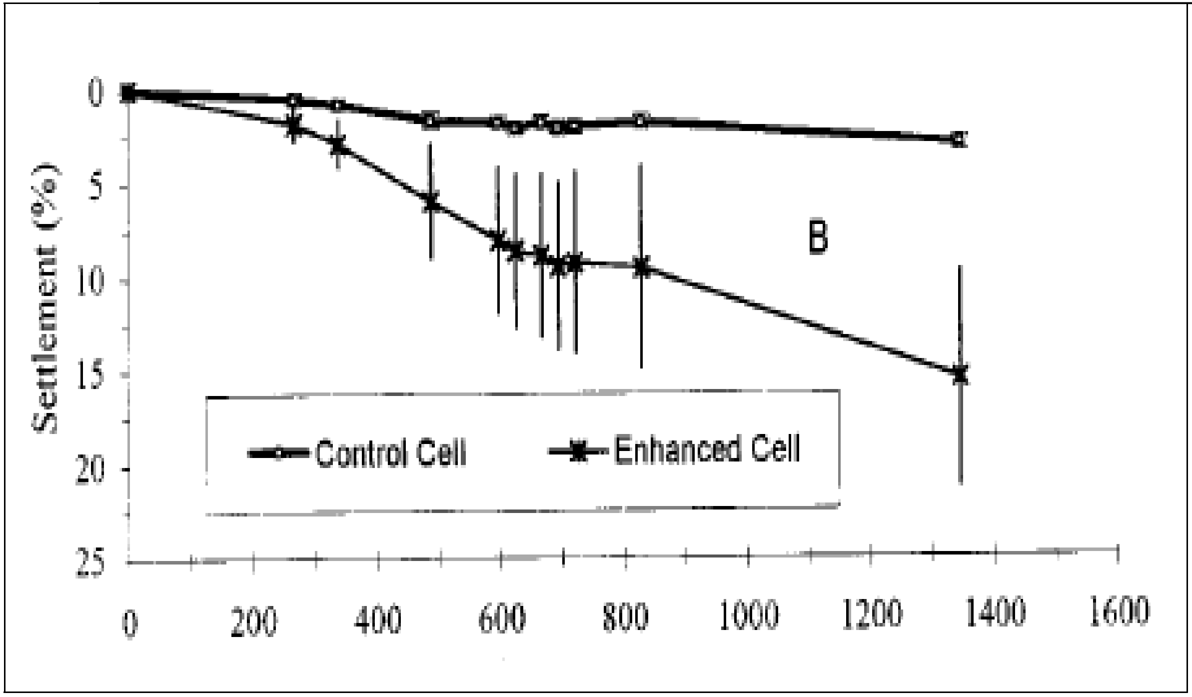


Figure 2-4 Average settlement in wet/dry cells (Mehta et al., 2002).

In a study by Wall and Zeiss (1995), no difference was observed between settlement magnitude and pattern for MSW landfill cells having refuse at inherent moisture and those at field capacity. This suggests that due to high refuse permeability, pore water pressure build up is not of concern.

Municipal Solid Waste (MSW) long-term settlement theories:

The secondary consolidation in MSW is due to creep and biochemical decay of the refuse. Sowers (1973) was the first to model secondary compression in landfills using a modification of Buisman's theory for soil compression. This assumes that secondary settlement is linear with respect to logarithm of time, which has been found from field data for MSW landfills.

Currently there are four settlement prediction models for MSW (Park et al., 2002).

a) Logarithmic function (Yen and Scanlon, 1975) expressed the strain rate (m) in terms of strain rate parameters.

$m = \frac{1}{Ho}\frac{dS}{dt} = c - d\log t$ m is the strain rate (T^{-1}), S is the settlement (L), Ho is the initial height of the landfill, c and d are strain rate parameters (T^{-1}).

Sohn and Lee integrated this strain rate to give the settlement over time as

$S = Ho\int m.dt = Ho\left(ct - \frac{d}{\ln 10}(t\ln t - t\right)_{to}^{t1}$ to is the age of fill at beginning of settlement computation period and t1 the age at end of this period. Limits for obtaining a positive settlement give $t1 \leq 10^{c/d}$. The main limitation of this method is the model is an entirely empirical way to curve-fit observed data.

b) Rheological model (Edil, 1990) proposed the Rheological model of Gibson and Lo (1961) for secondary compression to predict long-term settlement as

$\frac{S}{Ho} = \varepsilon(t) = \Delta\sigma(a + b\{1 - e^{[-(\lambda/b)t]}\})$ Where ε(t) is strain, Δσ= compressive stress ($L^{-2}M$) a is primary compressibility parameter($L^{2}M^{-1}$) λ/b is the rate of secondary compression (T^{-1}). Plotting $\log_{10}(\Delta\varepsilon(t)/\Delta t)$ versus $\log_{10}t$ we get slope of line = -0.434(λ/b) and intercept as $\log_{10}(\Delta\sigma\lambda)$. Denoting t_k as the time to complete primary compression we get

$a = \varepsilon(t_k)/\Delta\sigma - b\{1 - e^{[-(\lambda/b)t_k]}\}$. The model assumes that secondary settlement is linear with respect to the logarithm of time. Estimation of the time to complete primary compression i.e. t_k is difficult as primary and secondary compression occur simultaneously. The model also needs to be verified for its sensitivity to t_k.

c) Power Creep Law (Edil, 1990) applied the power creep law as $\frac{S}{Ho} = \varepsilon(t) = \Delta\sigma m(t/t_r)^n$. Where m is a reference compressibility ($L^{2}M^{-1}$), n is rate of compression. The power creep function has been found (Gibbons, 2002) to fit the observed data across 7 landfills comprising of 35 individual locations. The study also combined data across the sites to develop a time series model to fit all observations, and indicated that this model can be used to predict settlement at a location using settlement data from sites having similar settling characteristics.

d) Hyperbolic function has been used first by Ling et al. (1998) as

$$\frac{S}{Ho} = \varepsilon(t) = \frac{t}{\frac{Ho}{\rho o} + \frac{Hot}{S_{ult}}}; \quad \text{thus} \quad \frac{t}{\varepsilon(t)} = \frac{Ho}{\rho o} + \frac{Ho}{S_{ult}}t$$

S_{ult} is the ultimate settlement of the fill at t(∝).

The major limitation of this model is that it inherently predicts negative values for strain for short durations of time.

The results obtained by using these models in a study at by Park et al. (2002) are displayed below in Figure 2-5. As observed only the Rheological model seems to under predict the strain in MSW landfills whereas all three i.e. logarithmic, power creep and hyperbolic functions yield fairly reasonable estimates.

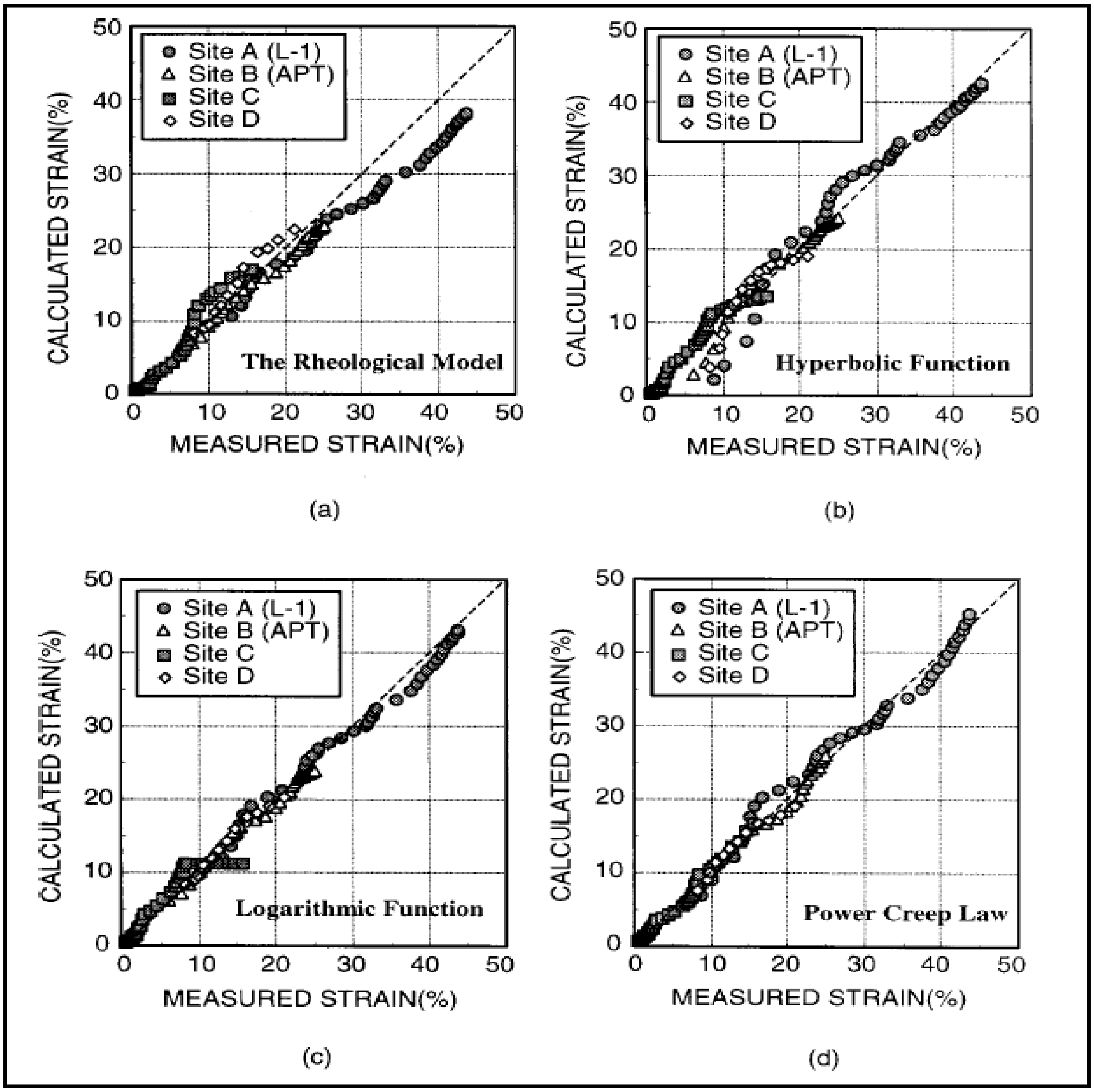


Figure 2-5 predicted % strain by 4 models (Park et al.,2002)

Specific criterion has not been established to measure material biodegradability and the extent to which refuse has degraded to render a landfill safe for subsequent usage. Similarly waste moisture retention potential at various decomposition stages needs to be addressed. The aim of this study is to develop an easy and reproducible method to determine waste moisture retention i.e. a lab scale field capacity for MSW along with the associated compression in the refuse.

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CHAPTER III: Field Capacity and Settlement of Municipal Solid Waste – A laboratory method

ABSTRACT: A laboratory method to determine the field capacity for municipal solid waste is proposed in this paper. Refuse from two landfills was tested in the laboratory using various methodologies to consolidate the refuse and exclude moisture. The method adapted was chosen on the basis of reproducibility, accuracy and its ability to correlate with waste strength. The consolidation during the experiment was measured and compared with that obtained from four mathematical models. The data suggests applicability of this method to give estimates of field capacity, and the laboratory scale settlement can be used as a measure of refuse compressibility.

KEYWORDS: Refuse, bioreactor landfills, field capacity, settlement models.

Introduction: Municipal solid waste (MSW) disposal in landfills, requires estimation of refuse degradation and settlement behavior in order to utilize the available volume to its maximum capacity. Field capacity, the ability of refuse to retain water, is an important parameter in the water balance of active landfills. Due to space shortage with rising population and with the advent of bioreactor landfills it is imperative to achieve active degradation in landfills to yield rapid and more efficient stabilization of refuse. This can be achieved by operating landfills as bioreactor landfills, where additional water is added to promote rapid degradation. This results in reduction to time to closure, reduced monitoring efforts and presumably higher end usage potential. Bioreactor landfills also offer adequate leachate control during operation and attenuated leachate strength during closure period.

The settlement in landfills is a response to biochemical degradation and compaction including creep in the refuse. It is advantageous to estimate the settlement as it provides additional storage volume for MSW. The problems associated with settlement are rupture and failure of liners with leachate contaminating the ground water, disruption of leachate and gas conduits and control equipment and possible vermin nuisance due to exposure of refuse to atmosphere.

Factors affecting the ability of refuse to retain moisture indefinitely against gravity i.e. its field capacity, depend on site specific hydrogeological conditions, waste composition, in situ compaction, and biodegradation. The field capacity is a vital stastic for

MSW landfills since leachate production begins only after the field capacity is attained. There is no measure of field capacity as related to refuse strength or physiochemical characteristics. The mechanics of settlement from a study by Gibbons (2002) indicates that settlement data from various sites can be combined, and used to estimate model parameters for predicting settlement and effectively apply such a settlement model to various other landfills.

Research Objectives:

This study explores development of a laboratory methodology to consolidate refuse, and drain out moisture. The new method simulates the response of refuse to its imposed overburden and its ability to retain moisture. The laboratory scale experiment also offers advantages of short testing duration, ease in testing refuse samples and avoids field complications. The study aims to yield laboratory estimates for field capacity and strain, which would provide a rapid estimate of the relative ability of waste samples as regards to their in situ field capacity and compressibility.

MSW settlement mechanisms:

MSW settlement is composed of the combination of voids reduction, refuse compression, physiochemical change and biodegradation along with losses due to washout of leachate. The primary mechanisms of settlement in sanitary landfills are due to the following:

1. Mechanical changes to refuse as distortion, compression, and reorientation of bulk of refuse mass across lines of slippage. Most of these changes occur quickly in a timeframe of hours to weeks. These include impacts of landfilling, compacting effort, overburden and result in more or less immediate elastic compression.
2. Reorientation of particles, termed as raveling. This is comprised of movement of smaller sized particles into larger voids present in fresh MSW, and as such raveling is expected to be complete before refuse consolidation by creep can take effect.
3. Creep or secondary consolidation of refuse is its response to the applied stresses, biodegradation effects and losses due to washout or leachate production. These continue for a long period, typically up to 2-3 decades unless accelerated.

Bioreactor landfills have been observed to reduce this time for secondary consolidation to about 5 years (Yolo County 1997, Pacey et al. 1996, WMI 2000), thus offering substantial savings. Absence of data regarding settlement behavior for a conventional landfill, makes direct comparison with that for bioreactor landfills impossible, but a time frame of 30 years might be a good estimate. The water content for MSW landfills without water addition is typically 20-30 % by volume whereas bioreactor landfills necessitate operational moisture of 30-45 % (Pohland and Kim, 1999). Water is not only essential to promote rapid hydrolysis of the waste (Yuen et al., 2001) but also knowledge of field capacity is essential to maintain appropriate moisture levels in a landfill and control leachate production in time and magnitude.

The refuse settlement models used for describing the degree of settlement or compaction in a landfill are the following:

a) Logarithmic function Yen and Scanlon, (1975) expressed the strain rate (m) in terms of strain rate parameters. This is entirely empirical model proposed to calculate the rate of settlement as magnitude of settlement per unit time interval. Yen and Scanlon observed that the rate of settlement decreased with the logarithm of time according to the following.

$m = \frac{1}{Ho}\frac{dS}{dt} = c - d\log t$ where

S is the settlement (L),

Ho is the initial height of the landfill (L),

thus S/ Ho is the strain or degree of volumetric/height reduction of the waste,

'm' is the strain rate (T^{-1}),

and 'c' and 'd' are strain rate parameters (T^{-1}).

Sohn and Lee integrated this strain rate to give the settlement over time as:

$\frac{S}{Ho} = \int m.dt = Ho\left(ct - \frac{d}{\ln 10}(t\ln t - t)\right)_{to}^{t1}$ where

t_o is the age of fill at beginning of settlement computation period and t_l the age at end of this period. Limits for obtaining a positive settlement give that $10^{c/d} \geq t_{1.}$

b) Rheological model Edil, (1990) proposed the Rheological model of Gibson and Lo (1961) for secondary compression to predict long-term settlement of peats. Refuse and peats have large sized voids that compress quickly during initial and primary settlement. The larger part of settlement is due to secondary consolidation, which involves changes in matrix structure due to refuse breakdown and decay.

$$\frac{S}{Ho} = \varepsilon(t) = \Delta\sigma(a + b\{1 - e^{[-(\lambda/b)t]}\})$$ where

ε(t) is strain,

$\Delta\sigma$= compressive stress ($L^{-2}M$)

'a' is primary compressibility parameter ($L^{2}M^{-1}$),

and 'λ/b' is the rate of secondary compression (T^{-1}).

