CHARACTERIZATION AND EVALUATION OF GAS GENERATION POTENTIAL OF MUNICIPAL SOLID WASTE FROM A CLOSED SECTION OF A LANDFILL

by

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ABSTRACT

CHARACTERIZATION AND EVALUATION OF GAS POTENTIAL OF MUNICIPAL SOLID WASTE FROM A CLOSED SECTION OF A LANDFILL

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At present, there are more than 40 closed municipal solid waste (MSW) landfills around DFW and North Texas. A closed landfill might have potential benefits for gas recovery and utilization due to the presence of organic components in the MSW. The decomposition of organic components of MSW produces gas. The decomposition process after landfill closure may continue for 20 to 100 years, depending on the operational practice of the landfill. However, to evaluate the methane potential of a closed landfill, it is important to have the understanding of the characteristics of the existing or decomposed landfill wastes. The current study presents the characteristics of municipal solid waste samples, collected from a closed section (phase zero) of the City of Denton landfill in Texas. The phase zero section of landfill was operated as a pre subtitle-D conventional landfill. Twelve MSW samples were collected from the landfill using a 3ft diameter bucket auger sampler from two boreholes in November, 2010. The estimated age of collected MSW samples ranged from 9 to 25 years. Physical composition was determined by manual sorting of the samples. The average composition for landfilled waste was found to be paper (31%), plastic (10%), food waste (0%), textile and leather (2%), wood and yard waste (8%), metals (3%), glass (1%), styrofoam and sponge

(1%), C & D (5%), degraded fines (14%) and soils (25%). The composition had a very high percentage of soils and degraded fines. There was no food waste in the samples. The moisture content varied from 11% to 34%, with an average of 24.9%. The average compacted unit weight of the samples was determined both using both the standard proctor method and tensile compression machine applying overburden pressure. Average compacted unit weight was determined to be 58.8 lb/ft^3 and 49.1 lb/ft^3 for standard proctor and tensile compression, respectively. The permeability was found in the range of 10^{-4} to 10^{-5} cm/sec, with an average of $2.3X10^{-4}$ cm/sec. The particle size distribution of the samples was determined and compared to a previous study that indicated the degradation phase of samples. Approximate half of the samples were found to be phase I degraded samples, and other half were between phase I and phase IV degradation level.

The volatile solids (VS) tests were being performed to evaluate the level of degradation of the collected solid waste. Based on the test results, average volatile solids (VS) of all landfilled samples was determined to be 63.1%. The biochemical methane potential (BMP) was predicted from a correlation with volatile solids tests results. Gas generation of the closed landfill section of City of Denton landfill was predicted using a first order gas generation model. The predicted maximum gas generation volume was determined as $9.37X10^9$ ft^3, when Lo was assumed to be 140 m^3/Mg. However, the predicted gas volume was determined as $6.69\ X10^9$ ft^3, when Lo was assumed to be 100m^3/Mg. The future gas generation potential of the existing landfilled solid waste varies between 65% and 20%.

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CHAPTER 1

INTRODUCTION

1.1 Background

Municipal solid waste (MSW) is made up of household and commercial waste, including package wrappings, food scraps, grass clippings, computers, and refrigerators. It does not contain industrial, hazardous, or construction waste. According to US Environmental protection agency (EPA) (2009), total Municipal Solid Waste generated in USA was 243 million tons and 54.3% of this waste generation was landfilled, 33.8% was recycled and composted, and 11.9% was converted to energy as shown in Figure 1.1. Organic materials were largest component of the waste stream. Before recycling, the composition of waste was as follows: paper and paper products included 28 percent, yard trimming and food scraps 28 percent, 9 percent of metals, and rubber, leather and textiles accounted for 8 percent, wood 7 percent, glass 5 percent, and other miscellaneous consisted of 4 percent.

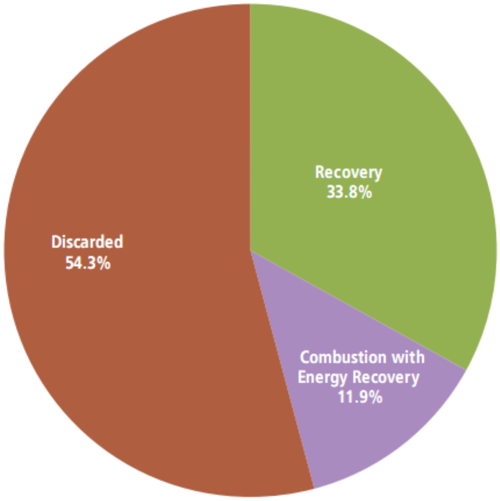


Figure 1.1 Management of MSW in United States in 2009

A MSW Landfill is an engineered site for waste disposal or waste burial. Many solid waste landfills in the United States were constructed prior to current federal regulations (40 CFR, Part 258) promulgated under authority of Subtitle D of the Resource Conservation and Recovery Act (RCRA) in 2011. Pre-Subtitle D landfills were typically unlined with minimal or no leachate collection systems. These landfills, many of which are closed now, might be a significant source of leachate and landfill gas (LFG). During the lifetime of the final cover there is a possibility of deterioration of the final cover. This may allow water to get into the landfill, with the presence of moisture; the landfill may start producing gas again, as presented in Figure 1.2.

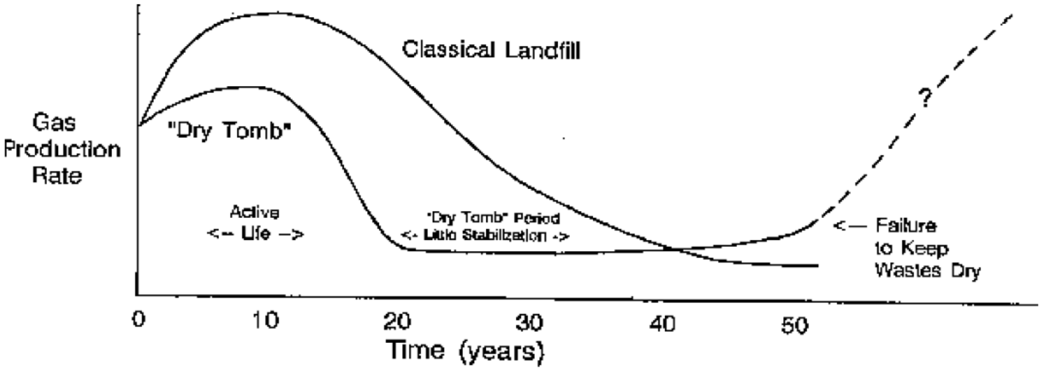


Figure 1.2 Landfill Gas Productions in Dry Tomb and Classical Landfills (Lee and Jones Lee, 1999)

At present, the post closure monitoring period for landfills is set as 30 years, with expectation that solid waste will be decomposed during this period. And landfill site may be stabilized for further development. However, there is no specific or scientific reason to believe that landfill will be stabilized after 30 years. Particularly for a dry tomb landfill, it may take as long as 50 to 100 years.

Lee and Jones-Lee (1999) discussed that once a landfill is closed and the low-permeability landfill cover is installed, the rate of moisture entering the landfill will be very low, and gas production may decrease due to absence of water or moisture. Even after decades of landfill closure, the unfermented organic components of the waste can again initiate producing gas. The gas generation is proportional to the moisture content of the waste.

According to Lee et al (1999), another issue that is not incorporated into evaluation of landfill gas production in landfills is that much of the municipal solid waste placed in landfills is deposited inside polyethylene bags. These bags, while crushed, are not shredded and may act as barriers to moisture interacting with the components within the bags; this may inhibit the fermentation of the organics in bagged wastes due to low moisture content. The plastic bags decompose slowly and, even though the duration of the integrity of the polyethylene plastic bags is unknown, it is likely to be on the order of at least decades. The net result is that the production of landfill gas in a Subtitle D landfill can potentially take place over many decades and could extend to hundreds of years. At present there is no reliable way to predict landfill gas production rates and duration of production in closed Subtitle D landfills.

In a conventional or dry tomb landfill, the main concept is to prevent the intrusion of moisture in to the waste. The initial moisture present in the waste stream and the moisture intrusion during landfilling operation is the only moisture present for the degradation of the wastes in the landfill. Additional moisture might infiltrate later if the landfill cover is deteriorated. It is very likely that the wastes placed in a conventional closed landfill are mostly not degraded and have huge potential left for gas generation. Therefore it is important to determine the physical and engineering characteristics of landfilled municipal solid waste and, landfill gas potential of landfilled or partially degraded solid waste.

1.2 Research Objective

The major objective of the current study was to predict the gas potential of landfilled waste from a closed landfill. The landfilled samples were collected from a closed section of the City of Denton landfill, Texas. The specific tasks to accomplish the objectives were as follows:

(i) Collection of landfilled solid waste

(ii) Determination of the physical composition of the collected waste

(iii) Determination of degradable and non-degradable percentage of collected sample

(iv) Determination of the moisture content of waste samples

(v) Determination of the unit weight of the waste samples

(vi) Determination of hydraulic conductivity of MSW samples

(vii) Determination of particle size distribution of samples

(viii) Determination volatile solids of MSW samples

(ix) Determination of gas potential using US EPA's 1st order gas generation model

1.3 Thesis Outline

The thesis report consists of five chapters as follows: Introduction (Chapter1), Literature Review (Chapter 2), Methodologies (Chapter 3), Results and Discussion (Chapter 4), Conclusions and Recommendations for future studies (Chapter 5).

Chapter 2 contains the previous work and studies related to the present research work. Studies related to landfilled sample characterization and gas evaluation are included. The methodologies applied to evaluate gas generation and gas potential for MSW are presented in this chapter. Both laboratory scale and field scale studies for landfill gas estimation are presented here. Discussions of gas models are also included at the end of the chapter.

Chapter 3 describes location of area of study and locations of sample collection. The test methodologies for characterization and prediction of gas potential of the recovered landfilled samples are presented here.

Chapter 4 focuses on the results and discussions. The gas generation potential of the closed section of the landfill was predicted from the volatile solids test results. The 1st order gas generation model was used to simulate the gas generation of the closed landfill section and to predict the gas generation capability.

The recommendation for future studies (Chapter 5) summarizes the results and outcomes for the present study and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

According to Hutzler (2004), the engineered method of solid waste disposal in which waste refuse is buried between layers of soil so as to fill in or reclaim low-lying ground is known as Landfill. According to US Air Quality Bureau (2010), a landfill where municipal solid waste will no longer be placed is defined as a closed landfill. At present, there are more than 40 (forty) closed municipal solid waste (MSW) landfills around DFW and North Texas. The decomposition process as well as gas generation of organic components may continue for 20 to 100 years, depending on the operational practices of the landfill. However, to evaluate the methane potential of a closed landfill, it is important to have the understanding of the characteristics of the existing or decomposed solid waste present in the closed landfill.

2.1.1 Municipal Solid Waste

According to the US EPA, Municipal solid waste (MSW) refers to the stream of waste collected through community sanitation services. MSW is defined as trash or garbage which consists of everyday items discarded after use, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries originated from homes, schools, hospitals, and businesses.

2.1.1.1 Fresh Municipal Solid Waste

The municipal solid waste from the working phase of the landfill during the filling operation is defined as fresh municipal solid waste. The fresh refuse represents the initial condition at the time of placing the waste in the landfill.

2.1.1.2 Landfilled Municipal Solid Waste

The municipal solid waste placed earlier is defined as the landfilled waste. There is no specific age limit for landfilled waste. Most of the researchers defined the landfilled waste as waste recovered from boreholes at different depths. The landfilled wastes are subjected to degradation, which is in most of the studies is a function of age and depth of filling.

2.2 Characterization of Landfilled Municipal Solid Waste

The composition of the waste, moisture content, organic matter content, permeability, particle size distribution, and specific gravity are important MSW characteristics. These parameters greatly influence the characteristics of the waste. The reliable knowledge of geotechnical properties of these waste materials is required for the evaluation and prediction of the actual behavior of the landfill. Therefore, there is a need to understand how the MSW characteristics with decomposition. However, determination of MSW properties is extremely difficult as stated by Manassero et.al (1997) due to the following reasons:

- It is difficult to obtain samples of large enough size to be representative of in situ condition,
- There are no generally accepted sampling procedure for waste materials,
- The properties of waste materials change drastically with time,
- The level of training and education of the personnel on site may be not high enough to deal with all necessary basic interpretations and understanding of the measurements, and,
- Municipal solid waste is inherently heterogeneous and variable among different geographical locations.

2.2.1 Physical Composition

Physical composition of the waste indicates the type and percentage of waste present in the total waste stream. Waste composition study is the most important tool for understanding waste performance and management. The waste composition can be determined by different procedures. For example, (1) Product data published by industry on national level can be used to estimate the physical composition (known as input method), (2) Manual sorting of samples, (3) The composition can be determined by photogrammetry, where photograph of representative portion is taken and then analyzed to determine the composition.

Due to the heterogeneous nature of the solid waste, the classification of waste is difficult. In the literature, several approaches have been adopted to classify MSW. The classification suggested by Landva and Clark (1990), based on their biodegradability, is shown in Figure 2.1.

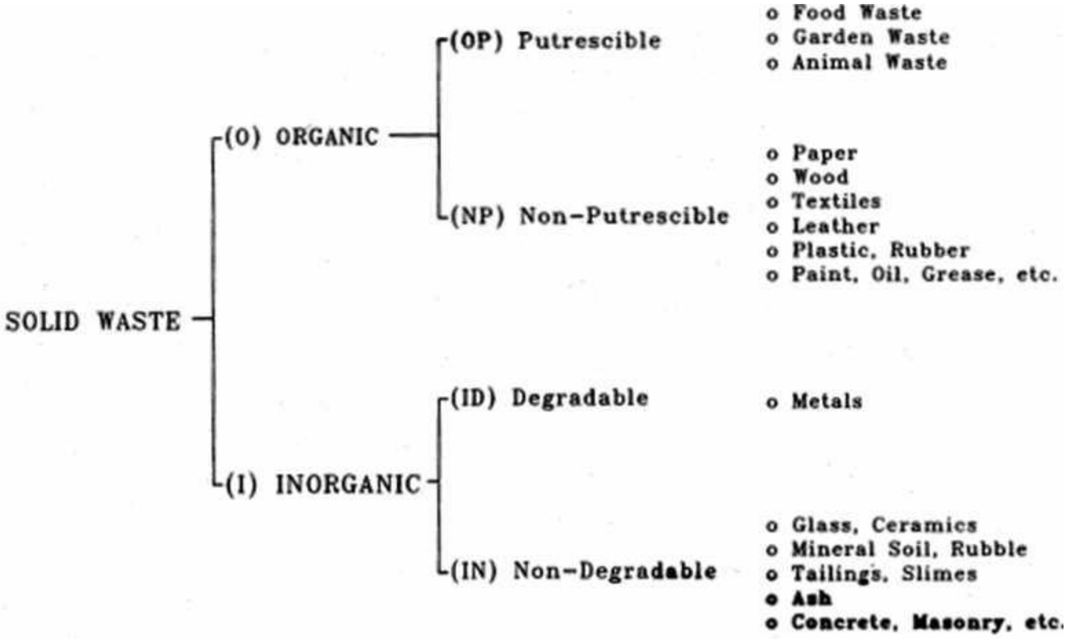


Figure 2.1 Solid Waste Classification Based on Their Biodegradability (Landva and Clark, 1990)

Landva & Clark (1990) recommended best methods to measure the properties of solid waste and their possible ranges based on landfills across Canada. According to the authors, augur drilling by solid stem 130 mm augur (140 mm bit) is the most suitable method for sampling both old and new waste fill. They also give a very thorough classification system for municipal solid waste. The typical composition and unit weight of solid waste in Canada are given in Table 2.1.

Table 2.1 Typical Refuse Composition from Canada (Landva & Clark, 1990)

Category	Percent of total weight
Food waste	5-42
Garden refuse	4-20
Paper products	20-55
Plastic, rubber	2-15
Textiles	0-4
Wood	0.4-15
Metal products	6-15
Glass & ceramics	2-15
Ash, rock & dirt	0-15

Kavazanjian et al. (2010) reviewed existing MSW classification systems, and the field and laboratory waste characterization programs. The proposed waste characterization procedure is designed to efficiently collect information on the factors that influence geotechnical properties of MSW as well as other potentially useful information on its physical properties. For the understanding of the physical factors influencing the mechanical response of MSW, modifications of the proposed characterization procedure will be required. However, the proposed procedure represents an important first step in standardizing the manner in which MSW is to be characterized for engineering analyses. The proposed procedure can be adjusted to minimize the effort required to collect relevant information on a site specific basis. According to the authors large diameter bucket auger boring was conducted for sample collection from tri-cities landfill and for the determination of in-situ unit weight using gravel replacement. Field logging of the boring included continuous visual description of moisture level, state of compaction, state of degradation, composition and apparent waste structure, using the classification scheme presented in Table 2.2.

Table 2.2 Landfill Field Waste Classification Scheme (Kavazanjian et al., 2010)

Moisture Content	
1	Dry dump moisture level
2	Wet moisture levels
3	Standing water

Compaction	
1	Slight-refuse easily falls out of bucket auger
2	Moderate-refuse falls out of bucket ager upon impact
3	Heavy-refuse falls out of bucket auger only after being struck multiple times

Degradation	
1	None-newspaper very legible, no refuse discoloration
2	Slight-some newspaper still legible, discoloration
3	Moderate-newspaper partly legible, highly discolored
4	High-newspaper highly faded gray to black

Composition	
1	Household-paper and plastics
2	Putrescible organics
3	Concrete, bricks
4	Wiring
5	Metal
6	Nonferrous Metal
7	Tiers
8	Asphalt
9	Soil
10	Medical
11	Indistinguishable
12	Glass
13	Other (specify)

Structure	
1	Layered
2	Encapsulated
3	Fibrous
4	Interlocked
5	Indistinguishable

Kavazanjian et al. also provided a detailed characterization of a relatively representative sample of 5-10 kg of material. The sample was separated into following categories: paper, cardboard, plastics, rubber, wood products, textiles, concrete, metals, glass, soil and miscellaneous materials. Figure 2.2 is a graphical representation of results of segregation of the > 20 mm material for the five sample groups characterized from the tri-cities landfill.

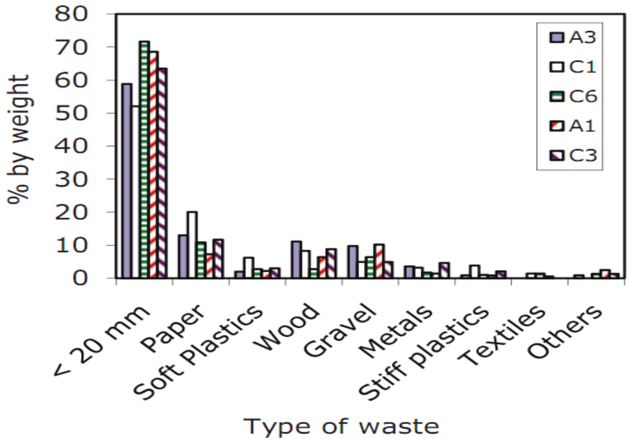


Figure 2.2 Percentage of Weight of the Various Waste Types for Five Different Waste Samples for Tri-Cities Waste. (Kavazanjian et al., 2010)

Gomes et al. (2005) conducted a study to characterize the solid waste being disposed at San Tirso landfill. For different ages of waste three different profiles were selected. Profile A still in operation and other two closed (profile B and C). One of the closed zone, profile C is coming waste of old dumpsite and profile B is preselected and treated wastes disposed between 1998 and 1999.

Laboratory experiments determined physical, chemical, compressibility and shear strength characteristics; the field monitoring program of determined displacement, lateral deformations, horizontal pressure and pore water pressure. The physical tests included classification of wastes, determination of volumetric weight, moisture content and organic content of waste. Table 2.3 shows the waste composition of profile B (closed zone and waste from 1998-1999).

Table 2.3 Waste Component by Weight Percentage of Profile B from San Tirso Landfill, Portugal (Gomes et al., 2005)

Waste Component (wt %)								
Plastic	Textile	Soil	Metal	Wood	Glass	Rubber	Paper	Other Organics
37.4	33.3	11.2	10.2	2.8	2.8	1.3	0.9	0.1

Gabr and Valero (1994) evaluated the geo-environmental properties and long-term deformation parameters of solid waste from two different landfills. Both the landfills had accepted waste for about fifty years. Aged samples were recovered from the sites using an auger rig and fresh samples were collected from the surface. The composition of the wastes is shown below in Table 2.4.

Table 2.4 Composition of Fresh Waste and Aged Waste (Gabr and Valero, 1994)

Category	**Percentage of total weight (Dry Basis)**	
	Aged Sample	Fresh Sample
Paper	0	29
Plastic	13	7
Food Waste	0	23
Wood	9	10
Textiles	23	5
Metal	10	1
Glass and Ceramic	10	8
Ash	19	17
Miscellaneous	14	0

Gabr and Valero (1995) conducted a research program to estimate the geotechnical properties of 15 to 30 year old municipal solid waste. A drill rig was used to recover samples up to 42 m depth. According to the authors, due to the age of the tested waste samples food waste, garden waste, and paper products made up a much smaller portion than for fresh samples. The textiles, rock, and soil made up a larger portion of the aged samples. The composition presented in this paper is given in Table 2.5.

Table 2.5 Composition of MSW (Gabr and Valero, 1995)

Category	**% of Total Weight**	
	Test Samples	Typical Refuse
Food waste	0	5-42
Garden refuse	0	4-20
Paper Products	2	20-55
Plastic & rubber	13	2-15
Textiles	23	0-4
Wood	9	0.4-15
Metal products	10	6-15
Glass, ceramics	10	2-15
Ash, rock, soil	33	0-15

Reddy et al. (2009) conducted studies on geotechnical properties of fresh MSW of Orchard Hills landfill. Shredded waste was used to determine the physical properties. Samples were collected from working phase. The composition of the samples is presented below in Table 2.6. The dry gravimetric moisture content was found to be 44±1%. The samples had an average specific gravity of 0.85.

To determine the compression ratios the testing was performed on samples with four different initial moisture contents from 44% to 100%. All compression ratios were in a range of

0.24-0.33, with an average of 0.27. The drained cohesion of fresh MSW varied from 31-64 KPa and the drained friction angle ranged from 26-30°. The friction angle, φ was lower and drained cohesion, c was higher with the increase in strain.

Table 2.6 Typical Composition of Fresh MSW at Orchard Hills Landfill (Reddy et al., 2009)

Category	Waste type	Waste composition (% by wet mass)	
Easily biodegradable	Cooking waste	6.6	6.9
	Garden waste	0.3	
Medium Biodegradable	Paper	8.2	24.6
	Cardboard	13.3	
	Food carton	0.0	
	Sanitary waste	3.1	
Hardly biodegradable	Textiles	5.8	19.2
	Nappies	1.7	
	Wood	11.7	
Inert waste	Metal	4.4	29.2
	Plastic bottles	5.7	
	Other plastics	5.3	
	Special waste	0.0	
	Medical waste	0.1	
	Other waste	3.5	
	Inert waste	5.8	
	Glass	4.4	
Residual fines	Fines (<20 mm)	20.1	20.1

Suthatip et al. (2006) conducted research on the biodegradability of the reference material (food, wood and paper) and excavated MSW samples from a closed landfill aged approximately 20 years. The composition of waste recovered from the closed landfill is presented in the Figure 2.3.