Plotting $\log_{10}(\Delta\varepsilon(t)/\Delta t)$ versus $\log_{10}t$ we get slope of line = -0.434(λ/b) and intercept as $\log_{10}(\Delta\sigma\lambda)$. Denoting t_k as the time to complete primary compression we get

$$a = \varepsilon(t_k)/\Delta\sigma - b\{1 - e^{[-(\lambda/b)t_k]}\}$$

c) Power Creep Law Edil, (1990) applied the power creep law used to predict time dependant consolidation under constant stress as :

$$\frac{S}{Ho} = \varepsilon(t) = \Delta\sigma m(t/t_r)^n$$ where

'm' is a reference compressibility ($L^{2}M^{-1}$),

and 'n' is rate of compression.

d) Hyperbolic function has been used first by Ling et al. (1998) and is an empirical model.

$$\frac{S}{Ho} = \varepsilon(t) = \frac{t}{\frac{Ho}{\rho o} + \frac{Hot}{S_{ult}}}$$

To formulate the model parameters ρo ($L^{1}T^{-1}$) and S_{ult} (L^{1}) a plot of time against time/strain yields as :

$$\frac{t}{\varepsilon(t)} = \frac{Ho}{\rho o} + \frac{Ho}{S_{ult}}t$$ where

S_{ult} is the ultimate settlement of the fill at t(∝).

The principal aim of this study is to assess the field capacity potential of refuse by developing a methodology to simulate water expulsion from refuse in a short duration. This will help to yield preliminary estimates for refuse absorptive capacity, i.e. the moisture needed in addition to the in situ one, to achieve field capacity and thus aid design of leachate systems. This may be particularly important for bioreactor landfills as aggressive leachate recirculation has been proven to have disadvantages from structural stability (Reinhart, 1996) Moreover, state and federal regulations limit the maximum leachate head on the liner to 12". Hence it is desirable to avoid pore water pressure build up, which can occur before saturation of refuse due to waste heterogeneity (Maier, 2002).

Materials and Methods:

Sampling :

MSW landfills were sampled using a drill rig outfitted with a 36-inch bucket auger to collect refuse from different depths. The MSW wet density was obtained in the field using a realistic approach. Each ten-foot segment was placed into a tared roll-off box and weighed. This weight divided by the volume ($\pi r^2 h$- about 2.62 yd^3) gives the wet field density. The dry density was calculated from the wet density and the measured moisture content. Both wet and dry densities are reported in pounds per cubic yard (lbs/yd^3). This method has been shown to be unrealistic in several cases due to the drill system used, which may cause shearing and caving of refuse and thus add to the weight.

Ten-pound samples were collected from the top, middle, and bottom of each ten-foot section and shipped to Virginia Tech, Blacksburg, VA in coolers. Samples were received from landfill sites wrapped in HDPE plastic bags, double bagged, secured via duct tape to ensure air-tightness and housed in commercially available ice-coolers. These were stored in a laboratory freezer at 4^{o}C to retain in-situ moisture and pH of the waste.

Sample testing for field capacity:

Sample preparation

About 8-12 pounds of wet samples at approximately 20-45 % moisture content were available from several landfill sites. The samples were presorted to remove items having a least linear dimension in excess of approximately 4 inches to limit heterogeneity effects. Occasionally such items were a shoe or large wooden/metal debris. The available size was thus about 7.5 pounds of wet sample, which was found to be adequate to fill a commercially available bucket (test bucket) of 12" diameter, 14 3/4" height. The sample was spread evenly inside a rectangular plastic container approximately 48"X15"X12" and tap water applied by hand to wet the sample to yield a visible pliant and cohesive mixture. This was found to yield approximately 40-70 % moisture content necessary for the study. This wetted sample was put into a ‘test bucket’ as described below.

Selection of methodology:

Refuse was placed in test buckets and consolidated by various means to expel moisture and compress the waste. The test buckets had their bottom drilled with 1/8 th inch holes with even spacing of 21 holes, as displayed in Figure 3-1(4 in each quadrant, one on each axis of quadrant, and one in center).

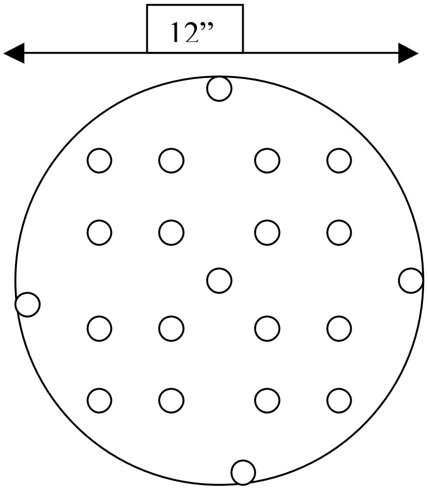

Figure 3-0 Pattern of holes (1/8 inch in test bucket bottom)

All test buckets were elevated on two opposite sides using wooden battens to ensure free drainage through the bottom. Seven and half pounds of wet sample was then hand placed in each of such test buckets.

Several methods were considered for measuring drainage behavior on a laboratory scale. Drainage by centrifugation was found to be impracticable for a sample weight of 8 pounds. Vacuum application was also ruled out, because of the inherent heterogeneity of MSW. The first method investigated was drainage of refuse by application of impact loading..

For impact loading, a compacting load of 10 pounds was dropped 50 times from one foot above the initial top surface of refuse in the ‘test bucket’. This results in the total compacted force of 500 ft-lb. Results applying impact loading indicated that such a method is inconsistent to correlate waste moisture retention with its physiochemical characteristics.

The next refuse compaction method investigated was compression by application of air pressure. Compressed air at 40 psi (pounds per square inch) was applied on the top of the ‘test bucket‘ ensuring proper sealing. The drainage pattern over a period of 1 hour was measured. This method was found to be unacceptable because it did not mimic actual landfill behavior. The time frame for drainage being in minutes, was unrealistic. It was thought that this was because water moved through the large uncompressed pores and these are not typical of landfill refuse. Moreover, the refuse compression could not be achieved using compressed air.

Chosen method:

The final method used and the one ultimately selected used a static load applied over several days to compact refuse and remove water. This was achieved by placing shot blast pellets on top of refuse in the test buckets. It was observed that the friction between the buckets did not hinder the settlement of refuse. Initially, experiments were conducted to determine load drainage characteristics and a load of 75 lbs yielding a pressure of 775 lbs/yd^2 on the refuse was applied. The results were compared over a period of 5 days with that obtained from a load of 40 lbs and were found to be statically similar. The drainage pattern using compressed air (40 psi) to drive out moisture from top (through the bottom holes) was monitored and found to be poorly correlated with refuse characteristics. Hence, for subsequent tests a load of 40 lbs was adopted and sample removed for moisture determination up to 5 days (moistures taken at 1 and or 2 and or 3 and 5 days) and the load replaced immediately. It was observed that the drainage was achieved within 5 days, since insignificant drainage occurred between 3 to 5 day period. It is also believed that evaporative losses would dominate over long test periods. Hence to limit evaporation interference the test was terminated at 5 day drainage period.

The initial settlement data was collected after allowing the load to uniformly compress the large voids in the hand packed test bucket for an initial time of 30 seconds and settlement following this initial period is reported. A commercially available wooden yardstick calibrated to an eighth of inch was used to measure settlement with readings reported to nearest one sixteenth of an inch by visual observation. The samples were undisturbed over the 5-day period, after which they were sampled for moisture content. The same sample was reused to determine the reproducibility of the method.

Laboratory Analysis:

In the laboratory, several parameters were measured in order to characterize refuse stability (Kelly et al, 2002). These parameters were pH, moisture content, volatile solids, cellulose, the major hemi-cellulose sugars (xylose, mannose, arbinose, and galactose), lignin, and biochemical methane potential.

Moisture Content: The moisture content was measured according to method 2540-B (APHA et al., 1995). For this analysis, 500-1000 g wet, unshredded MSW were put into an aluminum pan and dried at 105 °C until constant weight. (Usually less than two days.) The moisture content is expressed as percentage of the weight loss during drying divided by the original weight. The amount of moisture is expressed as percentage by weight, of both wet and dry weight of the refuse samples.

Volatile solids: The volatile solids were measured by using the 2540-E method (APHA et al., 1995). A 100-200 mg sample of dry, milled refuse was placed into an aluminum pan, and then into a muffle furnace (550 °C) for 20 minutes (after that no additional weight loss was expected). The reported volatile solids are the percentage by weight of refuse lost.

pH : The pH was measured by mixing 50% (% by weight) wet unshredded MSW sample and distilled water into a 1 L glass beaker. When the mixture reached equilibrium at 20 °C (about 5 hours), the pH probe was placed into the beaker and the reading was obtained. Cellulose and the hemicelluloses were measured by applying the ASTM E 1758-95^{e1} (1995). This method was chosen, because it is suitable for materials found in municipal solid waste samples.

Cellulose and Lignin analysis: Dried, shredded refuse samples were weighed (300 ±10 mg) and placed into a 16x100 mm glass tube. The cellulose was hydrolyzed in two stages to convert cellulose and hemicelluloses into their sugar monomers. In the first stage, 3.00 ± 0.01 mL of 72% w/w sulfuric acid (H_2SO_4) was added to the samples and stirred, and then the glass tubes were placed into the 35 °C water bath for one hour. In the second stage, the digested samples were transferred into 250 mL septa bottles with 84 mL of nanopure water dilution. The bottles were autoclaved for an hour at 121 °C and 15 psi. After the autoclaving, the bottles were allowed to cool for 20 minutes at room temperature. The samples were filtered through a weighed standard glass fiber filter and the residue retained on the filter was ignited to a constant weight at 550 ± 50° C. The increase in the weight of the filter is the amount of lignin in the sample. Kelly et al. (2002) showed that this includes plastics.

The filtrate was neutralized to pH between 5-6, with slurry form of $Ba(OH)_2$. The barium(II) sulfate precipitate was centrifuged and then filtered though a 0.45 micrometer pore size membrane and a reversed-phase cartridge. Finally, the glucose and the main four hemicelluloses were quantified using high performance liquid chromatography (HPLC) with reflective index detector and HPX-87C column. The water flow rate was set to 0.5 ml/min for easier peak separation. Both glucose and the four hemicelluloses (xylose, arbinose, galactose, and mannose) standard curves were run before the actual analysis, using D(+) xylose, D(+) mannose, D(+) galactose, D(+) arbinose, and D(+) glucose.

Biochemical methane Potential test: The biochemical methane potential (BMP) was modified from a procedure developed by Barlaz (Shearer et al., 2001). Two hundred milligrams of dry, shredded MSW were added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic media was added to each bottle. The media was made following Barlaz's methods except for two modifications. The vitamin solution was not included, and anaerobic digester biosolids from the Peppers Ferry anaerobic digester, Fairlawn, VA were added as inoculum at 10% by volume (Stinson and Ham, 1995.) The bottles were incubated for 45 days at 35 ^{o}C. One-liter Teflon gas sampling bags were connected to each bottle at the end of the incubation period for twenty minutes while agitating the bottle to relieve excess pressure. A 100 micro-liter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and flame ionization detector (FID). The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP was reported in units of milliliters of methane per gram of dry MSW at STP (mL CH_4/g).

The samples were analyzed in duplicates for celluloses, lignin and in triplicates for Volatile solids, Biochemical Methane Potential and waste Field capacity and settlement study.

RESULTS AND DISCUSSION

Field capacity: The waste characteristics of samples tested are presented in Table 3.1. The laboratory columns had refuse from Metro landfill in Milwaukee, Wisconsin.

Table 3.1 Waste characteristics: -

Green Valley/King George Landfill waste and waste from laboratory Columns.

Sample #	Landfill	Location	Depth (ft)	% wet Moisture	% dry Moisture	pH	Avg % V.S	Avg BMP (mL/g)	Avg. % Cellulose	Avg % Lignin	Cell/Lig Ratio
1	Green valley	TB 1	10 - 40	32.98	49.50	6.28	74.68	127.33	47.77	29.45	1.64
2	Green valley	TB 1	70-100	31.08	45.10	6.12	39.02	48.41	23.00	16.40	1.40
3	Green valley	TB 1	100-145	23.12	30.20	6.09	58.63	104.00	36.09	17.07	2.11
4	Green valley	TB 2	60-100	32.48	48.20	6.18	53.65	81.73	27.73	22.48	1.23
5	King George	CH 1	0-15	46.79	87.94	7.05	55.16	61.04	34.33	16.24	2.11
6	King George	CH 1	15-30	38.83	63.47	6.43	44.89	61.20	37.51	15.90	2.36
7	King George	CH 1	30-45	24.00	31.57	6.47	44.79	51.00	31.51	15.35	2.05
8	King George	CH 1	45-55	31.63	46.26	5.93	42.96	53.39	31.34	20.40	1.54
9	King George	CH 1	55-70	26.19	35.49	6.07	52.17	57.58	35.82	15.90	2.25
10	King George	CH 2	0-15	26.87	36.75	6.76	53.55	66.98	29.22	17.50	1.67
11	King George	CH 2	15-30	37.94	61.14	6.77	71.67	58.09	35.52	14.73	2.41
12	King George	CH 2	30-45	34.14	51.83	5.58	66.69	50.50	40.75	17.70	2.30
13	King George	CH 2	45-60	25.74	34.67	5.98	40.84	47.35	30.83	15.15	2.03
14	King George	CH 2	60-70	30.99	44.90	5.66	65.29	60.53	38.59	19.70	1.96
15	King George	BH 1	3-15	43.24	76.19	8.04	40.42	54.07	35.55	14.95	2.38
16	King George	BH 1	15-30	33.22	49.75	6.96	56.94	59.40	30.83	17.75	1.74
17	King George	BH 1	30-45	29.98	42.82	6.85	85.37	60.06	45.20	22.20	2.04
18	King George	BH 1	45-60	29.57	41.98	7.08	70.77	68.69	42.24	19.90	2.12
19	King George	BH 1	60-75	28.40	39.66	6.87	75.23	65.32	45.45	16.25	2.80
20	King George	BH 2	3-15	47.55	90.64	6.01	67.44	59.18	37.08	23.03	1.61
21	King George	BH 2	15-30	46.26	86.09	5.48	64.89	54.98	32.84	22.19	1.48
22	King George	BH 2	30-45	39.97	66.58	6.43	54.83	51.47	35.46	21.44	1.65
23	King George	BH 2	45-60	45.44	83.30	5.73	71.46	67.17	36.00	23.49	1.53
24	King George	BH 2	60-75	40.19	67.19	5.30	70.84	60.72	39.53	25.71	1.54
25	King George	BH 3	3-15	30.70	44.31	5.51	72.03	61.84	48.24	15.25	3.16
26	King George	BH 3	15-30	35.71	55.54	6.31	59.14	53.76	35.17	14.40	2.44
27	King George	BH 3	30-45	39.86	66.27	7.60	53.11	53.95	26.29	26.50	0.99
28	King George	BH 3	45-60	43.87	78.17	6.14	69.18	62.57	35.48	20.43	1.74
29	King George	BH 3	60-75	35.18	54.26	6.83	45.47	56.48	18.94	20.52	0.92
30	Column	COL 1					63.63		23.95	23.00	1.04
31	Column	COL 2					39.73		18.68	23.90	0.78
32	Column	COL 4					42.33		11.18	24.05	0.46
33	Column	COL 11					75.00		24.20	31.53	0.77

It is observed that the waste characteristics are intermediate between fresh refuse and well-degraded refuse. Fresh refuse will generally have Volatile Solids of approximately 70 %, Cellulose of 30-40 % and a BMP of 150 mL/g. Stable or degraded MSW will have a Volatile Solids content of 20 % or less and a BMP of 20 ml/g or less (Kelly et al.2002). The amount of cellulose (11.18-47.77 %), volatile solids (39.02-85.37 %), BMP (47.35-127.33 mL/g) and the high cellulose/lignin ratio (0.46-3.16), implies that the waste is not well stabilized, but has undergone some degradation.