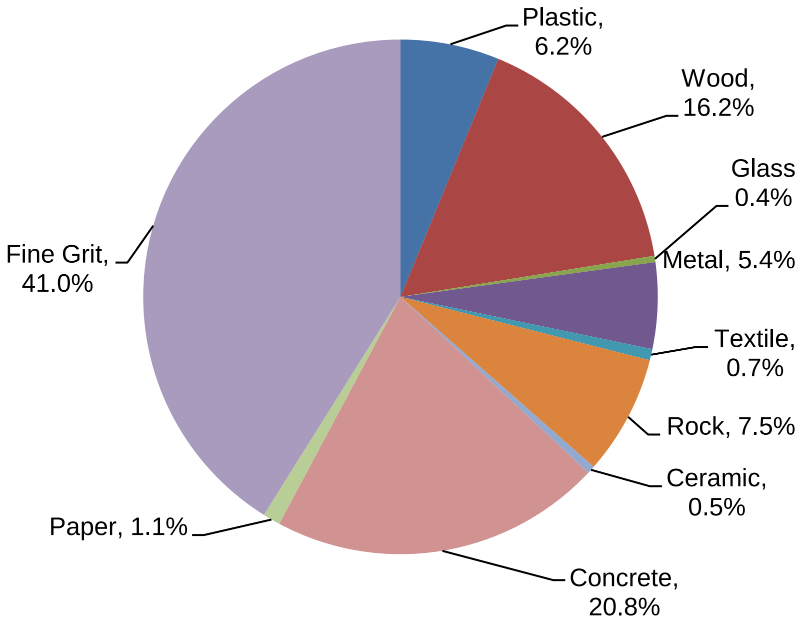


Figure 2.3 Composition of Recovered Waste from Japan (Suthatip et al., 2006)

Chiemchaisri et al. (2007) investigated the solid waste characteristics and their relationship to gas production in tropical landfill. They observed the incoming solid waste stream was mainly composed of paper, plastic, food and foam. The plastic and foam are resistant to biodegradation. The average composition at different depths is presented below in Table 2.7.

Table 2.7 Physical and Chemical Characteristics of Fresh and Buried Samples from Thailand (Chiemchaisri et al., 2007)

Parameters	Sample/Depth				
	Fresh	1.5	3	4.5	6
Physical Characteristics					
Density (Kg/m3)	250	240	840	1360	1260
Waste Composition (% w/w)					
Food/Vegetable Waste	54.6	6.9	9.6	4.1	1.1
Paper	8.9	ND	3.8	ND	ND
Plastic and foam	17.1	69.1	43.6	13.5	26.6
Other Organics	10.2	0.1	4	2.5	3.1
Inorganic Materials (glass,metals,stone)	5.3	2.2	ND	2.7	4.2
Others (hazardous, Unidentifiable fraction)	3.9	21.7	39	77.2	65
Chemical Characteristics					
Moisture content (%w/w)	65.2	39.6	60.1	57.1	54.2
Total Solids (%w/w)	34.8	60.4	39.9	42.9	45.8
Volatile Solids (%TS)	80.5	46	44.1	29.8	22.1
Ash (%TS)	19.5	54	55.9	70.2	77.9
Carbon	44.7	25.56	24.51	16.57	12.28
Hydrogen	5.1	3.06	2.94	1.98	1.47
Oxygen	29.37	15.8	15.09	9.88	6.9
Nitrogen	1	1.24	1.23	1.07	1.05
Phophorus	0.2	0.15	0.16	0.14	0.18
Sulfur	0.05	0.18	0.19	0.19	0.24

2.2.2 Moisture Content

The moisture content of the waste is a good indication of the decomposition level of the waste. Decomposed waste has less paper and food content which are the main components that hold the moisture. Therefore if the degradation of the waste is higher the moisture content may be lower than fresh waste.

Carboo et al. (2005) conducted physico-chemical analyses of municipal solid waste in Accra metropolis of Ghana. The annual waste generation rate was 3.7×10^4 tons/year (2001). However, the existing collection system managed to collect only 55% of the total generation. The physico-chemical studies were conducted to identify the physical and chemical composition of the MSW to be disposed of. For sampling, the three distinct zones were selected according to the income level and density of population of the residents. Three different zones were zone A with high income low density, zone B with middle income medium density and zone C with low income and high density. From each zone, ten household were randomly selected for sample collection. Samples were collected for two months on every other day. In determination of burning capacity moisture content is one of the most important parameters. The higher the moisture content the longer time will be required for the material to be burned. The moisture contents from different zones are presented in the Table 2.8.

Table 2.8 Moisture Content of MSW in the Accra Metropolitan Area, Ghana (Carboo et al., 2005)

Zone	Moisture Content (%) (Gravimetric)
A (high income)	62.2
B (middle income)	46.9
C (low income)	39.8

The data showed a trend that with higher income zone, the moisture content is higher. This might be because of the fact that the high income areas residents are more likely to dispose of the refuse that contain higher amounts of energy-rich bonds. For high income zone the waste is mainly paper and for low income zone the waste becomes heterogeneous and due to that bond energy decreases. The paper is mainly made of H-bond. H-bond has high attraction to water that might be a reason for higher water content in higher energy rich bond compounds.

Gomes et al. (2005) conducted a study to characterize the solid waste being disposed at San Tirso landfill. They found moisture content ranged from 61% near the surface (recent waste) to 117% at 11m depth (3 year old waste). More degraded waste has higher percentage of fines present which increases the moisture content of the waste.

According to Landva & Clark, (1990), the moisture content increases with increasing organic content, which can be up to 120% (wet weight) and 65% (dry weight).

From the comparative study between fresh and landfilled samples conducted by Gabr and Valero (1995), the fresh sample average moisture content was found to be 20% on a dry weight basis and the landfilled sample moisture content ranged from 60% to 150% on a dry weight basis. No significant trend was found between depth and moisture content.

Zhu Xiang-rong et al. (2002) has reported average moisture content was 30% and the water content gradually decreased with depth.

For the landfilled samples Gabr and Valero (1995) reported moisture content to be ranged 30% to 130 % (at the surface) on a wet weight basis.

Hossain et al. (2008) reported after complete degradation moisture content was found to be increased from 55% to 64.7% for the simulated ELR landfill reactors build in the laboratory.

2.2.3 Unit Weight

Unit weight of waste is directly related to the size of particles present in the landfill. If the particles are finer there are less voids, the unit weight becomes higher. For the degraded samples, the particle size becomes smaller. So the unit weight will increase accordingly.

Landva & Clark (1990) gave a very thorough classification system for municipal solid waste. According to them, in situ unit weight measurement of MSW can yield values ranging from 6.8 to 16.2 KN/m^3. The unit weight of the cover soil needs to be measured separately.

Zhu Xiang-rong et al. (2002) reported geotechnical behavior of the MSW in the Tianziling landfill, which was 13 years old. They showed that an MSW has high compressibility, and the shear strength of MSW gradually increases with the increase in normal stress, filling depth and time.

The density of MSW ranges from 8 KN/m^3 to 16.8 KN/m^3. The specific gravity ranges from 1.92 to 2.62, which is smaller than common soil and greatly discrete because of higher organic content.

Gabr and Valero (1995) achieved a maximum dry unit weight of 9.3 KN/m^3 from standard proctor test.

Hossain et al. (2008) reported dynamic properties of MSW in a bioreactor landfill with degradation. The state of decomposition was quantified by methane yield, pH, and volatile organic content. Remolded samples from the laboratory bioreactor were used to determine the geotechnical properties of MSW. The percent fines increased from 10% after the first stage to 39% at the end of fourth and last stage. The same trend of increasing with degradation was reported for unit weight of MSW. It ranged between 8.5-9.1 KN/m^3 in phase I to 10.7-11.2Kn/m^3 for phase IV. The authors established a relationship of shear strength of MSW with the degree of decomposition of MSW in this paper.

According to Chen et al. (2009), the use of a single compressibility value in settlement calculation leads to inaccurate predictions. They considered the compressibility parameter as a function fill age and embedding depth of the MSW. They collected 31 borehole samples by drilling from Qizhishan landfill in Suzhou, China. The test results showed that the compressible components of MSW decreased and incompressible components increased with the fill age. The values of void ratio decreased with depth. The unit weight varied within a range of 5 to 15 KN/m^3 and the values increased with the increase of depth of landfill.

Chiemchaisri et al. (2007) found from their study that the density of the waste increased along the depth from 240 kg/m^3 at top to 1260 kg/m^3 at the bottom.

2.2.4 Hydraulic Conductivity

Permeability increases with a decrease in unit weight and decreases with an increase in unit weight. Hossain et al. (2009) conducted a research to compute permeability based on 4 lab scale bioreactors representing 4 stages of decomposition. The study was conducted on waste collected from transfer stations. The moisture content was fixed at 55%, temperature at 22-29^{o}C, and recirculation was done 4 days a week. Based on the test results, it was found that permeability of MSW in a bioreactor decreases from 10^{-2} cm/s to 10^{-4} cm/s with decomposition, with density being the same. Also, increase in density results in decrease in permeability. Accelerated degradation causes significant decrease in degradable constituents. The percentage decrease in volatile solids increases significantly at each stage of decomposition. The authors also noted the change in particle size with decomposition. The particles are relatively larger during the initial stages. The finer percentage increases from 10% to 39% as decomposition moves from phase 1 to phase 4. The authors conclude that, instead of using one average value for the full landfill height and time, variation of permeability should be considered.

Reddy et al. (2009) investigated the hydraulic conductivity of MSW landfills. They provided a comparative assessment of measured hydraulic conductivity based on the laboratory tests and field studies. A series of laboratory tests were performed on fresh and landfilled waste collected from Orchard Hill landfill using small scale and large scale rigid wall permeameter and small scale triaxial permeameter. The fresh samples were collected from the working phase and the landfilled waste was collected from a landfill cell subjected to leachate recirculation for 1.5 years, using a 0.9 m diameter boring auger from the borehole. Using a small scale permeameter, the fresh sample permeability was reported in a range of $2.8\text{x}10^{-3}$ to $11.8\text{x}10^{-3}$ cm/s with dry unit weight of 3.9-5.1 KN/m^3 and for the landfilled waste the permeability was reported in a range of $0.6\text{x}10^{-3}$ to $3.0\text{x}10^{-3}$ cm/s for a dry unit weight of 4.5 KN/m^3 to 5.5 KN/m^3. The researchers concluded that the landfilled MSW posses lower conductivity than the fresh MSW. The decrease in permeability is a function of particle size and compaction. For the landfilled waste, the particle sizes are smaller and finer particles are present due to degradation, so the compaction is higher and less voids present in the sample. The researchers also reported that permeability is significantly influenced by the vertical stress.

2.3 Landfilling Method and Operation

Municipal solid waste landfills can be operated way in two different ways. Traditionally, no moisture was added to the wastes in order to avoid more leachate generation and keep it dry. This type of landfilling operation is defined as dry tomb or conventional landfill. However, the settlement rate was very low in a traditional landfill, to soon the landfill runs out of space and a new landfill space must be found. A new idea was evolved to enhance settlement with the addition of moisture. The landfill operated with moisture addition within the waste mass is known as a bioreactor landfill or Enhanced Leachate Recirculation landfill (ELR).

The operational practice of a landfill influences the waste degradation, leachate generation, settlement and gas generation of the landfill. Moisture addition may reduce the post operation landfill monitoring period from 50 years to 10 years.

Barlaz et al. (2002) reported a relative study of refuse decomposition in the presence and absence of leachate recirculation in the landfill operation. The addition of supplementary water was suggested for enhancing the decomposition. Two test cells, including one enhanced cell and one control cell, were built and operated for three years. The settlement and temperature was monitored for both cells. The temperature was monitored by thermistors which were placed at the bottom, middle and top layers of the fill depth. Temperature in both cells reached up to 50-55°C, but in the controlled cell it decreased and became stabilized at 25-32°C. It also decreased in the enhanced cell, but increased with the addition of leachate and stabilized at 35-40°C. The settlement for the control cell was much less than enhanced cell and also the controlled cell settled at significantly slower rate than enhanced cell. The samples were collected using a bucket auger and hollow stem auger from two boreholes at the controlled cell and three from enhanced cells. The average moisture content of borings from controlled section was determined to be 14.6 and 19.2% and for the enhanced sections 38.8, 31.7 and 34.8%. The average volatile solid was reported as 40.1 and 42.6%, respectively. The (C+H)/L ratios for the enhanced cell and controlled cell were 1.09 and 1.44. With degradation, L increases and (C+H) decreases, which results into lower (C+H)/L ratios. So the lower ratio for the enhanced cell indicates the higher decomposition. Barlaz et al. (2002) found strong correlation between the volatile solids and (C+H)/L. BMP test results showed average BMP from enhanced cell to be 24ml CH^4/dry g, which is significantly lower than the BMP of control cell, which was 30.9ml CH^4/dry g. However, the sample BMP values were inconsistent; some BMP results in enhanced cell showed higher values than control cell. High moisture content is suitable for methanogenesis, but no correlation could be established between BMP and moisture content. Barlaz et al. (2002) reported that the samples with high BMP in the presence of high moisture content had not been exposed to favorable environmental conditions for long enough for decomposition. The studies suggested regardless of the variability the data presented, recirculation enhances the degradability, moisture content and settlement of the landfill.