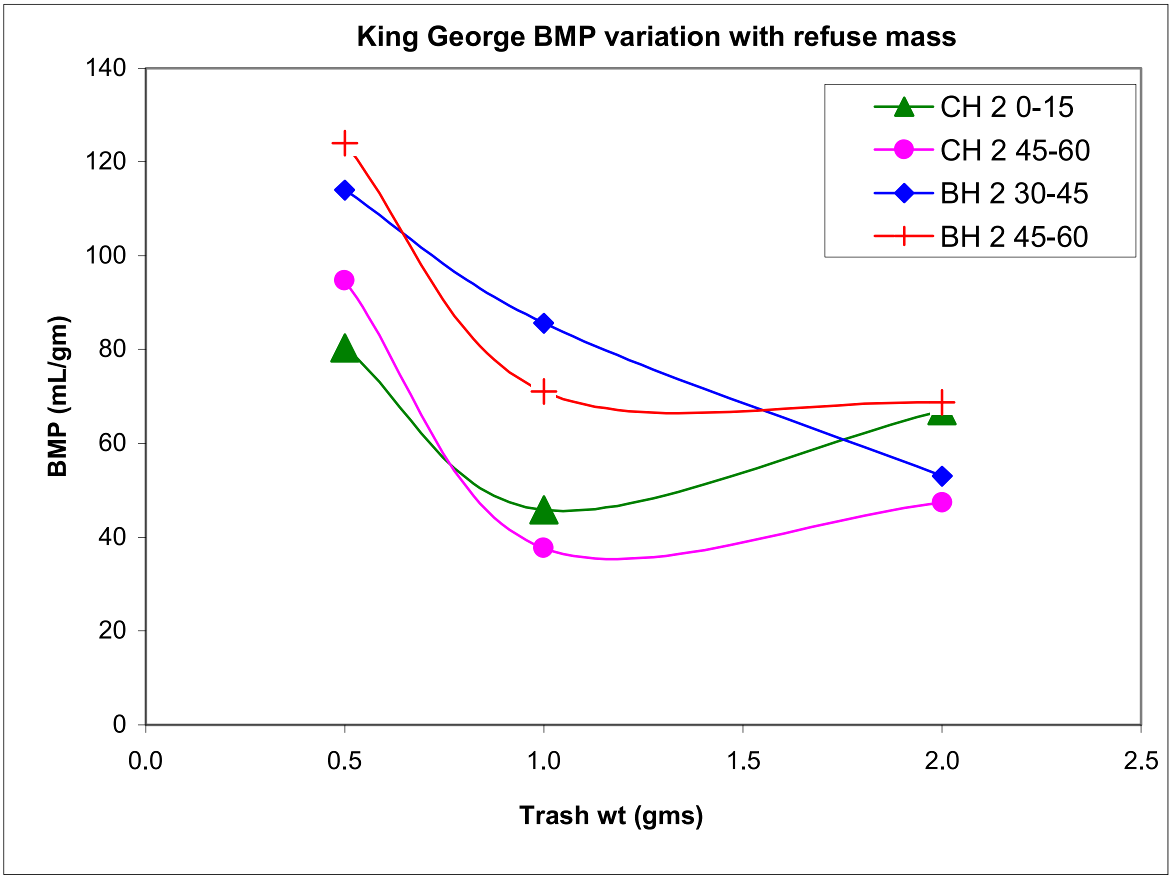

Fig 3.1 –BMP variation with refuse content.

King George landfill samples did not have a variation of BMP with that of different cellulose or volatile solids content. To investigate this lack of BMP variation and absence of high methane potential in any of the samples the BMP test was repeated on a limited samples by varying the refuse concentration in a standard BMP test. The standard BMP test using 2 grams of dry refuse in BMP serum was incubated as procedure to yield methane, and the test was also carried out for samples wherein the refuse mass was reduced to 1 gram and 0.5 grams. The results are displayed in Figure 3.1, which indicate a higher yield of methane content per unit weight of dry refuse i.e. BMP of samples which is of the order of 2-3 times for 0.5 grams of refuse compared with the standard BMP test using 2 grams of refuse. This implies the inability of the standard BMP test to yield accurate estimates of methane potential, which could be attributed to inhibition of methanogens in the test due to refuse toxicity at higher concentration. This hindrance to methane formation could also be due to the fly ash, which can influence the pH of the medium used for BMP. This nature of the standard BMP test suggests site-specific test response, and the need for modification of the standard test to yield the actual methane potential.

Figure 3.2 displays drainage behavior for Green Valley using a impact loading of 500 ft-lbs. It is observed that this method drains samples within the test duration of 2 days, but the drainage may not yet be complete. Moreover, it is seen that initial moisture influences the final moisture, as seen from different drainage rates and final moistures.

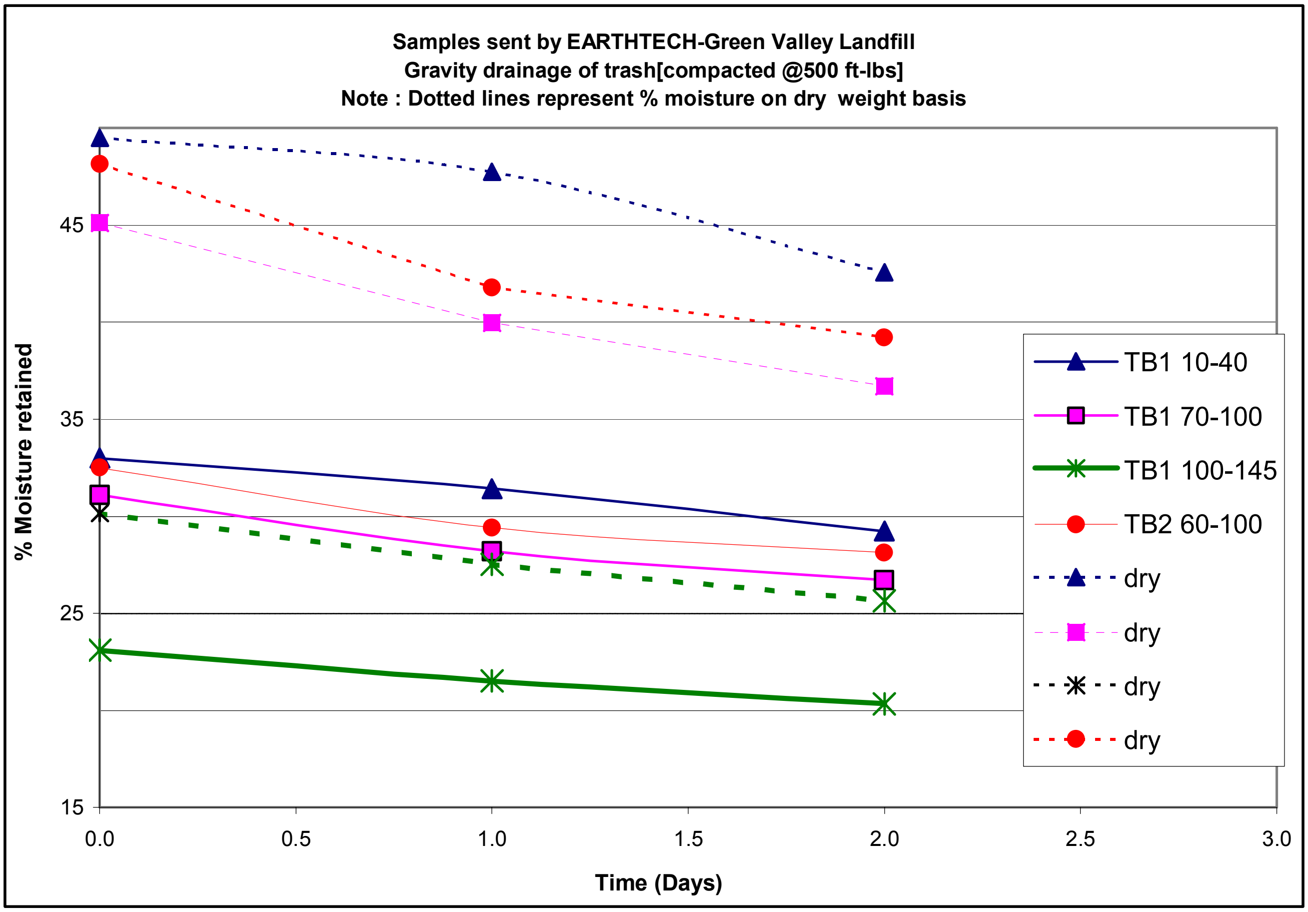

Fig 3.2 –2 Day moisture retention Green Valley.

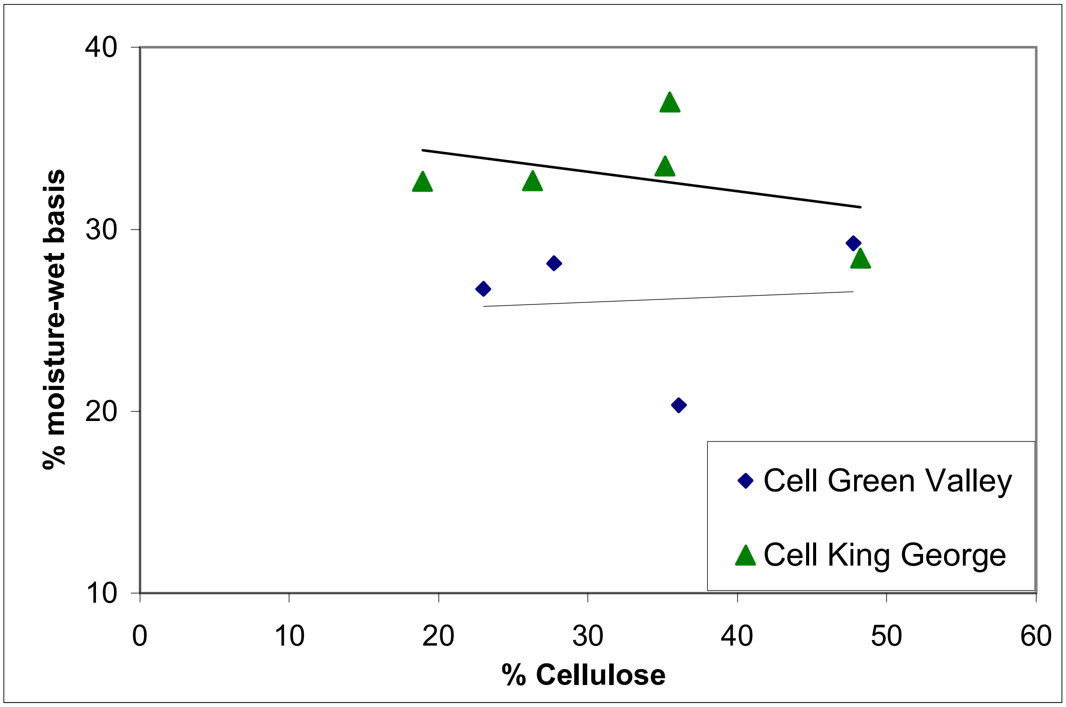

Fig 3.3 a) –2 Day wet moisture Green Valley, 3 day wet moisture King George, 500 ft-lbs impact loading. Note: Cell denotes cellulose.

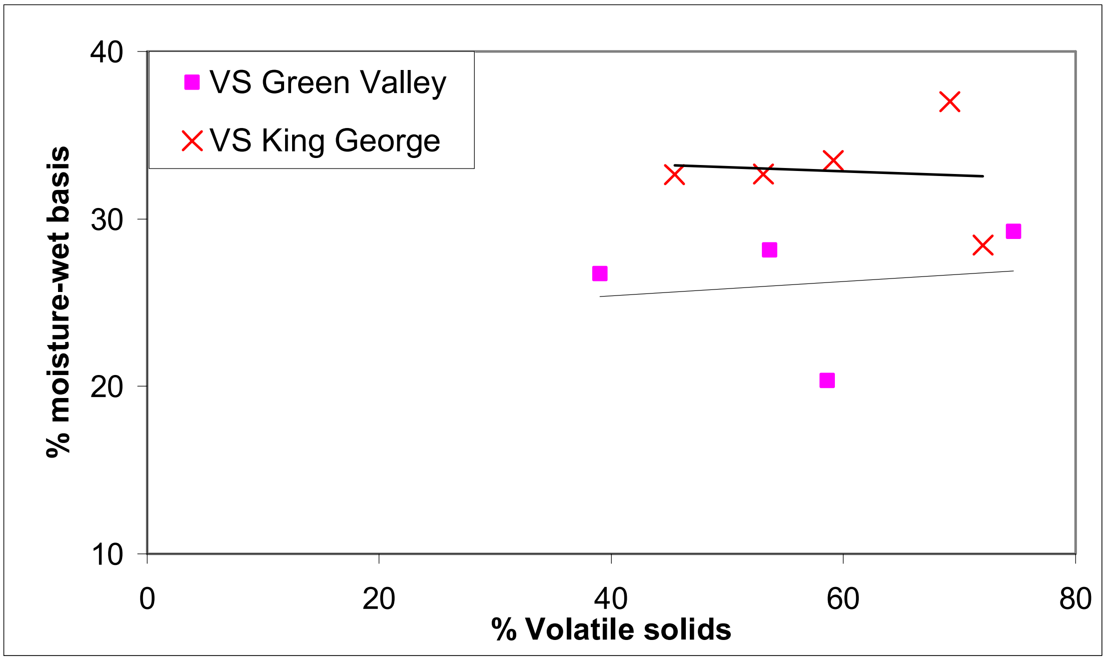

Fig 3.3 b) –2 Day wet moisture Green Valley, 3 day field capacity King George, 500 ft-lbs impact loading. Note: VS denotes volatile solids.

Figures 3.3 a and b show the absence of any correlation between field capacity and refuse Cellulose and Volatile Solids content respectively, using impact loading of 500 ft-lbs. The field capacity is expected to vary directly with the above parameters, whereas data from this method shows a poor inverse or almost no relationship. This suggests that the impact loading method is not appropriate for defining the relationship between refuse stability and its moisture retention potential or there is no relationship between waste stability and field capacity. To explore this further, an alternative method was used.

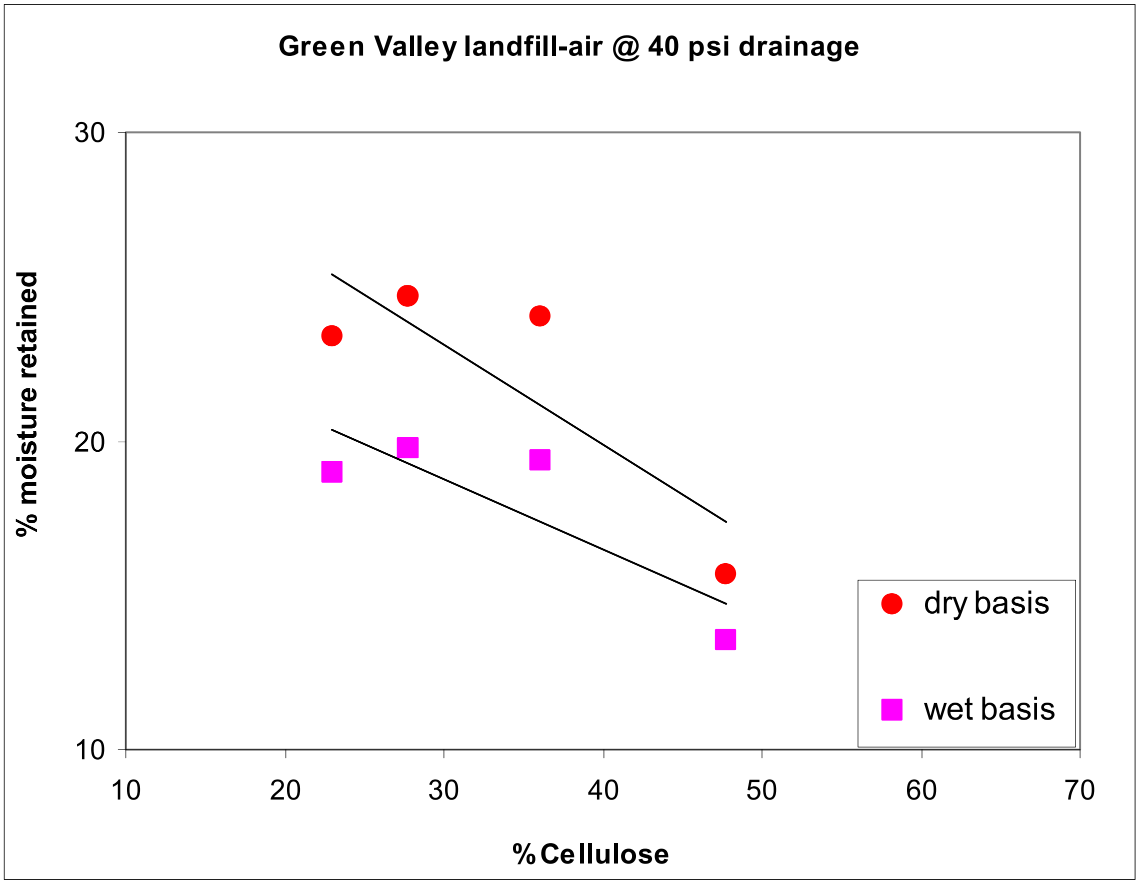

Fig 3.4 – moisture content, 60 min drainage compressed air 40 psi

In the alternate method, compressed air at 40 psi was passed from top of a sealed test bucket so as to drain the sample by driving out moisture through the bottom holes. It was found that the refuse samples were drained of moisture without any change in their height. This implies that moisture was squeezed out by air pressure through the voids alone and compression of refuse was not achieved. Data using compressed air at 40 psi to drain sealed test buckets is presented in Table 3.2 and Figure 3.4. It can be seen from Figure 3.4 that an inverse relationship between moisture retained i.e. field capacity and the cellulose content is obtained from waste drainage by passing compressed air through it. This implies that the test fails to drain the samples uniformly with respect to the physio-chemical characteristics of the waste, since increasing waste organic content i.e. higher cellulose and Volatile Solids content, should retain more moisture. This method extrudes moisture from refuse but the has a time scale of minutes whereas in actual landfills the timescale is of the order of years, this could lead to inapplicability of the method due to difference in mechanism of water expulsion. Furthermore this method failed to consolidate the samples. Therefore, this method was considered unacceptable.