2.4 Evaluation of Landfill Gas Generation Potential

The MSW degrades with time in the presence of a suitable environment. The degradation of wastes produces gas. Prediction of the rate of gas production of landfills is important for the optimization of energy recovery and for estimating greenhouse gas emissions.

2.4.1 Landfill Gas Composition

According to the report of RUST Environment and Infrastructure, (1991) landfill gas recovery and utilization can be viable energy resources. The landfill gas is mostly composed of methane, carbon and minor amounts of NMOC. Approximately methane present in landfill gas is 40%-60%.

2.4.2 Evaluation of Gas potential

To evaluate the potential of gas generation of a closed landfill, the remaining potential of gas can be predicted from direct laboratory tests like volatile solids or biochemical methane potential test. It can also be predicted from gas models with the actual waste generation and placement data and valid assumptions.

2.4.2.1 Volatile Solids of Municipal Solid Waste

Volatile solids tests are relatively easy to perform but still a good indication of the remaining gas generation potential of the waste.

Kelly et al. (2006) conducted a study to determine which parameters are most indicative of stability of the landfill waste. For this particular study, samples were collected from 12 different landfills aged from fresh to 11 years old. Tests were conducted to determine cellulose, lignin, and biochemical methane potential and volatile solids along with the plastics of the collected samples. The main objective of the study was to determine which methods accurately predict the biodegradable or organic fraction of waste and the point where the degradation of waste becomes stable. The degradation phenomenon was different for individual landfills because of the heterogeneity of waste and the unique landfill conditions. The researchers plotted the VS, Cellulose, BMP and Lignin of the samples with the age of the waste. It was observed that most samples had less than 5% Cellulose after 5 years in the landfill. From the data it was observed the bioreactor landfills were more degraded and the values of VS, Cellulose, Lignin and BMP were lower for ELR landfills. According to the researchers, the BMP values are supposed to be good indicators of degradation but are subjected to the variability of inoculums type. The BMP with age plot showed a similar trend as Cellulose with age. Kelly et al developed correlations between Cellulose and VS, Lignin and VS, BMP and VS; and Cellulose + Lignin and VS. The Cellulose versus VS showed a stronger correlation with VS than Lignin and BMP, as illustrated in Figure 2.4. The authors commented that Cellulose could be reasonably predicted from VS.

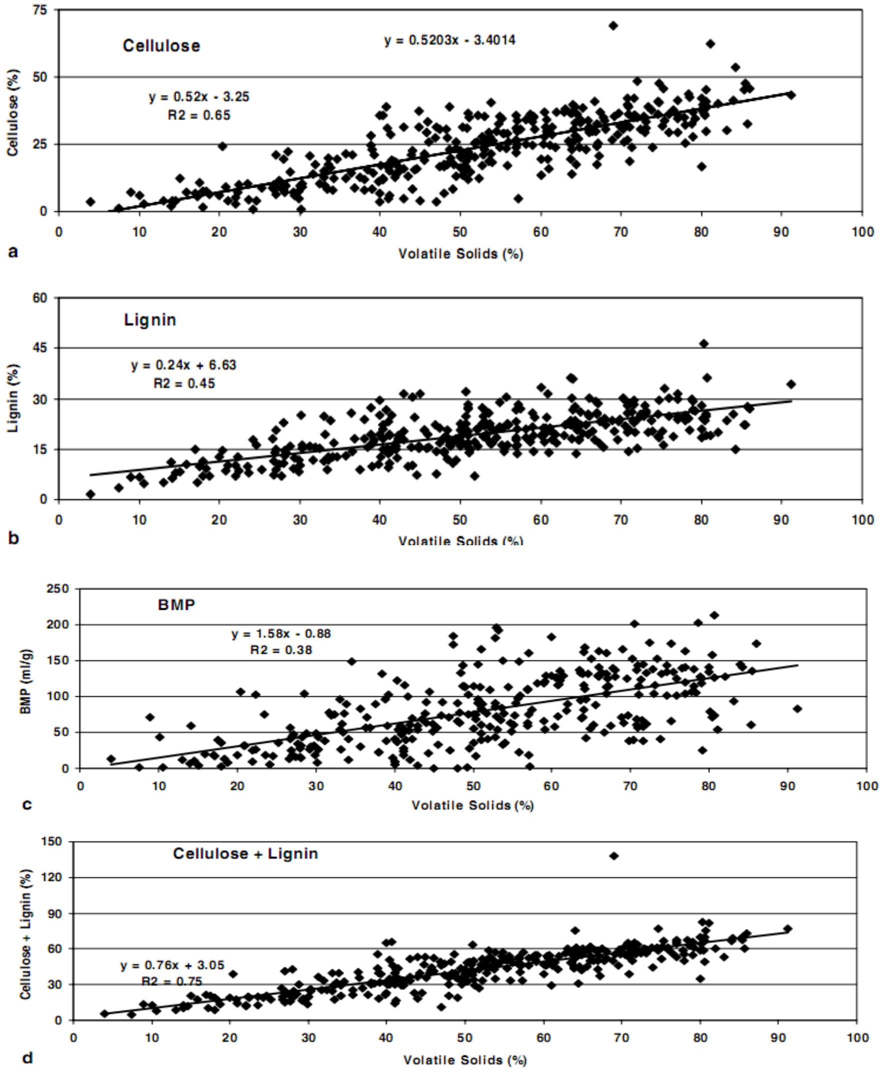


Figure 2.4 Relationship between Volatile Solids and (a) Cellulose, (b) Lignin, (c) BMP and (d) Cellulose + Lignin using Data from 12 Landfills.

Gabr and Valero (1995) conducted a research program to estimate the geotechnical properties of 15 to 30 years old municipal solid waste. A drill rig was used to recover samples up to 42 m depth. According to the authors, based on the age of the tested waste samples food waste, garden waste, and paper products made up a much smaller portion than in fresh samples. The textiles, rock, and soil made up the larger portion of the aged samples. The composition presented in this paper is given in Table 2.5. The organic content was 33% and pH was measured to be 8.8.

Kavazanjian et al. (2010) collected landfilled sample from tri-cities landfill. The organic content was estimated to be for the sample groups A3, C6 and C3 respectively 13%-23%, 11%-13%, and 17%-27%. A3 waste was retrieved from depth of 25.6- 26.2 m and 15 years old, C3 retrieved from depth of 3.5-4.5m and 2 years old, C6 group samples retrieved from depth of 7.6-9.6 m and less than 1 year old at the time of drilling.

Gomes et al. (2005) conducted a study to characterize the solid waste being disposed at San Tirso landfill. For different ages of waste three different profiles were selected. Organic content at surface ranged from 43%-63% for recent wastes and for 56% for 3 year old waste.

Townsend et al. (1996) studied the conversion of an existing conventional landfill to leachate recirculated landfill. The samples of leachate, landfill gas and landfilled solid waste samples were collected and analyzed before and after leachate recycle for four years to observe the effect of leachate addition to the waste. The researchers reported an increase in moisture content of the MSW due to recirculation. The leachate was recycled by means of an infiltration pond leachate recycle system. Four infiltration ponds were constructed for recycle for the whole landfill except the controlled section where no recirculation was conducted. There was not a significant change reported for the leachate quality. The total sample volatile solids, Biodegradable Organic Fraction (BDOF) volatile solids and BDOF ultimate methane yield were plotted with estimated sample age as presented in Figure 2.5.

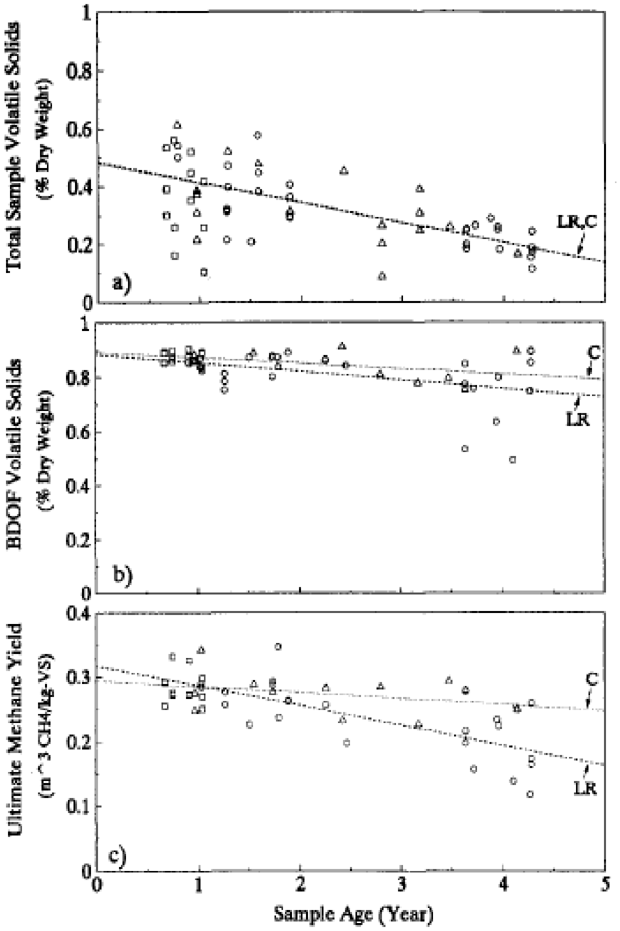


Figure 2.5 MSW Sample Characteristics with Age: (a) Total Volatile Solids, (b) BDOF Volatile Solids and (c) Ultimate Methane Yield BDOF: ◦ Leachate Recycled Area, Δ Controlled Area (C), and ☐ New Waste Area.

The total volatile solids content decreased with sample age for both the leachate recycle area and control area. The BDOF volatile solids did not show any significant correlation with age in both areas. For the ultimate methane yield the samples from controlled area no significant correlation with age was found. However, the leachate recycled area displayed a significant correlation of volatile solids with sample age. The landfill subsidence results and ultimate methane yield indicated that the degree of stabilization was greater in the wet area.

2.4.2.2 Biochemical Methane Potential of Municipal Solid Waste

Owens et al. (1993) conducted research on the Biochemical Methane Potential (BMP) of different components of MSW. The BMP analysis was done using the modified method with sludge from treatment plant as inoculums. BMP was determined on per kg of VS. Both fresh and oven dried samples were used but no significant difference of results was observed. The tests were done extensively on different types of papers and wood and yard waste present in MSW. For different types of paper, the BMP values are presented in the Figures 2.6 and 2.7. The average BMP for paper was calculated to be 0.28 m^3/ kg VS.

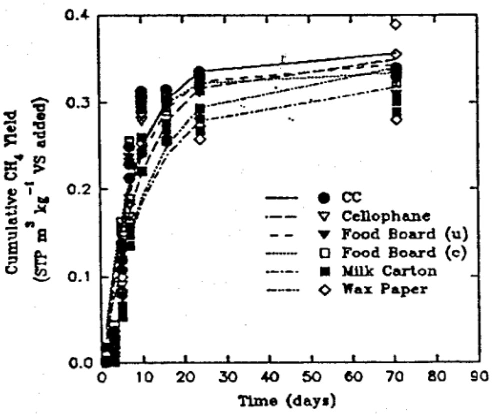


Figure 2.6 BMP Cumulative Methane Production of Paper Products. (Owens et al., 1993)

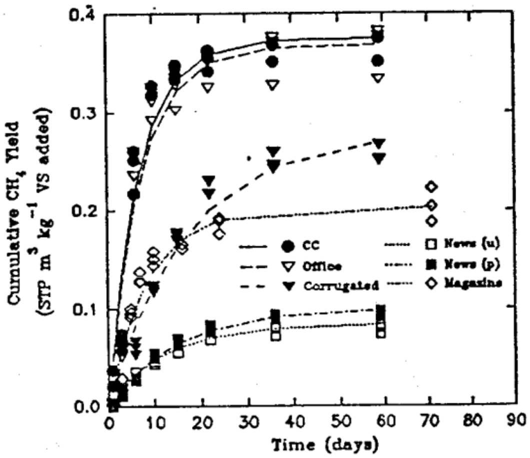


Figure 2.7 BMP Cumulative Methane Production of Food Packaging. (Owens et al., 1993)

For the yard waste samples, BMP cumulative methane production values are illustrated in Figure 2.8.

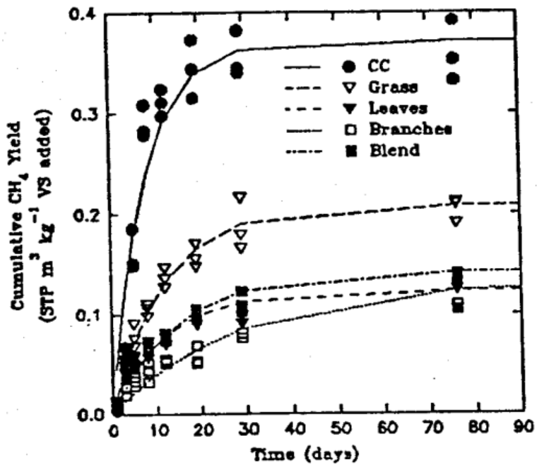


Figure 2.8 BMP Cumulative Methane Production of Yard Waste Samples. (Owens et al., 1993)

The researchers assumed the degradation followed first order rate of decay. The production of methane was assumed to be:

$$Y = Y_{\mu} * (1 - \exp(-k * t))$$

where:

Y - is the cumulative methane yield at time t
Y_{μ} - is the ultimate methane yield
k^{μ} - is the first order rate constant

The parameters were determined using nonlinear regression fit. The first order rate constant k for paper and food packaging is presented in a Table 2.9.

Table 2.9 Volatile Solids and Decay Constant of Different Component of Samples (Owens et al., 1993)

Sample	Y_{μ} (m^3 kg^{-1} VS added)	k (d^{-1})
Paper samples		
Cellulose	0.375 (0.012)	0.145 (0.016)
Office	0.369 (0.014)	0.136 (0.017)
Corrugated	0.278 (0.012)	0.058 (0.006)
News (u)	0.084 (0.003)	0.084 (0.003)
News (p)	0.100 (0.003)	0.069 (0.004)
Magazine	0.203 (0.008)	0.116 (0.012)
Food packaging samples		
Cellulose	0.356 (0.020)	0.119 (0.017)
Cellophane	0.349 (0.023)	0.099 (0.016)
Food Board (u)	0.343 (0.020)	0.119 (0.018)
Food Board (c)	0.334 (0.017)	0.141 (0.020)
Milk Carton	0.318 (0.014)	0.087 (0.014)
Wax Paper	0.341 (0.022)	0.083 (0.012)

The research also indicated that the size of the particles for BMP test showed significant changes in BMP results. The finer particles are better. The coarser the particles reduce substrate accessibility and lower methane productivity.

Barlaz et al. (2002) reported a relative study of refuse decomposition in the presence and absence of leachate recirculation in the landfill operation. The addition of supplementary water was suggested for enhancing the decomposition. Two test cells, including one enhanced cell and one control cell were built and operated for three years. The (C+H)/L ratios for the enhanced cell and control cell was 1.09 and 1.44, respectively. With degradation, L increases and (C+H) decreases which results into lower (C+H)/L ratios. So the lower ratio for the enhanced cell indicates the higher decomposition. Barlaz et al. (2002) found strong correlation between the volatile solids and (C+H)/L. BMP test results showed average BMP from enhanced cell to be 24ml CH^4/dry g, which is significantly lower than the BMP of controlled cell 30.9ml CH^4/dry g. However, the sample BMP values were inconsistent; some BMP results in enhanced cell showed higher values than controlled cell. The high moisture content is suitable for methanogenesis. But no correlation could be established between BMP and moisture content. Barlaz et al. (2002) reported that the samples with high BMP in the presence of high moisture content was not been exposed to the favorable environmental condition decomposition for long enough to be decomposed. The studies reported suggested regardless of the variability the data presented showed recirculation to enhance the degradability, moisture content and settlement of the landfill.

2.4.3 Factors Affecting Gas Generation

Atmospheric concentration and emission rates at three landfill sites were observed by Chen et al. (2009). The researchers noted there were no notable variation in emission rate and atmospheric concentrations. Gas samples were collected from the field in acrylic chambers. Gas composition of the samples was analyzed using both gas chromatograph and FTIR spectrophotometer. The researchers reported the CH^4 concentration was low at the surface and increased by two orders of magnitude at 100m depth. In paddy fields the CH^4 emission rate has been found high at midnight and low in the early morning due to shallow root and substantial effect of soil temperature. According to the researchers, the emission rate depends on waste composition, total organic components, particle size, unit weight, temperature, moisture content, pH, and age of the waste. Gas extraction system, kind and depth of soil cover and methane oxidation also affects the emission rate.

2.4.3.1 Waste Composition

In general, the more organic matter in the waste, the more landfill gas will be produced. To break down the waste, the bacteria need small amounts of certain minerals like calcium, potassium and magnesium and some other nutrients. With the presence of these nutrients, the bacteria produce gas rapidly. The rate of gas production depends on the composition of the waste.

Suthatip et al. (2006) conducted research on the biodegradability of the reference material (food, wood and paper) and excavated MSW samples from a closed landfill aged approximately 20 years. The composition of waste recovered from the closed landfill is presented in the Figure 2.9.

To measure the remaining potential of biodegradability and further methane generation, BMP tests were conducted on the excavated MSW samples and reference materials. To simulate the biodegradation in aerobic condition of the landfill, waste respiration tests (AT4) were also performed. The test results are shown in the Table 2.10.

Table 2.10 Fiber Contents, %TOC, %Ignition loss, AT4 Values and BMP Results (Suthatip et al., 2006)

Parameters	Food	Paper	Wood	Excavated sample
Hemicellulose (%)	0.29	8.75	13.24	5.8
Cellulose (%)	7.13	74.18	38.64	54.82
Lignin (%)	0.29	5.25	24.90	11.97
(C+H)/L ratio	25.78	15.79	2.08	5.07
AT4(mg O_2/g-DS)	95.84	9.36	32.80	9.89
Total gas production(ml/g-VS)	931.02	918.36	110.92	162.44

The AT4 value for the excavated sample indicates that the waste was less stabilized. The methane production rate for food was much higher like paper. On the contrary wood generated less methane. Food and paper are readily decomposable, while because of the crosslink structure of lignocelluloses, wood had not undergone much biodegradation. According to Funoaka et al. (1990) hydrolysis of wood is slow because of cellulose in wood has crystallinity and it is covered by lignin. The excavated sample was degraded slowly. Research on methanogenic conversion of lignocellulosic components in MSW suggested that the presence of lignin reduces methanogenic degradability. The researchers reported that the cellulose presented in the excavated refuse sample maybe was not available for anaerobic biodegradation. The cumulative CO_2 + CH_4 production of each test material (CO_2 + CH_4) ; CH_4 and CO_2 with time are presented in Figure 2.9. (Suthatip et al., 2006)

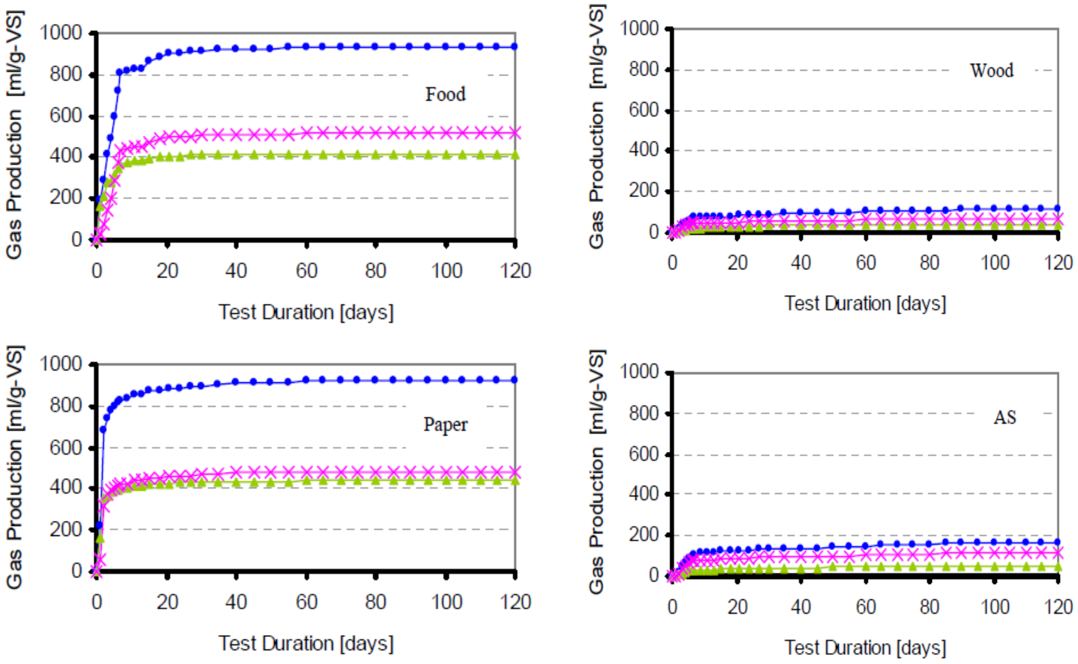


Figure 2.9 Cumulative CO_2 + CH_4 Production of Each Test Material: ♦CO_2 + CH_4; X CH_4 and Δ CO_2 (Suthatip et al., 2006)

The researchers concluded that the excavated old refuse was not much transformed into methane and carbon dioxide gases as the readily degradable components were not present in the sample and the sample was mostly consisting of slowly degradable organic carbon.

2.4.3.2 Particle size

Gomes et al. (2005) conducted a study to characterize the solid waste being disposed of at San Tirso landfill. For different ages of waste three different profiles were selected. Profile A was still in operation and other two closed (profile B and C). One of the closed zone, profile C is coming waste of old dumpsite and profile B is preselected and treated wastes disposed between 1998 and 1999.

Laboratory experiments including physical, chemical, compressibility and shear strength characteristics and field monitoring program of displacement, lateral deformations, horizontal pressure and pore water pressure is determined. The physical tests included classification of wastes, determination of volumetric weight, moisture content and organic content of waste. Table 2 shows the waste composition of profile B (closed zone and waste from 1998-1999).

The volumetric weights for profile B at height 0.6m and 11m was 11.0 KN/m3 and 11.6 KN/m3 respectively. Moisture content ranged from 61% near the surface (recent waste) to 117% at 11m depth (3 year old waste). Organic content at surface ranged 43%-63% for recent wastes and for 3 year old waste 56%. The particle size distribution curve is shown below in Figure 2.10.

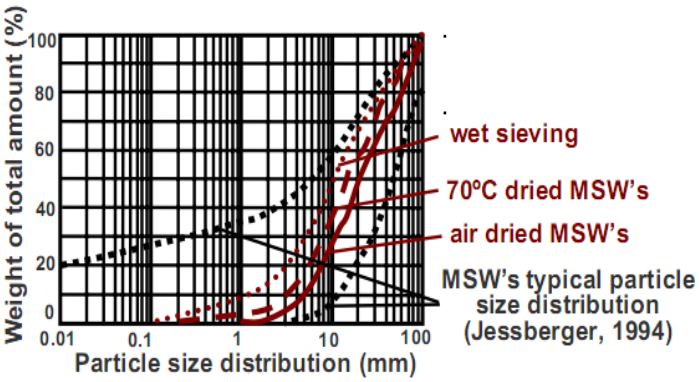


Figure 2.10 Particle Size Distribution Curve (Gomes et al., 2005)

2.4.3.3 Moisture Content of the Waste

A moisture content of about 40% by weight is required for maximum bacterial activity and maximum rate of gas production. According to Christensen and Kjeldsen (1989), analysis of the characteristics of closed Subtitle D landfills and the processes that govern landfill gas production shows that landfill gas production rates are directly proportional to the moisture content of the wastes between about 20% moisture and close to waste saturation, where there is free moisture adjacent to the waste particles. If moisture is below 20%, there is insufficient moisture in the waste to support biological activity of the bacteria responsible for landfill gas production. Compaction of the waste and the presence of layers of poorly permeable material such as clay used for covering will tend to reduce gas production because they obstruct the passage of moisture. Recirculating leachate back into the waste tends to increase the rate of gas production.