Table 3.2 Drainage for Green Valley samples using air at 40 psi.

Sample			Drainage	% wet	% dry
Location	**Depth(ft)**	**Bucket no**	**duration(min)**	**Moisture**	**Moisture**
TB 1	10 - 40	4	0	33.00	49.49
			5	30.78	44.46
			15	27.83	38.56
			35	16.37	19.58
			60	13.58	15.71
TB 1	70-100	9	0	31.10	45.12
			5	26.27	35.62
			15	20.18	25.29
			35	19.57	24.32
			60	18.98	23.42
TB 1	100 - 145	3	0	23.10	30.15
			5	22.49	29.02
			15	21.33	27.12
			35	20.29	25.45
			60	19.37	24.02
TB 2	60-100	7	0	32.50	48.16
			5	27.75	38.41
			15	26.50	36.05
			35	25.12	33.54
			60	19.80	24.69

The application of a static load to consolidate refuse was then investigated. Typical refuse average density in a landfill is about 2000 lbs/yd^2, implying an overburden pressure of 2000 lbs/yd^2 for every yard of waste depth. Waste drainage by static load of 75 lbs to yield an overburden pressure of 775 lbs/yd2 was adopted and the results for are presented in Table 3.3. It is seen that the test overburden pressure as well as size of refuse drained is of an order less than that in actual landfills. The drainage behavior is mimicked as in actual landfills as evident from waste compression results.

Table 3.3 Reproducibility for static load (75 lbs) drainage-King George BH2 samples

Sample		Initial	% wet Moisture in sample for trial		
Location	Depth(ft)	Moisture	1	2	3
BH 2	3-15	44.44	32.71	27.64	25.45
BH 2	15-30	44.74	35.12	29.79	28.56
BH 2	30-45	38.05	30.32	25.91	24.94

The test appeared to be reproducible, but warranted further investigation and statistical validation. The effect of overburden pressure was thought to influence drainage pattern and mechanism. Hence to investigate this trend the same test was repeated using a 40 lbs static load to yield an overburden pressure of 443 lbs/yd$_2$ and the results are compared with those for the 75 lbs static load. These are depicted in Figure 3.5.

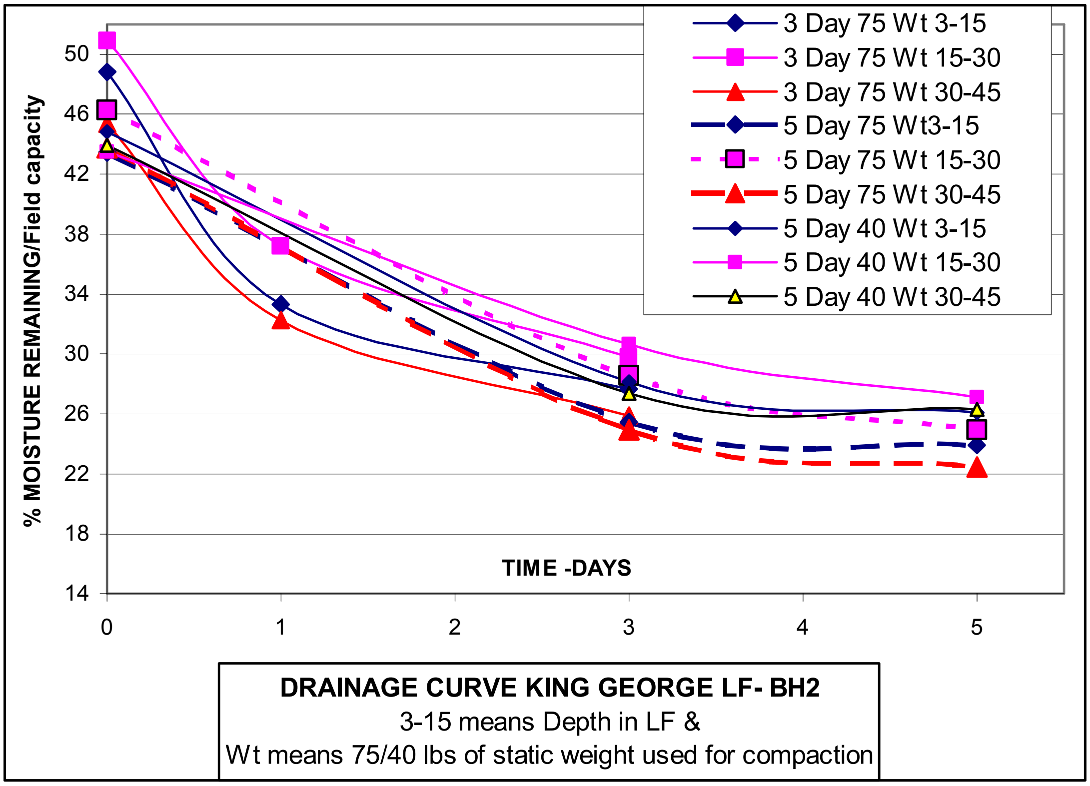

Figure 3.5 –Drainage Behavior for BH2 King George landfill for static loads 75/40 lbs.

It is seen that the static load drainage test is reproducible within a 1-2 % moisture content range and the initial moisture content does not appear to influence the final moisture content. Furthermore there was no significant difference in drainage between 75 or 40 lbs static load, and the variation of the drainage rate remained the same for both amounts of imposed loads. This is believed to be an indication of the same drainage mechanism independent of both the initial moisture content of the waste and the imposed loads. Hence to facilitate more trials, the 40 lbs static load test was adopted and studied in detail. Tables 3.4, 3.5, 3.6 and 3.7 display the samples obtained using 40lbs static load with gravity drainage. Moisture retained after 5 day drainage period is reported as percentage of wet and dry refuse weight.

Table 3.4 -% moisture retained Bio-Hole 1, King George samples.

			40 lbs, gvt drainage, Trial #				
Location	**Depth(ft)**	**Duration**	**1**	**2**	**3**	**4**	**5**
BH 1	3-15	0 Day (wet)	42.77	43.22	46.37	45.68	45.47
		0 Day (dry)	74.85	76.4	86.46	84.09	83.39
		5 Day (wet)	26.98	27.39	27.69	28.49	29.00
		5 Day (dry)	37.02	38.00	39.82	39.83	40.84
BH 1	15-30	0 Day (wet)	39.64	40.89	39.30	45.43	46.69
		0 Day (dry)	65.81	69.43	64.74	83.27	87.57
		5 Day (wet)	28.78	29.04	29.67	30.13	29.53
		5 Day (dry)	40.44	40.94	42.18	43.12	41.90
BH 1	30-45	0 Day (wet)	42.37	43.92	40.24	46.61	47.24
		0 Day (dry)	73.59	79.57	67.34	87.29	89.55
		5 Day (wet)	34.46	35.14	34.92	35.49	34.96
		5 Day (dry)	52.62	54.5	53.66	55.02	53.76
BH 1	45-60	0 Day (wet)	43.20	42.06	36.47	40.26	45.59
		0 Day (dry)	76.23	74.4	57.41	67.39	83.79
		5 Day (wet)	31.71	32.36	32.51	32.42	33.12
		5 Day (dry)	46.47	47.91	48.18	47.97	49.52
BH 1	60-75	0 Day (wet)	40.57	39.52	41.69	45.16	43.48
		0 Day (dry)	68.51	65.25	71.91	82.36	76.92
		5 Day (wet)	33.15	33.42	33.26	33.87	34.15
		5 Day (dry)	49.65	50.27	49.89	51.21	51.85

Table 3.5 -% moisture retained Bio-Hole 2, King George samples.

			40 lbs, gvt drainage, Trial #					
Location	Depth(ft)	Duration	1	2	3	4	5	6
BH 2	3-15	0 Day (wet)	44.86	45.21	42.57	48.80	42.17	44.84
		0 Day (dry)	80.89	82.21	73.97	95.32	72.92	81.28
		5 Day (wet)	26.10	28.70	27.39	27.25	28.74	29.09
		5 Day (dry)	35.33	40.25	37.74	37.45	41.11	41.70
BH 2	15-30	0 Day (wet)	43.53	42.15	40.45	27.60	42.18	43.94
		0 Day (dry)	77.81	73.15	68.15	90.43	72.94	78.39
		5 Day (wet)	27.14	27.03	28.70	47.49	28.13	27.82
		5 Day (dry)	37.26	37.05	40.31	38.11	38.33	37.91
BH 2	30-45	0 Day (wet)	43.95	39.78	39.23	26.20	40.51	47.40
		0 Day (dry)	78.74	66.08	64.63	81.03	68.10	90.12
		5 Day (wet)	26.33	25.48	24.94	44.76	27.04	27.46
		5 Day (dry)	35.71	34.18	33.25	35.49	33.35	34.77
BH 2	45-60	0 Day (wet)	46.57	40.17	40.13	46.87	48.24	44.72
		0 Day (dry)	88.08	67.51	67.06	88.22	93.18	80.91
		5 Day (wet)	29.71	27.88	27.54	27.14	28.36	27.81
		5 Day (dry)	42.29	38.71	38.03	37.25	39.59	38.53
BH 2	60-75	0 Day (wet)	46.19	42.16	40.12	73.21	44.32	47.26
		0 Day (dry)	86.18	72.94	73.75	273.29	79.61	89.61
		5 Day (wet)	28.56	28.24	29.26	29.47	28.72	28.25
		5 Day (dry)	39.99	39.42	41.45	41.79	40.29	39.38

Table 3.6- % moisture retained Bio-Hole 3, King George samples.

			40 lbs, gvt drainage, Trial #					
Location	Depth(ft)	Duration	1	2	3	4	5	6
BH 3	3-15	0 Day (wet)	38.80	40.94	44.95	43.62	44.00	45.14
		0 Day (dry)	63.91	69.43	82.18	83.47	78.22	82.29
		5 Day (wet)	30.21	30.21	30.06	30.30	30.77	31.19
		5 Day (dry)	43.29	43.29	42.98	43.52	44.30	45.31
BH 3	15-30	0 Day (wet)	39.69	39.34	39.16	42.87	43.18	49.11
		0 Day (dry)	66.20	64.83	63.78	76.91	76.05	96.27
		5 Day (wet)	28.76	27.41	28.17	27.83	27.69	28.07
		5 Day (dry)	40.40	37.79	39.22	38.57	38.28	39.00
BH 3	30-45	0 Day (wet)	42.10	38.80	41.20	32.37	42.38	48.92
		0 Day (dry)	72.79	63.42	70.17	48.07	73.44	95.94
		5 Day (wet)	26.91	27.62	28.21	28.63	28.50	28.70
		5 Day (dry)	36.87	38.20	39.32	40.11	39.86	40.29
BH 3	45-60	0 Day (wet)	43.42	40.35	39.95	50.14	41.90	52.43
		0 Day (dry)	76.97	67.47	66.51	103.62	92.79	138.12
		5 Day (wet)	29.44	28.27	28.60	29.16	28.70	28.26
		5 Day (dry)	41.73	39.42	40.10	41.16	45.94	43.55
BH 3	60-75	0 Day (wet)	43.57	41.29	40.05	37.62	42.76	47.64
		0 Day (dry)	77.49	70.51	67.49	61.73	94.91	109.98
		5 Day (wet)	25.99	26.60	26.97	27.46	27.35	26.98
		5 Day (dry)	35.20	36.33	36.99	37.89	42.61	40.62

A total of 21 samples were tested in triplicate runs or more to check the drainage pattern for repeatability and accuracy.

Table 3.7- 40 lbs static load test for Green Valley and Column samples.

			40 lbs, gvt drainage, Trial #		
Location	Depth(ft)	Duration	1	2	3
TB 1	70-100	0 Day (wet)	47.18	45.71	48.81
		0 Day (dry)	89.31	84.19	95.37
		5 Day (wet)	25.63	25.91	26.33
		5 Day (dry)	34.47	34.98	35.74
TB 1	100-145	0 Day (wet)	48.86	44.58	46.97
		0 Day (dry)	95.56	80.43	88.57
		5 Day (wet)	32.74	33.34	34.41
		5 Day (dry)	48.68	50.03	52.46
COL 1	-	0 Day (wet)	51.16	51.50	49.86
		0 Day (dry)	104.76	106.17	99.43
		5 Day (wet)	27.45	28.04	28.62
		5 Day (dry)	37.83	38.97	40.09
COL 2	-	0 Day (wet)	52.82	51.62	46.72
		0 Day (dry)	111.95	106.71	87.68
		5 Day (wet)	25.58	26.11	26.02
		5 Day (dry)	34.36	35.34	35.18
COL 4	-	0 Day (wet)	48.54	48.99	42.48
		0 Day (dry)	94.34	96.03	73.16
		5 Day (wet)	24.67	24.84	23.82
		5 Day (dry)	32.75	33.06	31.27
COL 11	-	0 Day (wet)	50.56	49.14	50.47
		0 Day (dry)	102.27	96.60	101.92
		5 Day (wet)	28.22	28.81	29.36
		5 Day (dry)	39.30	40.48	41.56

The analysis of these results for waste from Green Valley landfill/Columns and King George landfill are displayed in table 3.8 a) and 3.8 b) respectively. The moisture retained in a sample after the 5 day test duration, with 40 lbs static load is the laboratory derived field capacity. The field capacity was found to be independent of the waste moisture content at the start of the test as seen from the regression coefficient r^2 values. Only in the case of column 4 waste, r^2 value being 0.99 suggests dependency of the field capacity on the initial moisture of the waste. The T-test numerical value of 0.0442 (5 day moisture wet basis) for column 4 waste implies, that the populations of initial and final moistures are different i.e. moisture content of sample after testing is significantly different than that before. Hence it is implied that drainage has occurred in the sample. This implies that the chosen test is impartial to the waste moisture at the start of the test i.e. the test squeezes out water from the waste in a manner independent of the moisture present at start.

This t-test form used here assumes that the variances of both ranges of data are unequal; it is referred to as a heteroscedastic t-test. The T-test determines whether two sample means are equal, i.e. it is the probability of samples coming from populations of equal mean. The results show very low T-test values suggesting significantly different numerical value of waste moisture after drainage, and along with low r^2 values indicate waste drainage behavior. The F-test was used to compare variances in the moistures content before and after drainage. The F-test is a one tailed probability that variances in 2 different arrays are not significantly different. The F-test fails, indicating that the variances are significantly different, which implies independency of final moisture on the initial moisture.

Table 3.8 a) Analysis of field capacity data for Green Valley Landfill and Column samples.