According to US EPA (2008) the monitoring period for closed landfills is at present 30 years. Christensen and Kjeldsen (1989) suggested that there could be moisture intrusion through the cover layer of the soil which cannot be virtually inspected in the field. So there is no reliable way to predict landfill gas production rate and duration of production in closed subtitle D landfill as they are dependent on the rates of deterioration of plastic layers in the landfill cover and plastic bags that exist within the landfill. Lee reported a study on unreliability of the landfill gas production rate and duration for closed subtitle D MSW landfills. It was observed that landfill gas production rate is directly proportional to the moisture content of the wastes between about 20% moisture and close to waste saturation where there is free moisture adjacent to the waste particles. After the closure of the landfill the unfermented organic components of the waste begin to produce gas, which is proportional to the moisture content of the waste, as presented in Figure 2.11.

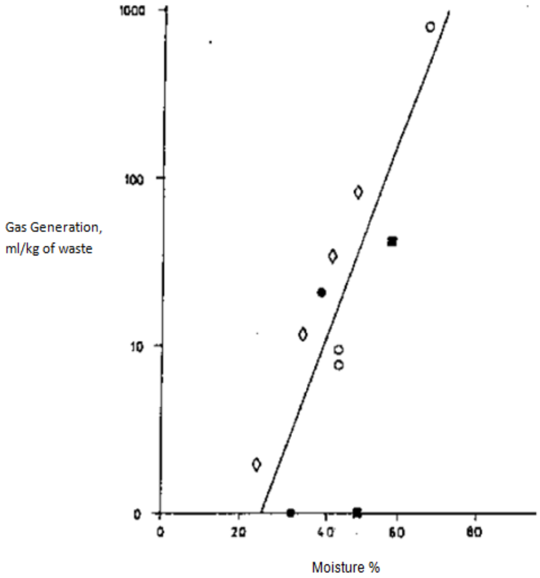


Figure 2.11 Landfill Gas Generation Rate as a Function of Moisture (Christensen and Kjeldsen, 1989)

2.4.3.4 Age of the Waste

Landfill gas production begins as soon as waste has been deposited, but anaerobic methane production only occurs when all of the available oxygen has been depleted. Peak landfill gas production generally occurs about a year after deposit and thereafter gradually declines. Significant gas production is generally completed within about 20 years of deposition, but every site is different. Where gas production is slow, the period of significant gas production may extend for 40 or 50 years.

The pattern of gas production for an entire site is the sum of the performance of all of the individual components of waste. Some will be rapidly enter the gas generation stage, others will be slower.

Similarly, the period of significant gas production will vary, and for an entire site most often extends over several decades.

Landfill gas generation has two primary time-dependent variables:

(i) Lag time and

(ii) Conversion time.

Lag time is the period from waste placement to the start of methane generation (see Figure 2.12, start of Phase III). The conversion time is the period from waste placement to the end of methane generation (Figure 2.12, end of Phase V). For example, yard waste has very short lag and conversion times, while leather and plastic have very long lag and conversion times.

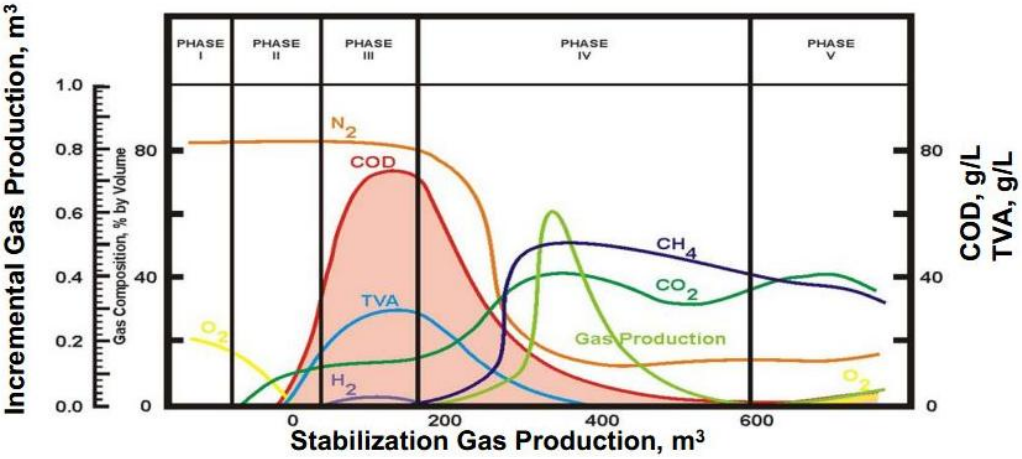


Figure 2.12 Modified from Pohland and Harper, 1986

2.4.3.5 Temperature of the Waste

Higher temperatures promote volatilization and chemical reactions within the waste so the trace gas component of landfill gas tends to increase with higher landfill temperatures.

Zhu Xiang-rong et al. (2002) reported geotechnical behavior of the MSW in Tianziling landfill which was built in 13 years. It was filled by stages and has three platforms. They reported the temperature of the boring was between 30°C to 46°C.

Barlaz et al., (2002) reported a relative study of refuse decomposition in the presence and absence of leachate recirculation in the landfill operation. Temperature in both cells reached up to 50-55°C but in the controlled cell it decreased and became stabilized at 25-32°C. It also decreased in the enhanced cell but increased with the addition of leachate and stabilized at 35-40°C.

Hossain et al. (2009) conducted a research to compute permeability based on 4 lab scale bioreactors representing 4 stages of decomposition. The measured temperature was at 22-29^{o}C.

Studies (EMCON, 1998) have shown that anaerobic gas production in lower temperatures (100°F to 1300°F or 38°C to 540°C) produces significantly higher methane (45 to 57%) and lower carbon dioxide (40 to 48%).

2.4.3.6 Availability of Oxygen

In aerobic environment the biodegradation is rapid and produced gas contains mostly carbon dioxide. In a typical landfill where waste is quickly compacted and covered, aerobic degradation only occurs until the entrained oxygen is used up in newly deposited waste. Where oxygen is not available, the waste is broken down by anaerobic bacteria that produce landfill gas, containing roughly equal amounts of methane and carbon dioxide.

2.4.3.7 Effect of Leachate Recirculation

Barlaz et al. (2002) conducted a research in Yolo County landfill project to observe early and greater methane energy recovery as an effect of water and leachate addition. They reported conventional landfilling produced insufficient gas for collection and had substantial fugitive emissions. Enhanced leachate recirculated cells initially resulted in high methane recovery due to effects of both moisture and temperature effects. Also the conventional landfill cell produced high methane due to the temperature effect. The gas production of conventional landfill was half of the production of recirculated cell. However, after the initial burst the productivity of the dry cell was flatten to nearly zero.

A side by side comparison was made on the presence and absence of leachate recirculation in Yolo County landfill by Mehta et al. After three years of operation, waste was drilled from the borings. The extent of decomposition of excavated sample was determined by the Biochemical Methane Potential (BMP) test and ratio of Cellulose + Hemicellulose to Lignin ((C+H)/L as presented in Figure 2.13. The (C+H)/L ratio were 1.09 to 1.44. The authors' commented that these data correlate well with the increased methane production in the enhanced cell.

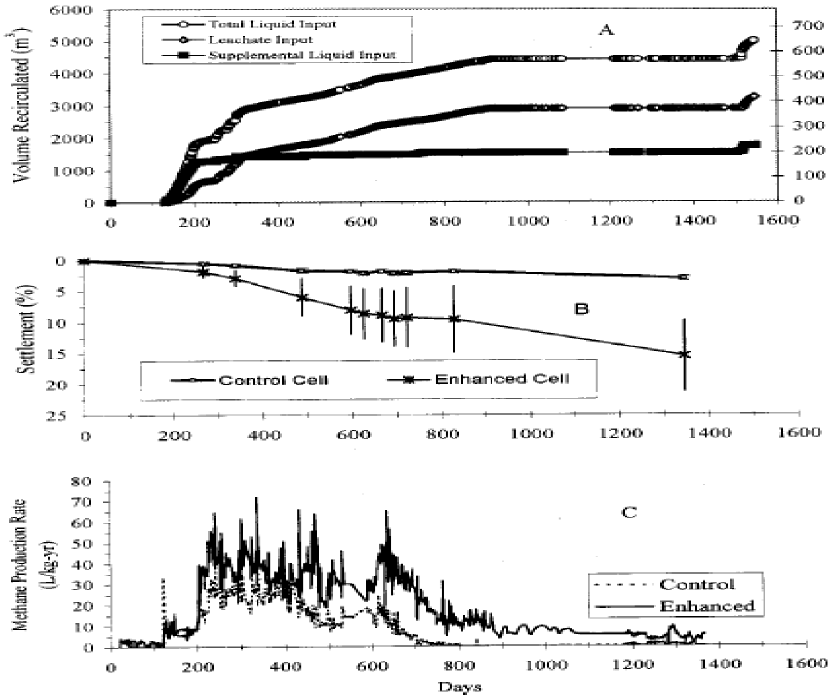


Figure 2.13 (a) Cumulative Liquid Input for Recirculation of Leachate and Supplemental Liquids (b) Refuse Settlement over Time and (c) Methane Production Rate in Enhanced and Control Cells.

Measured average methane yield for enhanced cell was 24.0 mL CH^4/dry g. So the remaining methane potential of the enhanced cell is estimated to be 130,368 m^3. This estimation was based on the presence of 6612 metric ton of wet waste. If 50% of the remaining methane potential as measured in /bmp test were to be produced then the measured yield for the landfill would become 71.5 L/wet-kg. And similarly from controlled (non-recirculated) cell ultimate methane yield was estimated to be 40 L/wet-Kg. If 100% of the remaining methane potential as measured in the Bmp test were to be produced, then the measured yield for the landfill would become 79.9 L/wet-kg. Similarly, for the controlled (non-recirculated) cell ultimate methane yield estimated to be 52.0 L/wet-Kg. The analysis conducted suggested that significantly more CH^4 can be expected from both cells. The refuse was not uniformly wet in the cell and therefore the refuse was partially decomposed. The sample composition, BMP and Volatile solids data are presented in Table 2.11.

Table 2.11 Sample Composition, BMP and Volatile Solids

Boring	H_20	Cellulose	Hemicellulose	Lignin	$(C+H)/L_i$	Volatile Solids	BMP
(depth)	(%)	(%)	(%)	(%)		(%)	(ml $CH_{4)}$
C2(5.4)	1.04	1.19	1.02	1.13	1	1.12	1.56
C2(7.1)	1.01	1.04	1.01	1.15	1.12	1.05	1.33
E1(1.8)	1.04	1.4	1.46	1.21	1.16	1.13	1.96
E2(2.8)	1	1.11	1.08	1.07	1.18	1.04	2.08
E2(4.5)	1.03	1	1.05	1.1	1.09	1.17	1.7
E2(6.4)	1.04	1.15	1.36	1.3	1.12	1.24	1.03
E2(8.2)	1.18	1.28	1.05	1.06	1.3	1.09	1.06
E2(9.2)	1.32	1.13	1.21	1.92	2.21	1.2	1.34
E3(3.2)	1.08	1.45	1.54	1.19	1.22	1.22	4.22
E3(5.3)	1.01	1.76	1.43	1.46	1.13	1.18	4.87

Morris et al. (2003) conducted studies on field scale. Two test cells were prepared, one with recirculation and another without recirculation. The researchers reported waste characterization studies indicated that significantly more degradation of paper had occurred in the recirculated cell than the conventional cell. The recirculated cells were more degraded and had more fine components and also were less odorous. The gas generation of the conventional cell was only 10% of the gas generation from recirculated cell based on measured data from the field for 7 years as shown in Figure 2.14. According to the authors, addition of moisture shortened the duration of landfill gas production compared to the conventional landfill cell. The authors suggested that methanogenic conditions were not fully established in the conventional cell during the monitoring period of these 7 years.