Sample #	Location	Depth(ft)	Duration	Mean	Std Dev	t test	r2	Ftest	CI	LCL	UCL
16	TB 1	70-100	0 Day (wet)	47.23	1.55	-	-	-	1.75	45.48	48.99
			0 Day (dry)	89.62	5.60	-	-	-	6.33	83.29	95.96
			5 Day (wet)	25.96	0.35	0.00112	0.3840	0.0982	0.40	25.56	26.36
			5 Day (dry)	35.06	0.64	0.00316	0.4005	0.0257	0.72	34.34	35.79
17	TB 1	100-145	0 Day (wet)	46.80	2.14	-	-	-	2.43	44.38	49.23
			0 Day (dry)	88.19	7.57	-	-	-	8.57	79.62	96.76
			5 Day (wet)	33.50	0.85	0.00378	0.0846	0.2692	0.96	32.54	34.45
			5 Day (dry)	50.39	1.92	0.00961	0.0967	0.1203	2.17	48.22	52.56
18	COL 1	-	0 Day (wet)	50.84	0.87	-	-	-	0.98	49.86	51.82
			0 Day (dry)	103.45	3.55	-	-	-	4.02	99.43	107.48
			5 Day (wet)	28.04	0.59	0.00001	0.5590	0.6271	0.66	27.37	28.70
			5 Day (dry)	38.96	1.13	0.00038	0.5569	0.1835	1.28	37.68	40.24
19	COL 2	-	0 Day (wet)	50.39	3.23	-	-	-	3.66	46.73	54.04
			0 Day (dry)	102.11	12.77	-	-	-	14.45	87.66	116.57
			5 Day (wet)	25.90	0.28	0.00547	0.2741	0.0153	0.32	25.58	26.22
			5 Day (dry)	34.96	0.53	0.01174	0.2980	0.0034	0.59	34.37	35.55
20	COL 4	-	0 Day (wet)	46.67	3.64	-	-	-	4.11	42.56	50.78
			0 Day (dry)	87.84	12.74	-	-	-	14.42	73.42	102.26
			5 Day (wet)	24.44	0.55	0.00772	0.9911	0.0442	0.62	23.82	25.06
			5 Day (dry)	32.36	0.96	0.01670	0.9907	0.0112	1.08	31.28	33.44
21	COL 11	-	0 Day (wet)	50.06	0.80	-	-	-	0.90	49.16	50.96
			0 Day (dry)	100.26	3.18	-	-	-	3.60	96.67	103.86
			5 Day (wet)	28.80	0.57	0.00001	0.0059	0.6791	0.65	28.15	29.44
			5 Day (dry)	40.45	1.13	0.00028	0.0065	0.2247	1.28	39.17	41.73

Table 3.8 b) Analysis of field capacity data for King George Landfill

Sample #	Location	Depth(ft)	Duration	Mean	Std Dev	t test	r2	Ftest	CI	LCL	UCL
1	BH 1	0-15	0 Day (wet)	44.70	1.60	-	-	-	1.40	43.30	46.11
			0 Day (dry)	81.04	5.10	-	-	-	4.47	76.57	85.51
			5 Day (wet)	27.91	0.82	0.00000	0.4678	0.2253	0.72	27.19	28.63
			5 Day (dry)	39.10	1.55	0.00002	0.7947	0.0405	1.36	37.74	40.46
2	BH 1	15-30	0 Day (wet)	42.39	3.43	-	-	-	3.01	39.38	45.40
			0 Day (dry)	74.16	10.53	-	-	-	9.23	64.93	83.40
			5 Day (wet)	29.43	0.53	0.00092	0.3291	0.0033	0.47	28.96	29.90
			5 Day (dry)	41.72	1.05	0.00220	0.3219	0.0006	0.92	40.79	42.64
3	BH 1	30-45	0 Day (wet)	44.08	2.92	-	-	-	2.56	41.52	46.63
			0 Day (dry)	79.47	9.28	-	-	-	8.13	71.33	87.60
			5 Day (wet)	34.99	0.37	0.00205	0.2828	0.0015	0.33	34.67	35.32
			5 Day (dry)	53.91	0.91	0.00337	0.2777	0.0005	0.80	53.11	54.71
4	BH 1	45-60	0 Day (wet)	41.52	3.42	-	-	-	3.00	38.52	44.51
			0 Day (dry)	71.84	9.96	-	-	-	8.73	63.12	80.57
			5 Day (wet)	32.42	0.50	0.00365	0.0291	0.0026	0.44	31.98	32.86
			5 Day (dry)	48.01	1.08	0.00562	0.0412	0.0008	0.95	47.06	48.96
5	BH 1	60-75	0 Day (wet)	42.08	2.26	-	-	-	1.98	40.10	44.07
			0 Day (dry)	72.99	6.79	-	-	-	5.95	67.04	78.94
			5 Day (wet)	33.57	0.42	0.00086	0.5608	0.0068	0.37	33.20	33.94
			5 Day (dry)	50.57	0.93	0.00161	0.5215	0.0020	0.81	49.76	51.39
6	BH 2	0-15	0 Day (wet)	44.74	2.37	-	-	-	1.89	42.85	46.64
			0 Day (dry)	81.10	8.02	-	-	-	6.41	74.68	87.51
			5 Day (wet)	27.88	1.16	0.00000	0.0621	0.1415	0.92	26.95	28.80
			5 Day (dry)	38.93	2.48	0.00002	0.0776	0.0222	1.98	36.95	40.91
7	BH 2	15-30	0 Day (wet)	39.98	6.19	-	-	-	4.95	35.03	44.92
			0 Day (dry)	76.81	7.65	-	-	-	6.12	70.69	82.93
			5 Day (wet)	31.05	8.08	0.05903	0.9732	0.5724	6.46	24.59	37.51
			5 Day (dry)	38.16	1.16	0.00005	0.1496	0.0008	0.93	37.23	39.09
8	BH 2	30-45	0 Day (wet)	39.51	7.21	-	-	-	5.77	33.74	45.28
			0 Day (dry)	74.78	10.13	-	-	-	8.11	66.68	82.89
			5 Day (wet)	29.34	7.61	0.03892	0.7353	0.9087	6.09	23.24	35.43
			5 Day (dry)	34.46	1.05	0.00018	0.5194	0.0001	0.84	33.62	35.30
9	BH 2	45-60	0 Day (wet)	44.45	3.51	-	-	-	2.81	41.64	47.26
			0 Day (dry)	80.83	11.20	-	-	-	8.96	71.87	89.79
			5 Day (wet)	28.07	0.90	0.00005	0.1155	0.0094	0.72	27.36	28.79
			5 Day (dry)	39.07	1.76	0.00022	0.1293	0.0010	1.41	37.66	40.47
10	BH 2	60-75	0 Day (wet)	48.88	12.20	-	-	-	9.76	39.11	58.64
			0 Day (dry)	112.56	79.02	-	-	-	63.23	49.34	175.79
			5 Day (wet)	28.75	0.51	0.00988	0.3259	0.0000	0.41	28.34	29.16
			5 Day (dry)	40.39	1.02	0.07546	0.4132	0.0000	0.82	39.57	41.20
11	BH 3	0-15	0 Day (wet)	42.91	2.51	-	-	-	2.01	40.90	44.92
			0 Day (dry)	76.58	8.07	-	-	-	6.46	70.12	83.04
			5 Day (wet)	30.46	0.43	0.00005	0.2201	0.0015	0.35	30.11	30.80
			5 Day (dry)	43.78	0.87	0.00016	0.1372	0.0002	0.70	43.08	44.48
12	BH 3	15-30	0 Day (wet)	42.23	3.82	-	-	-	3.05	39.17	45.28
			0 Day (dry)	74.01	12.31	-	-	-	9.85	64.15	83.86
			5 Day (wet)	27.99	0.47	0.00023	0.0057	0.0003	0.37	27.62	28.36
			5 Day (dry)	38.88	0.90	0.00089	0.0074	0.0000	0.72	38.15	39.60
13	BH 3	30-45	0 Day (wet)	40.96	5.39	-	-	-	4.31	36.65	45.27
			0 Day (dry)	70.64	15.58	-	-	-	12.47	58.17	83.11
			5 Day (wet)	28.10	0.70	0.00192	0.0007	0.0004	0.56	27.53	28.66
			5 Day (dry)	39.11	1.33	0.00416	0.0113	0.0000	1.06	38.04	40.17
14	BH 3	45-60	0 Day (wet)	44.70	5.30	-	-	-	4.24	40.46	48.94
			0 Day (dry)	90.91	27.32	-	-	-	21.86	69.05	112.78
			5 Day (wet)	28.74	0.48	0.00068	0.0016	0.0001	0.38	28.36	29.12
			5 Day (dry)	41.98	2.41	0.00697	0.3013	0.0001	1.93	40.06	43.91
15	BH 3	60-75	0 Day (wet)	42.16	3.41	-	-	-	2.73	39.43	44.88
			0 Day (dry)	80.35	18.48	-	-	-	14.78	65.57	95.14
			5 Day (wet)	26.89	0.54	0.00009	0.1073	0.0010	0.43	26.46	27.32
			5 Day (dry)	38.27	2.80	0.00233	0.5055	0.0008	2.24	36.03	40.52

Furthermore, it is observed that the standard deviation of field capacity is much lower than that of the initial moisture of waste. Also the confidence interval (CI) for final moisture is less in range than that for initial moisture, which suggests reproducibility of method to yield the same moisture retention value for repeated runs with different initial moistures. Confidence limits based on a significance level of 95 % are displayed in Tables 3.8 a) and 3.8 b), CI is the confidence interval and UCL and LCL are the upper and lower confidence limits respectively. All the data is valid at 5 % significance level and the error bars for field capacity are plotted in Figure 3.6.

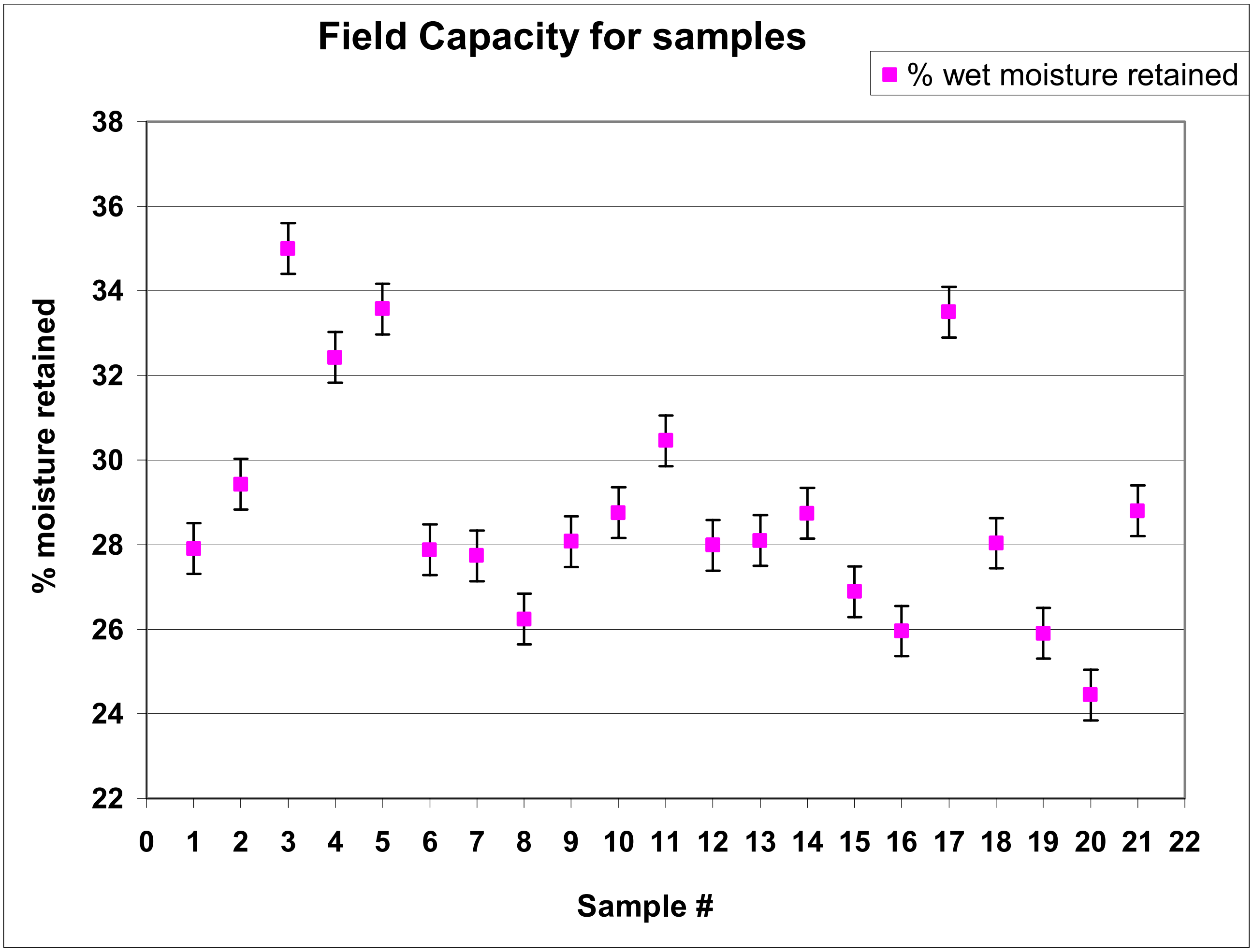

Figure 3.6 Y bar errors for the field capacity ($\alpha = 0.05$)

Note: Samples numbered according to Tables 3.8 a & 3.8 b

Figure 3.7 a) and b) display correlation of cellulose and Volatile Solids with the field capacity, respectively. The cellulose in MSW is thought to be responsible for the major part of its moisture retention potential. The water retention of refuse should vary with its cellulose content and inversely with its stability. As expected the water retention potential correlates very well with cellulose content of the waste. Thus this method is useful in estimating field capacity potential for refuse. This is useful in design of leachate systems and also in estimating the moisture required to support enhanced biodegradation.

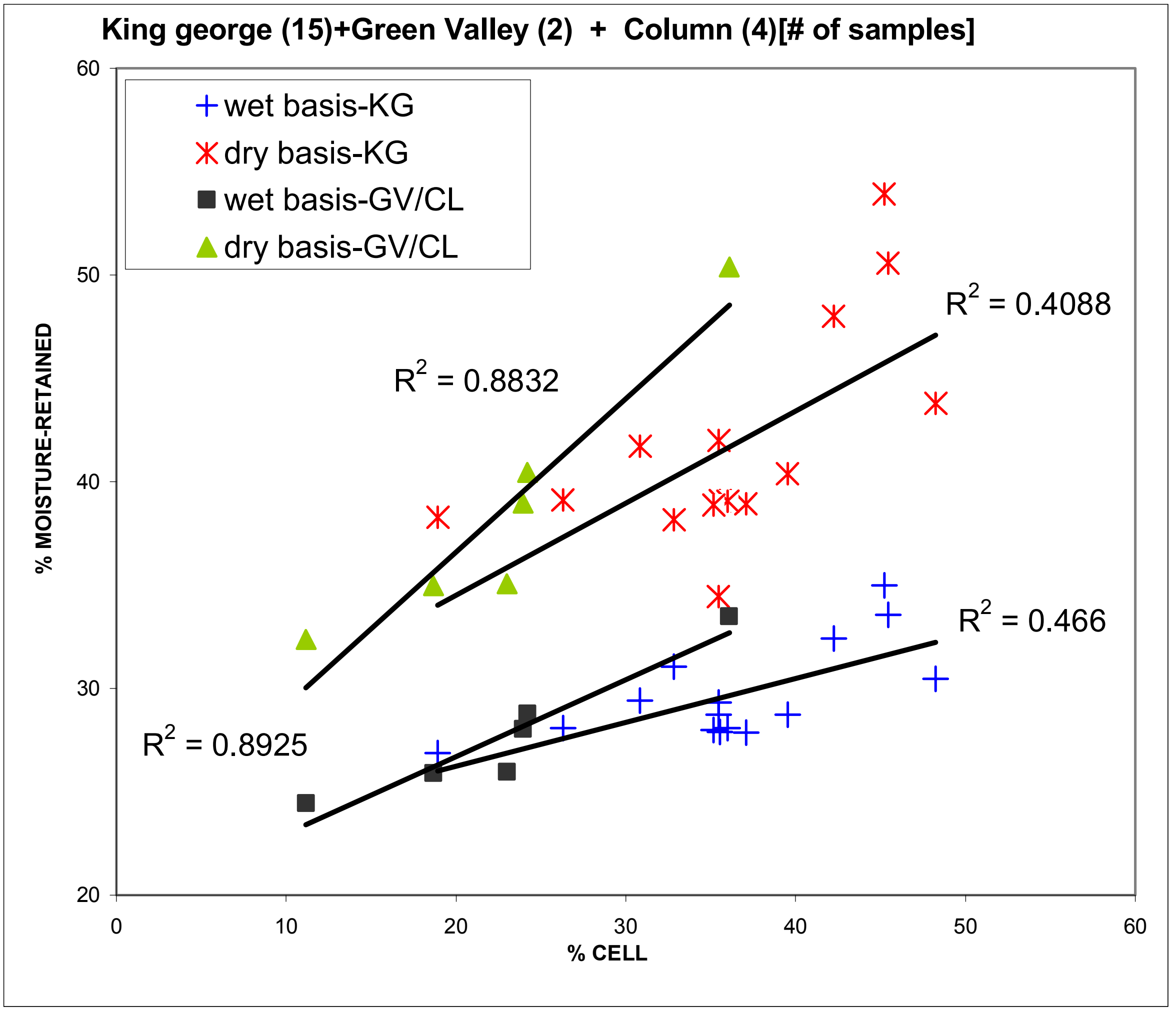

Figure 3.7 a) - Static load 40 lbs., 5 day

Cellulose correlation with laboratory field capacity.

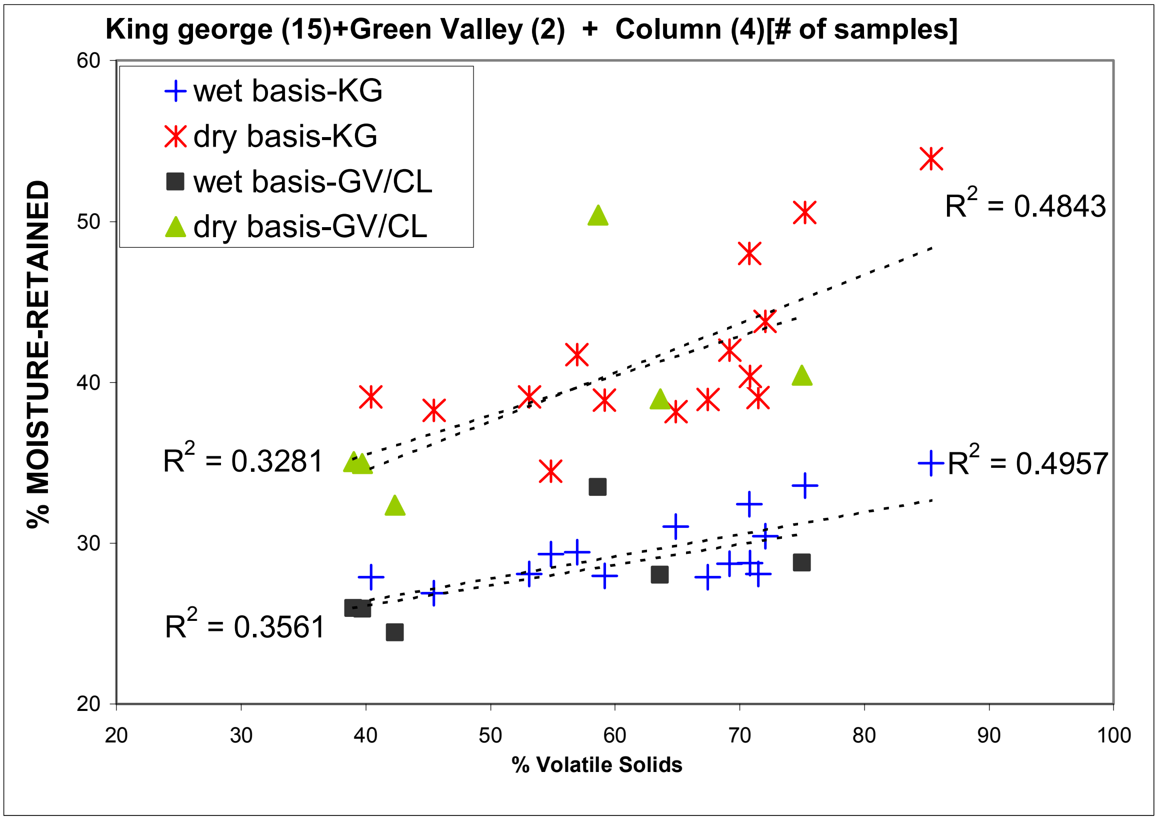

Figure 3.7 b) - Static load 40 lbs. Volatile solids correlation with field capacity. KG- King George landfill, GV – Green Valley landfill & column samples

Settlement Models:

The settlement in terms of percentage strain in the laboratory experiments is displayed in Table A.1 in appendix. The models are named M1 through M4 as below:-

M1 :-Yen and Scalon or logarithmic model.

M2 :- Rheological model of Gibson and Lo, modified by Edil.

M3 :- Power creep law applied by Edil.

M4 :- Hyperbolic function model.

The results predicted by Yen and Scalon model (Model M1) are of an order higher than actual data and hence predicted numerical values are not displayed. The model M1 is entirely empirical and uses the observed data to best-fit two strain rate parameters. In this study it is found that this model deviates significantly from observed data, which can be attributed to a lack of fit in absence of any physics for the model prediction.

The results of model predictions are displayed in Tables A.2 for Gibson and Lo (Model M2), Table A.3 for power Creep (Model M3), and Table A.4 for Hyperbolic function (Model M4). The individual models i.e. M1, M2, M3 and M4 are compared statistically with the laboratory result and the result displayed in Table A.5. The rheological model has a sound physical interpretation of consolidation terms i.e. consists of primary and secondary consolidation terms but the model deviates significantly from observed data. This is due to the fact that the model predicts the primary consolidation based on the time at which a change in settling rate occurs i.e. a mathematically undefined time based on visual observation of the strain rate. Moreover both primary and secondary consolidation are a simultaneous phenomenon and hence render the model inaccurate. It is observed that both M3 and M4 are comparable and fairly accurate for predicting the laboratory test as seen from the r2 and CORREL i.e. correlation coefficient. However, the probability that the model predicted numerical value being the same as that of the observed value as derived from the T-test indicate that model M3 predicts values more accurately than that by model M4. Similarly the variances in strain predicted by model M3 are less significantly different than those predicted by model M4 (with the actual strain). Hence, Model M3 i.e. the power creep law best predicts this laboratory scale settlement as per statistical analysis.

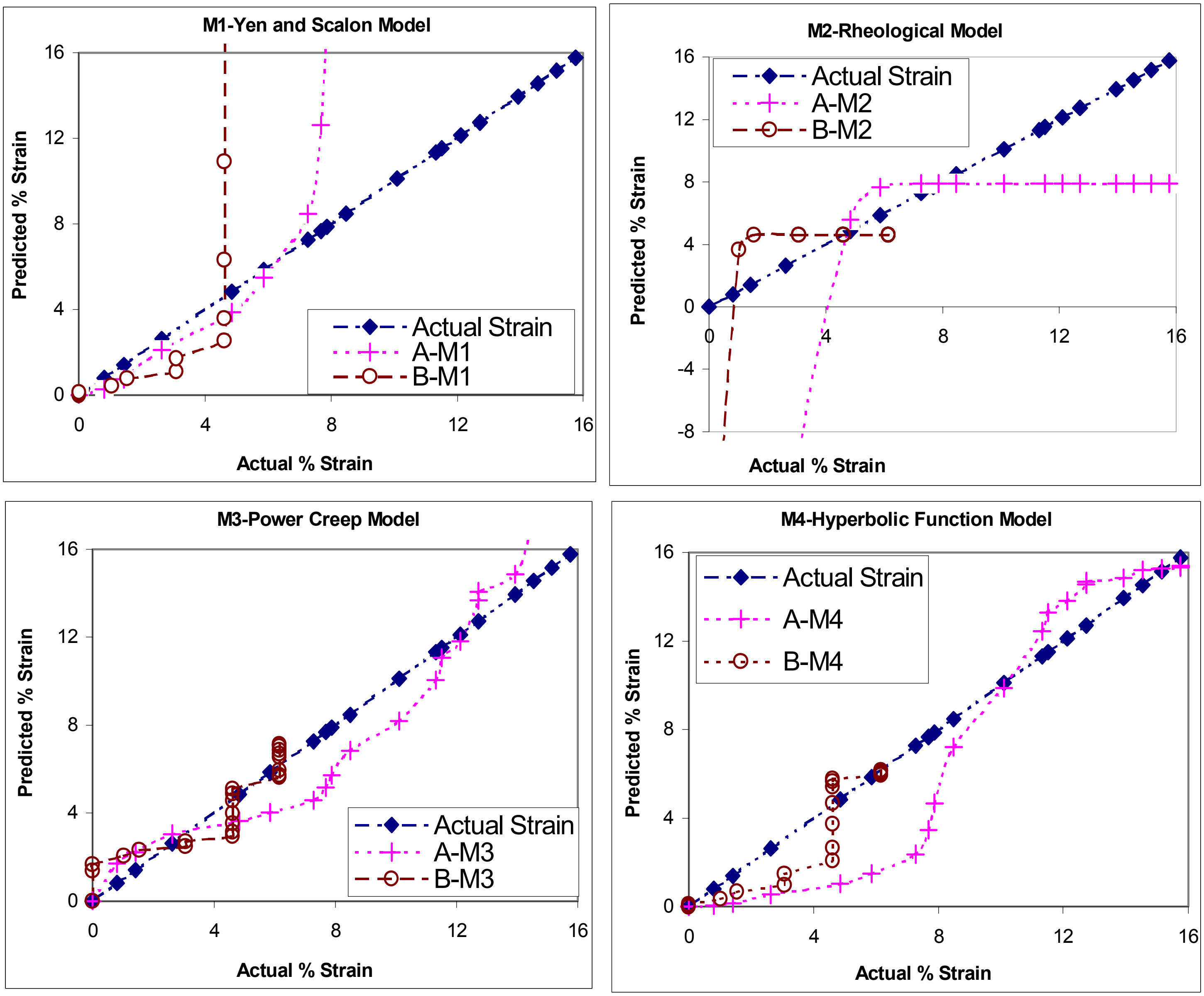

Figure 3-8 Predicted vs. actual strain by models

'A' is King George landfill sample BH3, 3-15 - chosen to display as it was found to incur the maximum strain.

'B' is Green Valley landfill sample, TB1, 70-100 chosen to display as it was found to incur the minimum strain.

Figure 3.8 displays actual and model predicted strains in the two samples, sample 'A'-King George landfill sample BH3 3-15 chosen as it incurred the maximum strain and 'B'-Green Valley landfill sample TB1 70-100 chosen as it incurred the minimum strain. Figure 3-8 shows that the Yen and Scalon model (M1) grossly overestimates the strain in the refuse, it appears that this empirical fit is not appropriate for this method. The Rheological model predicts negative strain at early times, which is absurd, moreover it shows a poor overall fit to the data. The logarithmic power creep law model (M3) and hyperbolic function model (M4) predict strains, which are of the magnitude of the actual ones. The logarithmic model (M3) overestimates the ultimate strain and has been found to be useful to predict strain associated with waste decomposition (Lee et al. 1999). This limits usage of the best fit model for this study and renders it useful only to data for which strain is actually measured i.e. that makes the model unreliable for prediction. The Hyperbolic model (M4) seems to override this limitation and closely approximates the ultimate strain in the samples. However the hyperbolic model is seen to underestimate the strain at short durations of time. For short duration of times i.e. where primary consolidation is seen to govern the strain in the samples observed from the change in strain rate from Figure 3.8 it is seen that model M1 yield fairly accurate estimates. The power creep model (M3) and the Hyperbolic function model (M4) were compared. It is observed from Figure A.1 in the appendix A, that the hyperbolic model is a better fit for all samples using the complete data i.e. settlement values for complete test duration of 5 days. To test the response of the models the models were recalculated using data up to first nine time points, i.e. up to end of estimated primary consolidation of 120 minutes. The results presented in Figure A.2 in the Appendix A confirm that the hyperbolic function is the best model, even using partial data. The field capacity data for a random refuse sample can be extrapolated from the known data using this method for refuse at similar stability i.e. having similar cellulose and volatile content. Prediction of settlement in the field presents a two fold aspect of final strain value and the variation of strain rate with time. The latter is site specific whereas the former can be estimated from this methodology. The method data can be compared with actual field strain data and results correlated with regards to waste stability and overburden pressure for both cases. The actual extrapolation cannot be made with a known degree of confidence as of now, but knowing the relative strain amongst samples for field and laboratory conditions rapid estimates for actual in-situ strain can be made from the laboratory data.

CONCLUSIONS:

A laboratory scale experiment to evaluate MSW characteristics has been developed. It is found that the method yields waste compression and drainage in a pattern that is reproducible and accurate. Field capacity derived from this method correlates well with waste physiochemical characteristics particularly with Cellulose content.

The settlement of waste observed in this method yields a rapid assessment to MSW compaction potential in the field and requires further study to interpolate laboratory data to field scale. Theoretical MSW settlement models can be used to verify and validate refuse settlement by this method to obtain a rapid assessment of waste compression particularly primary compression and the potential for secondary compression. The primary consolidation in the waste samples is best fit by the empirical Yen and Scalon model, however laboratory strain rates cannot be extrapolated to field values with current knowledge of MSW properties. The hyperbolic model best predicts the ultimate settlement obtained by this method and as such is useful to estimate ultimate strain in the field. Study to correlate the laboratory scale field capacity and settlement with various in situ wastes can be undertaken to yield an in sight to the applicability of this rapid assessment with a view for field estimates for refuse at various stages of decomposition.

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APPENDIX A

Table A.1 Actual % strain in waste samples Column headings are values of Time-t in Minutes

Location	Depth (ft)	0	0.5	1.5	5	10	15	25	40	60	120	240	540	780	1020	1800	2010	2490	4320	5040	5760	6480	7200
BH 1	3-15	0.00	0.60	1.49	2.09	2.69	3.28	3.28	3.28	3.28	4.18	5.07	5.07	5.97	6.27	6.57	7.16	8.06	8.96	9.55	9.85	9.85	9.85
BH 1	15-30	0.00	1.69	3.39	4.24	5.51	6.36	6.36	7.20	7.20	7.20	8.05	8.47	9.75	10.59	11.02	11.86	11.86	13.14	13.98	13.98	13.98	13.98
BH 1	30-45	0.00	1.06	2.13	2.13	3.90	4.26	5.32	5.32	6.38	6.38	7.45	8.51	9.57	9.57	10.64	10.64	10.64	12.77	13.83	13.83	13.83	13.83
BH 1	45-60	0.00	0.35	1.40	1.75	3.50	3.50	4.55	5.59	5.59	5.59	5.59	6.64	7.69	7.69	8.74	8.74	9.79	10.84	11.54	11.54	11.54	11.54
BH 1	60-75	0.00	1.59	2.38	3.17	5.56	5.56	6.35	6.35	6.35	7.14	7.94	9.52	9.52	10.32	11.11	11.11	11.11	11.90	12.70	12.70	12.70	12.70
BH 2	3-15	0.00	0.82	1.64	2.74	3.01	3.56	3.84	3.84	3.84	3.84	4.66	4.93	5.48	6.30	6.30	6.58	7.12	7.67	7.67	7.67	7.67	7.67
BH 2	15-30	0.00	0.53	1.32	2.37	3.17	4.22	5.01	5.54	6.07	6.60	6.60	7.39	7.39	8.18	8.18	8.44	8.44	9.23	9.23	9.23	9.23	9.23
BH 2	30-45	0.00	0.39	1.56	3.13	4.30	4.30	5.08	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	7.42	7.81	7.81	7.81	7.81	7.81
BH 2	45-60	0.00	0.65	1.51	2.58	3.87	4.52	5.38	6.67	7.74	8.60	9.46	9.68	10.54	10.75	10.75	10.75	11.18	11.83	12.26	12.47	12.47	12.47
BH 2	60-75	0.00	0.44	0.88	1.77	2.87	4.19	5.30	5.74	6.62	7.06	7.73	8.17	8.61	8.83	9.05	9.05	9.05	9.27	9.27	9.27	9.27	9.27
BH 3	3-15	0.00	0.81	1.41	2.63	4.85	5.86	7.27	7.68	7.88	8.48	10.10	11.31	11.52	12.12	12.73	12.73	13.94	14.55	15.15	15.76	15.76	15.76
BH 3	15-30	0.00	1.17	1.88	2.82	3.99	4.69	5.87	6.57	6.57	6.81	7.75	9.15	9.86	10.09	10.80	10.80	11.27	12.44	13.15	13.85	13.85	13.85
BH 3	30-45	0.00	1.06	1.85	2.64	4.22	5.01	5.80	6.33	6.60	7.39	8.18	9.50	9.76	10.55	11.35	11.35	11.35	12.14	12.93	12.93	12.93	12.93
BH 3	45-60	0.00	1.15	2.58	4.01	4.87	6.59	7.45	8.02	8.02	8.31	9.17	10.60	11.46	11.46	12.32	12.32	12.32	13.18	13.75	13.75	13.75	13.75
BH 3	60-75	0.00	0.83	1.93	3.58	5.51	6.06	6.89	6.89	7.44	8.26	9.09	11.29	12.12	12.40	12.40	12.40	12.40	13.22	14.05	14.05	14.05	14.05
TB 1	70-100	0.00	0.00	0.00	1.03	1.54	3.08	3.08	4.62	4.62	4.62	4.62	4.62	4.62	4.62	6.15	6.15	6.15	6.15	6.15	6.15	6.15	6.15
TB 1	100-145	0.00	1.29	2.59	4.21	4.85	5.50	6.15	6.80	6.80	7.77	9.39	10.68	11.33	12.30	13.92	14.56	14.56	14.56	14.56	14.56	14.56	14.56
COL 1	-	0.00	0.94	2.19	3.13	3.76	4.70	5.02	5.96	6.58	7.21	7.84	7.84	8.46	8.78	9.72	10.03	10.97	12.23	12.54	12.54	12.54	12.54
COL 2	-	0.00	0.81	1.63	3.66	4.07	4.88	5.28	6.10	6.10	6.10	7.32	7.32	8.54	9.76	10.98	10.98	10.98	10.98	10.98	10.98	10.98	10.98
COL 4	-	0.00	1.27	2.22	3.16	3.48	4.11	5.06	5.06	6.01	6.01	6.96	6.96	7.28	7.91	7.91	7.91	8.23	8.23	8.23	8.23	8.23	8.23
COL 11	-	0.00	0.66	1.64	2.62	3.61	4.59	4.59	4.92	5.57	5.57	6.56	6.56	7.54	7.54	8.52	8.85	9.51	10.49	11.48	11.48	11.48	11.48

Note: Samples are numbered subsequently as from top to bottom of this table as 1 through 21 respectively.