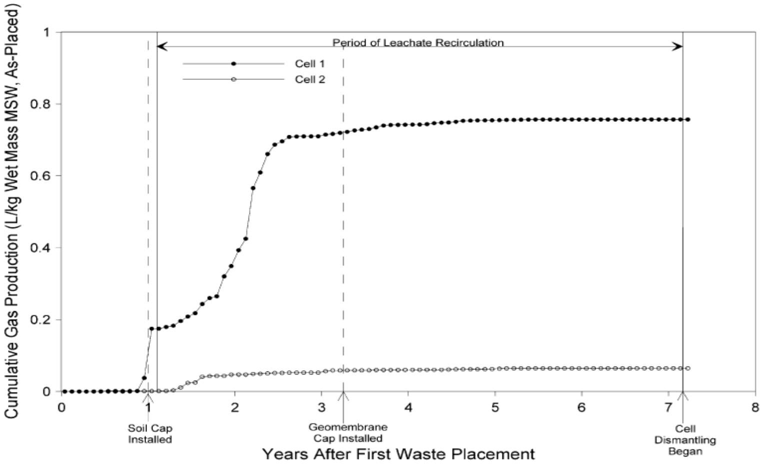


Figure 2.14 Cumulative Gas Productions in the Test Cells. Cell 1: With Addition of Moisture. Cell 2: Without Moisture Addition, Conventional Cell.

Bayard et al. (2005) conducted a comparative study of leachate recirculation between in situ and lab scale simulation. The landfilled waste was collected from Lons-Le-Salunier landfill and part of residue was collected from a sorting plant and public area. The waste composition of Lons-Le-Salunier landfill is presented ion table 2.12. A similar composition was used for the reactors.

Table 2.12 Sample Composition from France (Bayard et al., 2005)

Composition	Percent Weight (Wet Weight)
Fine Gray(Waste from Sorting Operations)	51.6
Fine Blue(<35 mm, obtained from waste sieving after sorting operations and Inert waste)	2.1
Refuse(<100 mm, obtained from waste sieving after sorting operations and Inert waste)	4.3
Inert Waste (like wood, plastic, gravel)	42.0

The reactors were set up to simulate waste anaerobic biodegradation with and without leachate recirculation. The researchers confirmed the beneficial effect of leachate recirculation, as it reduces the lag phase in the beginning of gas generation. They also reported an increase in carbon conversion rate and cumulative biogas production at the end of the incubation time, as illustrated in Figure 2.15. They also observed larger decrease of oxidative organic matter content and lipid index with leachate recirculation. The researchers performed BMP test and observed better waste biostabilisation with leachate recirculation.

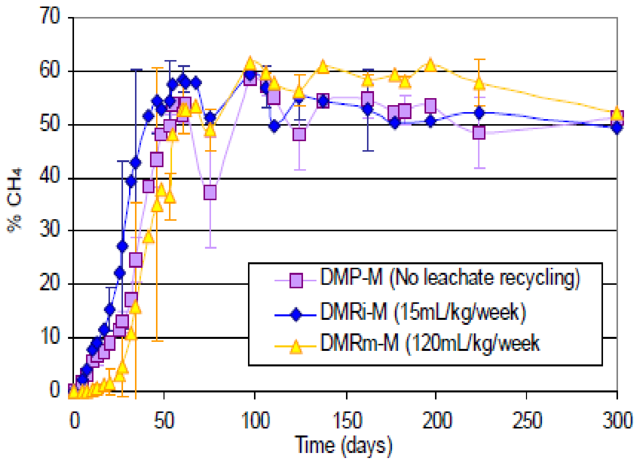


Figure 2.15 Gas Productions with Time (with and without Leachate Recirculation)

2.5 Landfill Gas Generation Models

Akunna et al. (1996) reported the findings of a study to estimate the methane potential of a closed landfill in Dundee. Five boring locations were selected based on the leachate and gas monitoring data of the buried wastes. The solid samples were analyzed using accelerated biodegradability test (ABT) in order to assess their state of degradation and methane potential of the landfill. Dundee landfill receives municipal solid and commercial wastes within the city boundaries and no leachate recirculation is practiced in the site. In this study a methodology based on leachate quality and a physical-chemical characteristic of waste was used to estimate methane production potential of a closed landfill. The study was compared to the biogas production potential from laboratory biodegradability studies and from simulation studies carried out with landfill gas simulation software, GasSim. In this study the historic leachate and gas flow monitoring data indicated that most solid wastes in the landfill were at the final stage of biodegradation process. In situ leachate was of low strength, indicating that most readily biodegradable organic matter has been stabilized. Low in situ temperatures (8-10°C) measure in the site indicates low degradation rates of the remaining organic matter. The methane generation rates calculated using GasSim at 20° C were comparable with the results obtained from ABT approach. These results showed that methane generation rate significantly decreases with the decrease in temperature and moisture contents. The results of the study showed that if leachate recycling is not practiced the leachate characteristics can be good indicator of the state of decomposition and biogas production potential of the site.

Townsend et al. (1996) evaluated the historic and current performance of gas collection and leachate recirculation system of the Highlands County Landfill, Florida. The landfill started accepting waste in March 1996. Horizontal perforated pipes were installed as waste was being placed in the landfill. These pipes were used for leachate recirculation as well as gas collection. Gas quality data was collected at different locations. Potential gas collection was modeled using a modified version of the protocol developed for United States Environmental Protection

Agency's Landfill Gas Emissions Model (LandGEM). For gas generation prediction, standard assumptions were used, along with waste tonnage records collected from the landfill. Several possibilities were explored with the help of this model. The results as presented in Figure 2.16 and Figure 2.17 indicated that the gas collection efficiency in the field is relatively low.

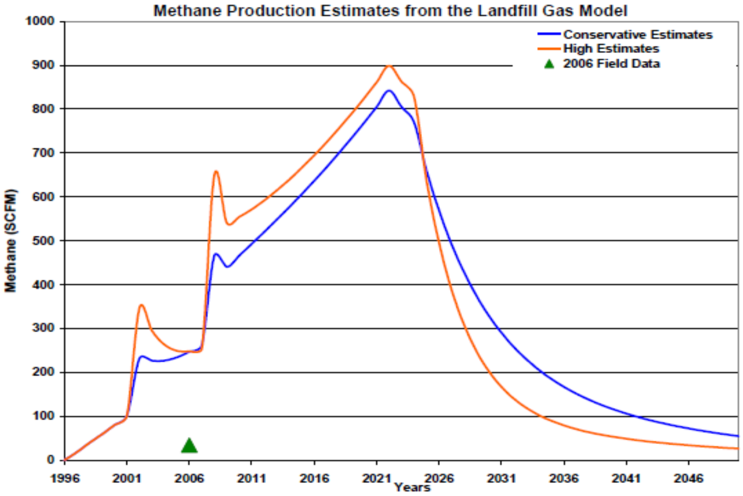


Figure 2.16 Methane Production Estimates over Time for Highlands County Landfill, Florida. (Townsend et al., 1996)

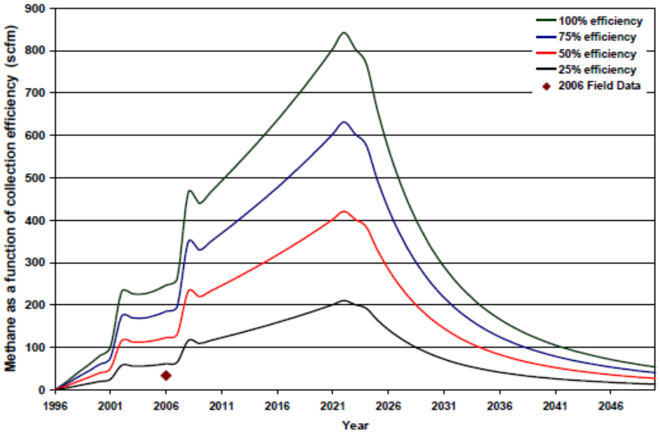


Figure 2.17 Methane Gas over Time as Function of Gas Collection Efficiency (Townsend et al., 1996)

The researchers collected samples from field by drilling. The moisture content of samples was determined. To evaluate the gas potential, BMP tests were conducted. BMP assess the degree of waste degradation. The temperature of the waste samples was recorded immediately after the collection of samples. The results suggested in the vicinity of leachate recirculation, the waste was more stabilized and does not have much remaining methane potential. The settlement of the landfill was also monitored using a vibrating wire settlement profiler.

Manzur et al. (2010) conducted research on landfill gas generation from aerobic and anaerobic biodegradation of organic materials in City of Denton landfill, Texas. Gas generation and composition data were monitored for ten lateral pipes. Three pipes were monitored for 365 days to evaluate the influence of moisture injection. The pipes were chosen in a way that two of the pipes were recirculating pipes and one was non recirculating pipe. The landfill gas composition and gas flow were measured for these three pipes. The average flow rate for the recirculating pipes were measured to be 15 ft^3/min and for the non recirculating 10 ft^3/min. From the test results the composition of the gas was found Methane 60% for recirculating pipes and 45% for non recirculating pipes. According to the researcher the gas flow rate was compared with the predicted flow rate to evaluate efficiency of leachate circulation system and gas collection system.

CHAPTER 3

METHODOLOGY

3.1 Background

The main objective of the study was to determine the physical and hydraulic characteristics of the collected sample from a closed section of city of Denton landfill and to evaluate the gas potential of the landfilled solid waste.

The physical and hydraulic characteristics of solid waste include physical composition, moisture content, unit weight, particle size distribution, and permeability. For the evaluation of gas potential, volatile solids tests were performed on the samples in the laboratory. The first order gas generate on model was used in this study to predict the future gas generation of the closed landfill.

3.2 Selected Study Area

The City of Denton Landfill is located on the south east side of Denton, Texas. The aerial view of the City of Denton Landfill is shown in Figure 3.1.

Figure 3.1 City of Denton Landfill

The City of Denton Landfill was built in 1983. The Denton landfill received its permit to start accepting waste on March 7, 1983 (permit number of 1590). Cell 1590 was pre subtitle-D. The permit was modified the permit number changed to 1590A. Initially the landfill started with 32 acres and then expanded in 1998. The expanded landfill covers a total of 252 acres, with 152 acres for waste and 100 acres for offices, buffer zone, compost and extra rented land. At present there are six cells in the landfill and the former cell is considered as cell zero or cell 1590 A. City of Denton landfill currently receives approximately 550 tons of MSW a day with 80% of the waste commercial and 20% residential. The landfill is a type I landfill which means that it is a standard landfill for the disposal of municipal solid waste (MSW). The landfill follows operational rules cited in the 30 TAC 330 subchapters D, which is provided by the Texas Administration Code. In 2009 the landfill transitioned to an enhanced leachate recirculation landfill to increase the gas production and capacity of landfill space.

For the present study solid waste samples were collected from two boreholes B-70 and B-72 of cell 1590 A as presented in Figure 3.2. These locations were chosen as the landfill owners operated drilling on these locations for gas pipe installation.