Table A.2 % strain predicted by Gibson and Lo model modified by Edil.

Sample #	0	0.5	1.5	5	10	15	25	40	60	120	240	540	780	1020	1800	2010	2490	4320	5040	5760	6480	7200
1	-171.91	-127.43	-69.49	-6.08	2.78	3.26	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28	3.28
2	-393.09	-291.47	-159.07	-14.20	6.06	7.14	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20
3	-387.39	-287.42	-157.18	-14.67	5.26	6.32	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38
4	-303.37	-224.93	-122.74	-10.93	4.71	5.55	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59	5.59
5	-481.57	-357.50	-195.86	-18.99	5.75	7.07	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14	7.14
6	-266.03	-187.06	-91.68	-4.63	3.57	3.83	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84	3.84
7	-426.61	-307.60	-158.68	-10.85	5.89	6.57	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60	6.60
8	-906.00	-512.91	-161.89	3.00	6.24	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
9	-389.25	-292.48	-163.96	-16.55	6.26	7.65	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74
10	-411.49	-298.35	-155.62	-11.20	5.86	6.59	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62	6.62
11	-293.33	-228.11	-136.98	-18.37	5.59	7.68	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88
12	-71.23	-19.58	3.62	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57
13	-345.90	-262.76	-150.72	-17.52	4.72	6.22	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33
14	-567.34	-404.26	-203.67	-12.51	7.29	8.00	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02	8.02
15	-410.68	-297.53	-154.81	-10.38	6.68	7.41	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44	7.44
16	-139.00	-82.45	-27.39	3.65	4.61	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62
17	-371.88	-289.07	-173.82	-25.31	4.07	6.57	6.79	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80
18	-298.81	-229.73	-134.91	-16.92	4.77	6.44	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58
19	-448.63	-317.90	-158.40	-9.24	5.58	6.08	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10	6.10
20	-551.10	-371.16	-167.09	-6.09	4.84	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06	5.06
21	-324.83	-236.01	-123.70	-9.38	4.30	4.89	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92

Table A.3 % strain predicted by power creep law

Sample #	0.5	1.5	5	10	15	25	40	60	120	240	540	780	1020	1800	2010	2490	4320	5040	5760	6480	7200
1	1.08	1.41	1.87	2.20	2.42	2.73	3.05	3.35	3.95	4.65	5.63	6.14	6.54	7.47	7.67	8.07	9.19	9.53	9.83	10.11	10.36
2	2.76	3.35	4.14	4.67	5.02	5.49	5.96	6.40	7.23	8.17	9.43	10.06	10.54	11.65	11.88	12.34	13.59	13.97	14.30	14.60	14.87
3	1.63	2.11	2.80	3.29	3.62	4.07	4.55	5.00	5.88	6.91	8.35	9.10	9.69	11.06	11.35	11.93	13.57	14.06	14.51	14.91	15.29
4	1.05	1.41	1.95	2.35	2.62	3.01	3.41	3.81	4.59	5.53	6.88	7.59	8.16	9.51	9.80	10.38	12.04	12.55	13.00	13.42	13.81
5	2.36	2.91	3.65	4.16	4.49	4.94	5.40	5.82	6.64	7.56	8.81	9.44	9.93	11.05	11.29	11.75	13.04	13.42	13.76	14.07	14.35
6	1.47	1.80	2.24	2.55	2.74	3.01	3.29	3.54	4.02	4.57	5.30	5.67	5.95	6.61	6.74	7.01	7.76	7.98	8.18	8.36	8.52
7	1.38	1.77	2.32	2.71	2.97	3.33	3.70	4.05	4.73	5.53	6.63	7.21	7.65	8.69	8.91	9.35	10.58	10.96	11.29	11.59	11.87
8	1.59	1.96	2.46	2.80	3.03	3.33	3.64	3.93	4.48	5.11	5.95	6.38	6.71	7.47	7.63	7.95	8.82	9.08	9.31	9.52	9.71
9	1.54	2.02	2.71	3.22	3.55	4.03	4.52	4.99	5.91	7.01	8.55	9.35	9.99	11.48	11.79	12.43	14.22	14.77	15.26	15.71	16.12
10	1.15	1.53	2.07	2.47	2.74	3.12	3.52	3.90	4.65	5.55	6.82	7.48	8.01	9.26	9.52	10.05	11.57	12.03	12.44	12.82	13.17
11	1.69	2.23	3.04	3.63	4.02	4.58	5.17	5.73	6.84	8.17	10.05	11.04	11.83	13.68	14.07	14.86	17.11	17.79	18.41	18.97	19.49
12	1.83	2.33	3.05	3.56	3.90	4.37	4.85	5.31	6.20	7.24	8.67	9.41	9.99	11.34	11.62	12.19	13.78	14.26	14.70	15.09	15.45
13	1.81	2.32	3.04	3.55	3.88	4.35	4.84	5.30	6.18	7.22	8.66	9.40	9.98	11.34	11.62	12.19	13.79	14.28	14.71	15.10	15.46
14	2.43	3.03	3.85	4.43	4.80	5.32	5.84	6.33	7.27	8.35	9.82	10.57	11.16	12.50	12.78	13.34	14.89	15.35	15.77	16.14	16.49
15	1.99	2.55	3.36	3.93	4.31	4.84	5.38	5.91	6.91	8.09	9.73	10.58	11.25	12.80	13.13	13.78	15.62	16.18	16.68	17.13	17.55
16	1.38	1.67	2.05	2.31	2.48	2.70	2.93	3.14	3.54	3.99	4.58	4.88	5.11	5.63	5.74	5.96	6.55	6.72	6.88	7.02	7.15
17	2.24	2.84	3.68	4.27	4.66	5.21	5.76	6.29	7.30	8.47	10.09	10.92	11.57	13.08	13.39	14.02	15.79	16.32	16.80	17.23	17.62
18	0.42	0.59	0.85	1.04	1.18	1.38	1.59	1.80	2.22	2.75	3.51	3.93	4.26	5.07	5.24	5.59	6.61	6.93	7.22	7.48	7.73
19	1.74	2.21	2.86	3.32	3.62	4.04	4.47	4.88	5.66	6.57	7.82	8.47	8.97	10.14	10.38	10.87	12.24	12.65	13.02	13.35	13.66
20	2.13	2.54	3.08	3.44	3.67	3.98	4.29	4.58	5.12	5.72	6.51	6.91	7.21	7.90	8.04	8.32	9.09	9.32	9.52	9.70	9.86
21	1.43	1.84	2.43	2.85	3.12	3.51	3.91	4.29	5.02	5.89	7.09	7.71	8.20	9.33	9.57	10.05	11.40	11.81	12.18	12.51	12.82

Table A.4 % Strain predicted by Hyperbolic function

Sample #	0	0.5	1.5	5	10	15	25	40	60	120	240	540	780	1020	1800	2010	2490	4320	5040	5760	6480	7200
1	0.00	0.02	0.06	0.19	0.37	0.55	0.88	1.34	1.88	3.16	4.79	6.72	7.46	7.92	8.67	8.79	8.99	9.36	9.43	9.49	9.53	9.57
2	0.00	0.04	0.13	0.43	0.84	1.22	1.92	2.84	3.87	6.08	8.49	10.89	11.70	12.19	12.94	13.05	13.23	13.58	13.65	13.70	13.74	13.77
3	0.00	0.03	0.10	0.34	0.66	0.96	1.53	2.30	3.18	5.18	7.55	10.12	11.05	11.61	12.50	12.64	12.86	13.29	13.37	13.44	13.49	13.53
4	0.00	0.03	0.08	0.28	0.54	0.79	1.26	1.90	2.63	4.29	6.27	8.44	9.22	9.70	10.46	10.58	10.77	11.13	11.20	11.26	11.30	11.34
5	0.00	0.06	0.16	0.53	1.02	1.47	2.28	3.29	4.38	6.51	8.62	10.51	11.11	11.45	11.98	12.05	12.18	12.41	12.45	12.49	12.52	12.54
6	0.00	0.03	0.09	0.29	0.56	0.81	1.26	1.84	2.47	3.75	5.06	6.27	6.67	6.90	7.25	7.30	7.38	7.54	7.57	7.60	7.61	7.63
7	0.00	0.06	0.17	0.55	1.04	1.48	2.23	3.11	4.00	5.59	6.98	8.10	8.44	8.62	8.90	8.94	9.01	9.13	9.15	9.17	9.18	9.19
8	0.00	0.04	0.12	0.38	0.72	1.04	1.59	2.27	2.97	4.31	5.57	6.64	6.98	7.17	7.45	7.49	7.56	7.68	7.71	7.73	7.74	7.75
9	0.00	0.07	0.20	0.63	1.20	1.72	2.62	3.73	4.86	7.00	8.96	10.62	11.12	11.41	11.84	11.91	12.01	12.20	12.23	12.26	12.28	12.30
10	0.00	0.13	0.37	1.13	2.02	2.73	3.81	4.89	5.81	7.16	8.10	8.73	8.90	9.00	9.13	9.15	9.18	9.24	9.25	9.26	9.26	9.27
11	0.00	0.06	0.17	0.54	1.04	1.51	2.36	3.47	4.68	7.22	9.89	12.46	13.31	13.81	14.58	14.69	14.88	15.22	15.29	15.34	15.39	15.42
12	0.00	0.04	0.12	0.38	0.74	1.09	1.72	2.56	3.51	5.60	7.96	10.40	11.24	11.75	12.55	12.66	12.86	13.23	13.31	13.36	13.41	13.44
13	0.00	0.06	0.17	0.54	1.04	1.49	2.31	3.34	4.44	6.62	8.76	10.69	11.30	11.66	12.19	12.27	12.40	12.64	12.69	12.72	12.75	12.77
14	0.00	0.07	0.22	0.71	1.36	1.94	2.96	4.19	5.46	7.82	9.99	11.80	12.35	12.66	13.13	13.20	13.31	13.51	13.55	13.58	13.61	13.63
15	0.00	0.08	0.22	0.72	1.37	1.96	2.99	4.24	5.53	7.93	10.14	12.00	12.57	12.89	13.38	13.44	13.56	13.77	13.81	13.84	13.87	13.89
16	0.00	0.04	0.11	0.37	0.69	0.98	1.48	2.08	2.67	3.74	4.67	5.43	5.65	5.78	5.97	5.99	6.04	6.12	6.13	6.15	6.16	6.16
17	0.00	0.10	0.28	0.90	1.70	2.41	3.62	5.04	6.46	8.98	11.16	12.90	13.42	13.70	14.13	14.19	14.30	14.48	14.52	14.54	14.56	14.58
18	0.00	0.04	0.11	0.37	0.71	1.04	1.64	2.44	3.34	5.29	7.46	9.67	10.43	10.89	11.60	11.70	11.88	12.20	12.27	12.32	12.36	12.39
19	0.00	0.08	0.24	0.75	1.41	1.99	2.96	4.08	5.17	7.06	8.63	9.85	10.20	10.40	10.69	10.73	10.80	10.93	10.95	10.97	10.98	10.99
20	0.00	0.11	0.32	0.98	1.76	2.39	3.33	4.30	5.12	6.32	7.16	7.74	7.89	7.98	8.10	8.12	8.15	8.20	8.21	8.22	8.22	8.23
21	0.00	0.03	0.08	0.28	0.54	0.79	1.26	1.89	2.62	4.27	6.23	8.38	9.15	9.62	10.37	10.48	10.67	11.03	11.10	11.15	11.20	11.23

Table A.5 Statistical analysis of model results

t-test				r2				F-test				CORREL			
M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4	M1	M2	M3	M4
0.0032	0.0902	0.9677	0.7515	0.8088	0.2635	0.9842	0.8982	5.66E-38	4.18E-16	0.7836	0.2024	0.8993	0.5133	0.9921	0.9477
0.0031	0.1309	0.9813	0.4949	0.7254	0.3481	0.9744	0.8803	2.07E-43	3.42E-21	0.7381	0.0757	0.8517	0.5900	0.9871	0.9383
0.0032	0.1310	0.9539	0.7046	0.7391	0.2870	0.9780	0.9173	1.27E-38	3.92E-20	0.6382	0.2017	0.8597	0.5357	0.9889	0.9578
0.0005	0.1343	0.9042	0.7075	0.8799	0.3260	0.9527	0.8799	6.04E-24	1.85E-19	0.3506	0.2202	0.9380	0.5709	0.9761	0.9380
0.0003	0.1420	0.9664	0.5364	0.8259	0.3750	0.9592	0.9214	5.44E-31	2.14E-23	0.5830	0.1221	0.9088	0.6124	0.9794	0.9599
0.0003	0.1395	0.9748	0.5308	0.8683	0.3568	0.9654	0.8859	4.74E-31	4.84E-22	0.6456	0.1014	0.9318	0.5973	0.9825	0.9412
0.0004	0.1694	0.9386	0.5516	0.6984	0.4480	0.8647	0.9234	1.89E-27	2.91E-24	0.2490	0.2194	0.8357	0.6693	0.9299	0.9609
0.0004	0.2199	0.9686	0.2366	0.5501	0.5352	0.7397	0.7257	2.29E-30	1.31E-30	0.2052	0.0687	0.7417	0.7316	0.8600	0.8519
0.0004	0.1457	0.9173	0.6051	0.7088	0.4135	0.8662	0.9486	7.24E-26	4.31E-21	0.2565	0.2829	0.8419	0.6431	0.9307	0.9740
0.0005	0.1634	0.9273	0.8044	0.5978	0.4454	0.7670	0.9820	4.30E-25	3.24E-23	0.1703	0.6041	0.7732	0.6674	0.8758	0.9910
0.0005	0.1102	0.9085	0.6433	0.8041	0.4017	0.9235	0.9187	4.35E-25	2.77E-17	0.2871	0.2287	0.8967	0.6338	0.9610	0.9585
0.0004	0.0402	0.9459	0.6302	0.8623	0.2047	0.9686	0.9165	7.30E-28	1.33E-01	0.5495	0.1675	0.9286	0.4525	0.9842	0.9573
0.0004	0.1191	0.9359	0.6418	0.8134	0.3731	0.9448	0.9426	8.81E-28	4.24E-20	0.4366	0.2125	0.9019	0.6108	0.9720	0.9709
0.0004	0.1516	0.9549	0.5237	0.7601	0.4184	0.9202	0.9210	1.31E-29	1.62E-23	0.3903	0.1476	0.8719	0.6469	0.9593	0.9597
0.0004	0.1334	0.9283	0.6043	0.7581	0.4089	0.9077	0.9407	3.01E-27	2.49E-20	0.3096	0.2247	0.8707	0.6395	0.9527	0.9699
0.0011	0.2303	0.8704	0.5964	0.6098	0.3870	0.8077	0.8421	1.52E-18	3.67E-15	0.7473	0.4808	0.7809	0.6221	0.8987	0.9177
0.0004	0.1052	0.9489	0.7791	0.8276	0.3519	0.9458	0.9421	1.77E-28	1.25E-19	0.5575	0.3142	0.9097	0.5932	0.9725	0.9706
0.0004	0.1251	0.0001	0.5969	0.8640	0.3566	0.9381	0.8973	2.63E-28	1.44E-19	0.1076	0.1453	0.9295	0.5972	0.9685	0.9473
0.0004	0.1475	0.9481	0.7063	0.7847	0.3858	0.9133	0.9084	3.48E-28	9.97E-23	0.4114	0.2794	0.8859	0.6211	0.9557	0.9531
0.0003	0.1650	0.9885	0.5707	0.6590	0.4306	0.8822	0.9699	1.81E-33	2.01E-27	0.5189	0.1838	0.8118	0.6562	0.9392	0.9848
0.0004	0.1260	0.9418	0.6273	0.8874	0.3325	0.9668	0.8783	6.36E-27	2.82E-20	0.5162	0.1495	0.9420	0.5766	0.9833	0.9372

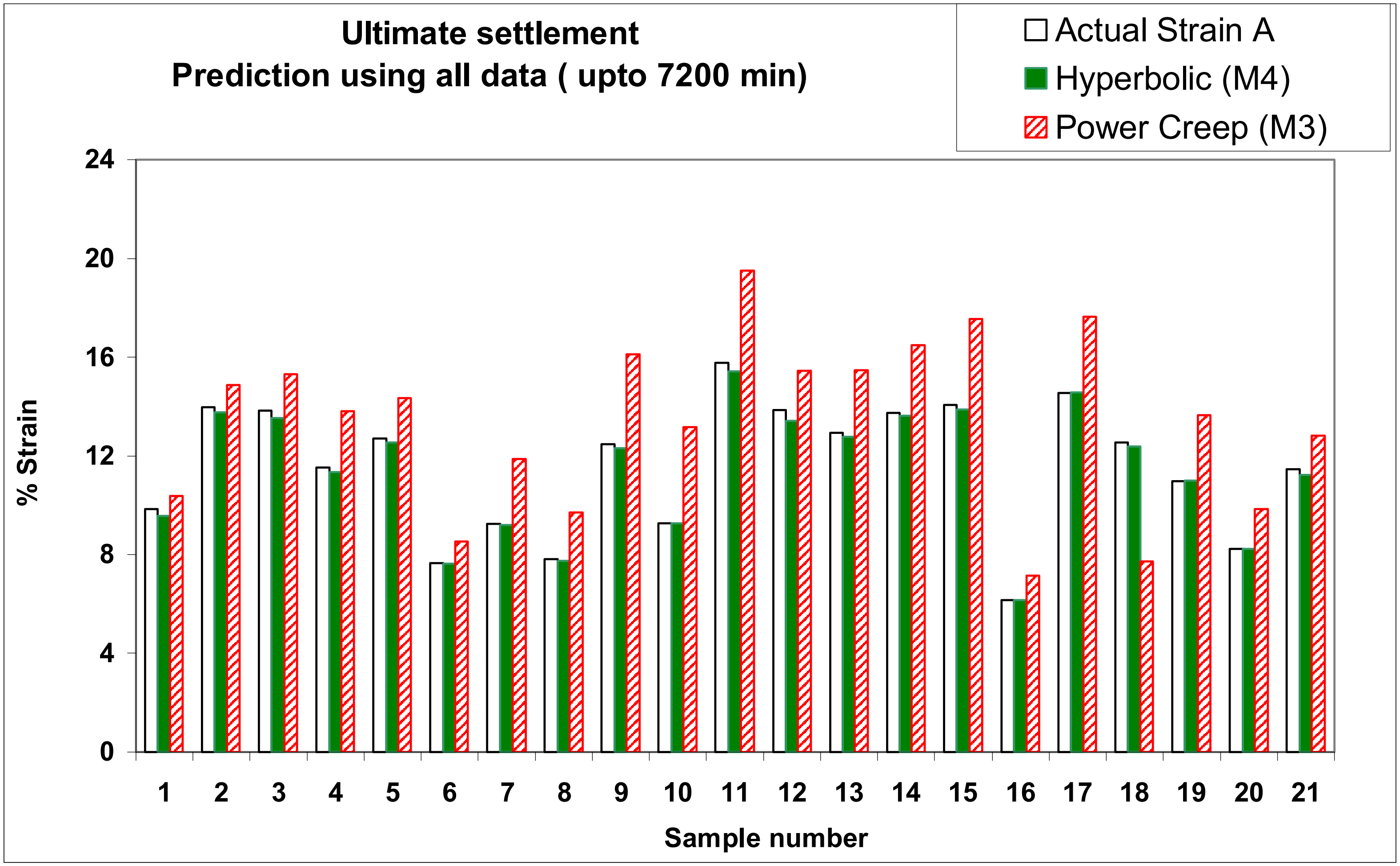

Figure A.1 Predicted Ultimate strain by models

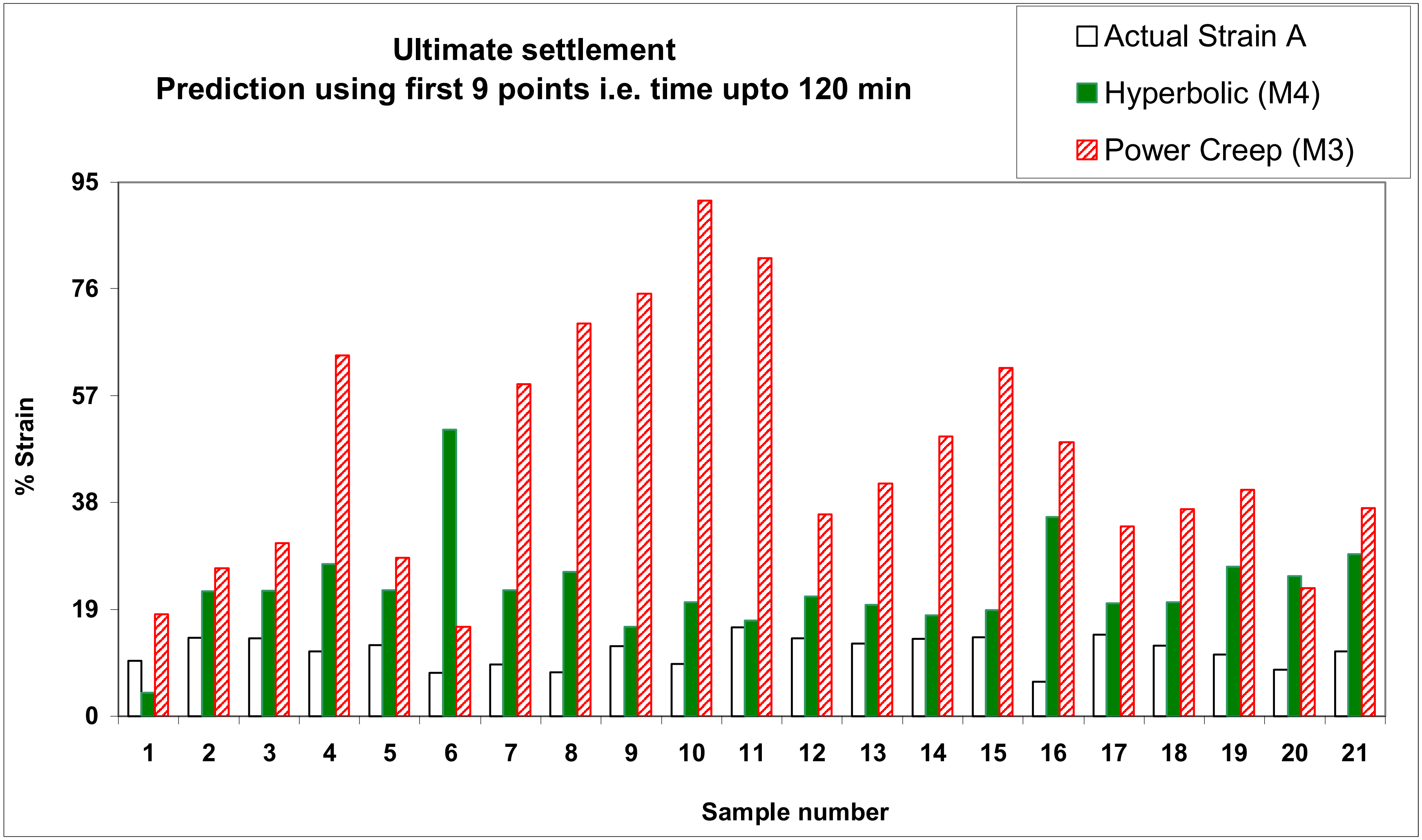

Figure A.2 Predicted Ultimate strain by models using 9 data points (time up to 120 min)

APPENDIX B

Table B.1 – Summary of biochemical parameters for Green Valley landfill.

Sampling Date	Landfill	Location	Depth (ft)	% wet Moisture	% dry Moisture	pH	Avg % V.S	Avg BMP (mL/g)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio
7/5/01	Green valley	TB 1	10 - 40	32.98	49.50	6.28	74.68	127.33	47.77	29.45	1.64
7/5/01	Green valley	TB 1	40-70	37.36	59.80	6.47	38.80	74.93	24.43	19.45	1.26
7/5/01	Green valley	TB 1	70-100	31.08	45.10	6.12	39.02	48.41	23.00	16.40	1.40
7/5/01	Green valley	TB 1	100-145	23.12	30.20	6.09	58.63	104.00	36.09	17.07	2.11
7/5/01	Green valley	TB 2	9-30	46.33	102.90	6.31	60.53	69.82	36.98	17.29	2.10
7/5/01	Green valley	TB 2	30-60	33.90	51.40	6.45	63.03	63.40	37.94	22.09	1.71
7/5/01	Green valley	TB 2	60-100	32.48	48.20	6.18	53.65	81.73	27.73	22.48	1.23

Table B.2 – Summary of biochemical parameters for Outer Loop Kentucky & Kettleman hills California landfills.

Sampling Date	Landfill	Location	% wet Moisture	% dry moisture	pH	Avg % V.S	Avg BMP (mL/g)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio
8/24/01	LOUISVILLE KY	1	39.78	66.62		41.64	2.41	-	-	
7/7/01	CA-KETTLEMAN	1	3.19	3.30	6.26	56.01	53.14	26.82	23.18	1.16
7/7/01	CA-KETTLEMAN	2	2.53	2.59	6.55	48.30	34.65	25.47	20.35	1.25
7/7/01	CA-KETTLEMAN	3	3.01	3.11	7.20	43.62	35.43	27.72	25.07	1.11

Table B.3 – Summary of biochemical parameters for Mohawk Valley landfill.

Note : Cellulose was below detectable limits.

Remarks	Sampling Date	Landfill	Location	Depth (ft)	% wet Moisture	% dry moisture	pH	Avg % V.S	Avg BMP (mL/g)
Mohawk Valley	12/10/01	LFB-1	S-1	8-10	9.24	10.18	7.20	1.78	5.97
Mohawk Valley	12/10/01	LFB-1	S-2	18-20	26.68	36.40	7.00	4.65	7.39
Mohawk Valley	12/10/01	LFB-1	S-3	20-28.5	62.63	167.63	6.85	10.74	10.65
Mohawk Valley	12/12/01	LFB-2	S-1	8-10	28.78	40.41	6.64	2.18	6.18
Mohawk Valley	12/12/01	LFB-2	S-2	13-15	17.28	20.88	6.32	8.68	9.90
Mohawk Valley	12/12/01	LFB-2	S-3	25-27	13.77	15.97	5.80	9.13	10.34
Mohawk Valley	12/12/01	LFB-2	S-4	33-35	23.46	30.66	6.20	7.93	9.01
Mohawk Valley	12/12/01	LFB-2	S-5	43-45	21.12	26.77	6.10	8.02	9.06
Mohawk Valley	12/12/01	LFB-2	S-6	55-57	17.64	21.42	5.40	8.47	9.29
Mohawk Valley	12/12/01	LFB-2	S-7	67-69	22.91	29.72	5.20	5.15	7.15
Mohawk Valley	12/12/01	LFB-2	S-8	76-80	17.32	20.94	5.35	7.81	9.26
Mohawk Valley	12/11/01	LFB-3	S-1	8-10	44.11	78.91	6.55	2.30	5.35
Mohawk Valley	12/11/01	LFB-3	S-2	20-22	14.73	17.27	6.45	3.20	8.55
Mohawk Valley	12/11/01	LFB-3	S-3	28-30	21.24	26.97	6.20	3.03	6.09
Mohawk Valley	12/11/01	LFB-3	S-4	36-38	20.75	26.18	6.80	2.85	5.43
Mohawk Valley	12/11/01	LFB-3	S-5	43-45	23.38	30.52	6.40	4.48	7.64
Mohawk Valley	12/11/01	LFB-3	S-6	53-55	22.61	29.21	5.65	7.24	8.85
Mohawk Valley	12/14/01	LFB-4	S-1	8-12	17.20	20.77	6.40	2.15	6.66
Mohawk Valley	12/14/01	LFB-4	S-2	18-20	20.95	26.50	6.30	4.88	8.12
Mohawk Valley	12/14/01	LFB-4	S-3	28-30	15.88	18.88	6.27	7.09	8.79
Mohawk Valley	12/14/01	LFB-4	S-4	38-40	22.26	28.63	6.66	5.58	7.98
Mohawk Valley	12/14/01	LFB-4	S-5	50-52	16.05	19.12	6.10	6.69	8.33
Mohawk Valley	12/14/01	LFB-4	S-6	56-58	19.74	24.60	5.80	2.05	6.10

Table B.4 – Summary of biochemical parameters for Waste Management Inc./USEPA

Landfill Bioreactor- Lake Mills, Indiana.

Note : Cellulose was below detectable limits.

Remarks	Sampling Date	Landfill	Location	Depth (ft)	% wet Moisture	% dry moisture	pH	Avg % V.S	Avg BMP (mL/g)
WMI/EPA LFBR	11/26/01	Waste Excavation	Composite waste	-	75.37	306.07	6.32	-	-
WMI/EPA LFBR	11/26/01	Incoming Waste	Composite waste	-	81.08	428.66	6.65	-	-
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	10-20	67.78	210.35	5.20	15.56	5.76
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	20-30	55.17	123.09	5.35	52.77	6.46
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	30-40	57.38	134.64	5.80	60.53	8.60
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	40-50	50.57	102.29	4.80	14.11	8.45
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	50-60	26.54	36.13	5.65	10.20	7.99
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-S	60-70	60.10	150.63	4.92	45.18	9.81
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	10-20	53.53	115.20	5.65	9.43	21.15
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	20-30	53.71	116.01	5.45	26.57	36.24
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	30-40	30.85	44.62	5.53	44.49	51.67
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	40-50	36.63	57.81	6.24	27.92	67.43
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	50-60	32.26	47.62	4.95	24.57	83.51
WMI/EPA LFBR	11/27/01	Lake Mills IA	6MW-N	60-70	30.13	43.11	4.90	29.40	99.93

Table B.5 – Summary of biochemical parameters for Bioreactor cells at Maplewood landfill, Jetersville VA.

Note : Available samples were in dry form.

Sampling Date	Landfill	Location	Depth (ft)	PH	Avg BMP (mL/g)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio
5/11/01	Maplewood	BH-1	0-10	5.70	125.56	29.50	30.20	0.98
5/11/01	Maplewood	BH-1	10-20	7.70	80.49	23.79	19.40	1.23
5/11/01	Maplewood	BH-1	20-30	5.30	113.07	21.00	20.40	1.03
5/11/01	Maplewood	BH-1	30-40	5.60	104.50	29.54	27.95	1.06
5/10/01	Maplewood	BH-2	0-10	5.80	106.98	34.73	24.15	1.44
5/10/01	Maplewood	BH-2	10-20	8.40	131.41	22.91	22.30	1.03
5/10/01	Maplewood	BH-2	20-30	8.20	71.69	26.73	23.50	1.14
5/10/01	Maplewood	BH-2	30-40	7.50	37.74	31.63	23.95	1.32
5/10/01	Maplewood	BH-3	0-10	5.30	25.40	34.50	26.40	1.31
5/10/01	Maplewood	BH-3	10-20	8.50	89.76	36.87	16.85	2.19
5/10/01	Maplewood	BH-3	20-30	5.50	79.24	39.72	24.20	1.64
5/10/01	Maplewood	BH-3	30-40	6.20	134.67	40.40	18.55	2.18

Table B.6 – Summary of biochemical parameters for Control cells at Maplewood landfill, Jetersville VA.

Sampling Date	Landfill	Location	Depth (ft)	% wet Moisture	% dry moisture	pH	Avg % V.S	Avg BMP (mL/g)	Cellulose (%)	Lignin (%)	Cell/Lig Ratio
8/7/01	Maplewood	CH 1	0-10	31.57	46.13	5.50	46.90	71.63	27.38	22.15	1.24
8/7/01	Maplewood	CH 1	10-20	40.72	68.70	5.54	55.34	73.89	29.08	21.35	1.36
8/7/01	Maplewood	CH 1	20-30	33.16	49.61	5.55	51.14	81.48	35.02	15.25	2.30
8/7/01	Maplewood	CH 1	30-40	38.47	62.53	6.89	57.50	81.02	30.37	26.95	1.13
8/7/01	Maplewood	CH 2	0-10	34.72	53.19	6.20	50.31	74.96	31.45	16.75	1.88
8/7/01	Maplewood	CH 2	10-20	40.05	66.82	5.77	45.96	73.29	33.44	19.25	1.74
8/7/01	Maplewood	CH 2	20-30	41.83	71.90	6.40	48.27	77.83	30.46	18.70	1.63
8/7/01	Maplewood	CH 2	30-40	52.70	111.42	7.60	74.57	101.80	36.13	25.25	1.43

VITA

Rajendra Vaidya was born on 20th October 1974, in Bombay India. He completed his Bachelor's degree in Civil Engineering in 1996. He worked as a civil engineer for Construma Consultants in Bombay for the period 1996-1997. Thereafter he graduated from Bombay university as a Masters in Environmental Engineer (1997-1998).

He worked in Bombay Municipal Corporation for the period 1998-2000, while completing his Masters and in fall 2000 started his graduate studies at Virginia Polytechnic and state University, USA. He has graduated in October 2002 and will work as an Environmental Engineer.