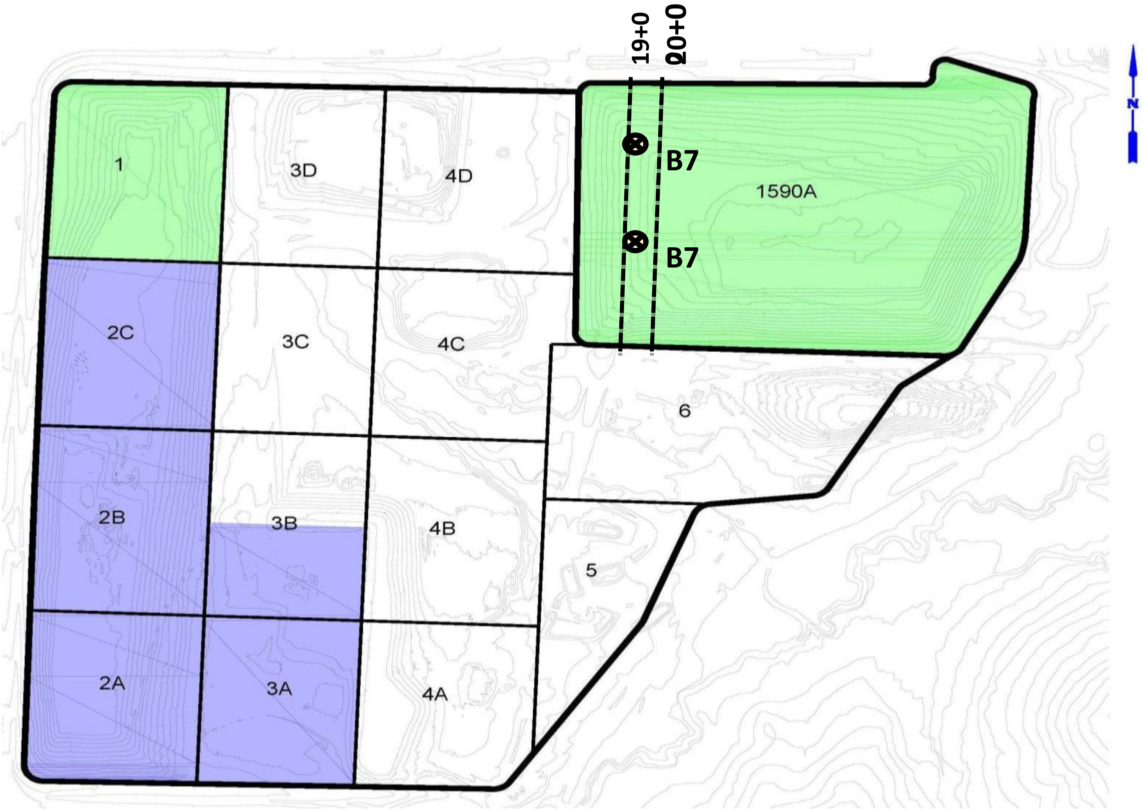
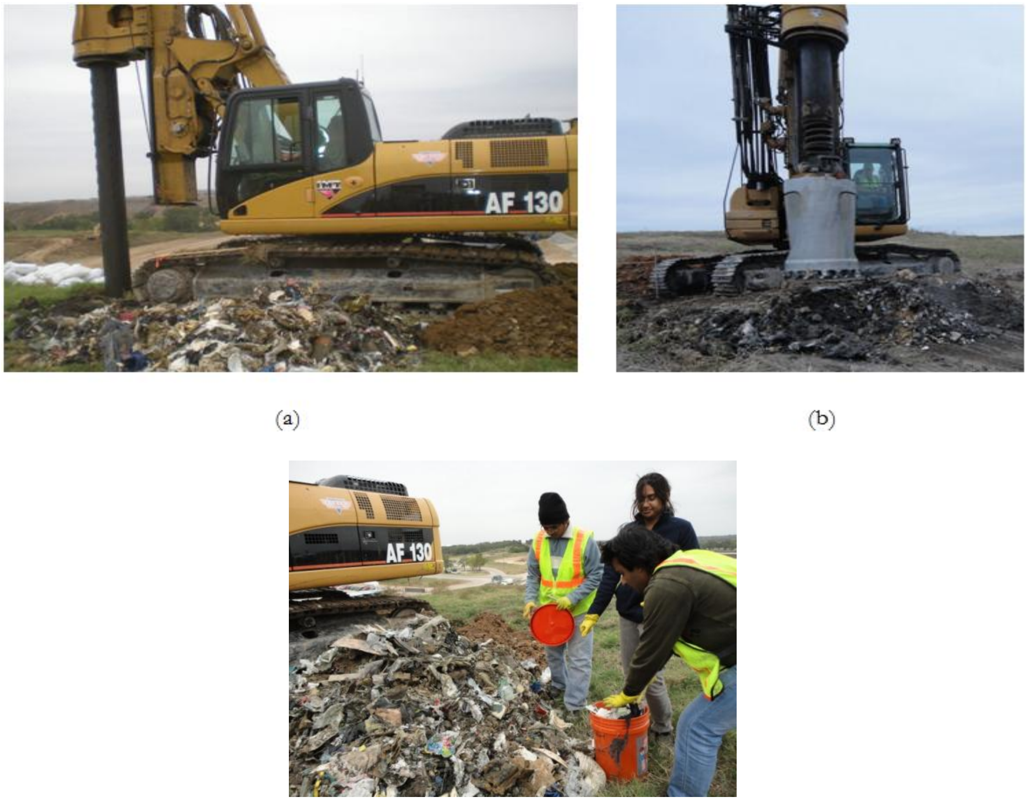


Figure 3.2 Locations of Boreholes in the Layout of the City of Denton Landfill

3.3 Sample Collection & Storage

Solid waste samples were collected from the Denton landfill in November 2010. A 3 ft diameter bucket augur attached to an AF130 Hydraulic Drill Rig was used for drilling, as shown in Figure 3.2. Solid waste samples were collected from 2 boreholes (B70 and B72). The boreholes were drilled on Cell 1590 of the landfill. The solid waste collected from that section of the landfill is as old as 25 years. Age of the sample was estimated from the dated newspapers and magazines of the collected samples.

Six samples were collected from each borehole starting at 10 ft depth and then at every 10 ft interval up to 60 ft. From previous research work conducted by Taufiq (2010), it was observed that the required MSW sample weight for characterization is 25 to 30 lbs. Therefore, 25 to 30 lbs of MSW was collected for each sample. The sample collection is presented in Figure 3.3 below.



(a) (b)

(c)

Figure 3.3 (a) AF 130 Hydraulic Drill Rig, (b) 3-ft Diameter Bucket Augur, and (c) Sample Collection

The collected samples were brought to the laboratory in lidded plastic buckets. All the bucket samples were stored and preserved at approximately 38°F (below 4°C) in an environmental growth chamber. The environmental growth chamber is shown in Figures 3.4 and 3.5.

‘

Figure 3.4 Environmental Growth Chamber

Figure 3.5 Samples Stored in Environmental Growth Chamber

3.4 Experimental Program

An extensive experimental program was developed for the current study. The experimental program is presented in table 3.1.

Table 3.1 Experimental Test Program

Test Type	Sample	No. of Tests
Physical Composition	Landfilled MSW	2x 6 = 12
Moisture Content	Landfilled MSW	2x 6 = 12
Unit weight (Standard Proctor Method)	Landfilled MSW	2x 6 = 12
Unit weight (using 60 KPa tensile-compression Machine)	Landfilled MSW	2x 6 = 12
Hydraulic Conductivity	Landfilled MSW	2x 6 = 12
Particle Size Distribution	Landfilled MSW	2x 6 = 12
Organic Content Test	Landfilled MSW	2x 6 = 12

The methodology adopted for determination of the physical characteristics and hydraulic characteristics are described in the following subsections.

3.4.1 Physical Composition

To determine the physical composition of the samples, each bucket was poured onto a large plastic sheet and manually separated into the following categories: paper, plastic, food waste, leather & textile, wood & yard waste, metals, glass, styrofoam & sponge, others (soil & fines), and construction debris, as shown in Figure 3.6.

Figure 3.6 Physical Composition of Waste

The paper category included of all kinds of papers like cardboard packaging, newspaper, magazines, office papers, etc. All plastic polythene bags, containers, food wrappers, plastic bottles were placed under plastic. Rubber was also considered with plastic. All clothes, fabrics, leathers, etc., and the construction insulation material thrown after demolition was also categorized as leather & textile. Branches, leaves & grass from garden trimming, and also broken pieces of wood from construction & demolition categorized as wood and yard waste. All metal cans, cutlery and food container were placed under metal category. Construction debris constituted of limes, bricks and stone chips, broken tiles etc. Any portion of the solid waste that could not be placed under any of the above mentioned categories, lumps of mud, and objects too small to separate was categorized as others. Also the others component was separated into degraded portion and soils later.

All the manually sorted components were then individually weighed, and the weights were presented as a percentage of total weight. The total weight in paper, food waste, leather & textile, and wood & yard waste categories were considered degradable and the rest of the total weight as non-degradable. The percentages of degradable and non-degradable portions were also determined.

3.4.2 Moisture Content

For determination of moisture content, three types of specimens can be used:

1. Grab sampling before sorting
2. Proportionately taking each component according to physical composition after sorting
3. Taking standard proctor compacted sample (proportional to composition)

For the current study, method 1 was used for moisture content determination. Moisture content of the samples were determined according to standard method ASTM D 2974 – 00 and APHA 2540 – B (Kelly, 2002). For each test, a minimum 2 lbs of waste were taken, so that it would be more representative of the original MSW. The measured samples were then dried at 105°C in the oven for 24 hours to determine the moisture loss. And the percent loss was determined on both dry weight and wet weight basis. Equations 3.1 and 3.2 were used to determine moisture content on wet weight basis and dry weight basis, respectively. Figure 3.7 shows sample being dried in the oven for the determination of moisture content. The wet weight moisture content is expressed as follows (Tchobanoglous et al., 1977):

$$Moisture\ Content, \%\ (wet\ wt\ basis) = \frac{a-b}{(a)} x100 \tag{3.1}$$

Where, *a* = initial weight of the sample as delivered; and

b = weight of the sample after drying.

Moisture contents can also be determined based on the following relationship

$$Moisture\ Content, \%\ (dry\ wt\ basis)\ = \frac{a-b}{(b)} x100$$

(3.2)

Where, *a* = initial weight of the sample as delivered; and

b = weight of the sample after drying.

Figure 3.7 Samples Placed in Oven for Determination of Moisture Content

3.4.3 Unit Weight

The unit weights of the samples were determined at their natural moisture content. The municipal solid waste was compacted as per Standard Proctor Compaction ASTM D698. A larger sized compaction mold with 6 inch inside diameter, 6.1 inch height, with a volume of 1/10 cubic feet with detachable collar was used. The mold was filled with three layers of solid waste up to the rim. A 5.5 lb hammer with 2 inch face was dropped 75 times for a fall height of 12 inch on each of 3 MSW layers to attain the required compaction. The use of 75 blows instead of 25 was determined based on the compaction energy per volume.

$$Energy\ transferred\ in\ standard\ proctor\ test,\ E = n \times \mathrm{h} \times P/V$$

Where, n = number of blows, h = fall height, P = weight of hammer and V = volume of the mold. P and h are equal for the regular sized and larger mold. For E to be same for both cases, n/V should be equal. As the volume of the mold (V) for the current study is three times larger, the number of blows (n) should also be three times more per layer. The weight of the mold was measured both before and after filling the waste. Equation 3.3 illustrates how to calculate compacted unit weight of solid waste. Figure 3.8 illustrates the sample preparation for unit weight determination.

Figure 3.8 Sample Being Compacted

$$Unit\ Weight = \frac{weight\ of\ compacted\ waste\ in\ the\ mold(lb)}{Volume\ of\ the\ Mold(ft3)} \tag{3.3}$$

The unit weight determined from the standard proctor does not consider the overburden pressure on the samples. As the samples were collected from different depths, the overburden pressure is different for the individual samples. For the samples recovered from the different depths, overburden pressure was determined. The samples were compacted by 60 KPa tensile-compression machines, as illustrated in Figure 3.9. The applied load was calculated from the overburden pressure and the cross sectional area of the mold.

Municipal solid waste when placed in the landfill is compacted with heavy compaction equipment. For the City of Denton, the compactor, commonly used provides 1000 to 1200 lb/yd^3 compaction. So for the overburden pressure unit weight of Municipal solid waste considered to be 45 lb/ft^{3,} which is equivalent to be 1200 lb/yd^3 of field compaction. And for the cover soil unit weight of 120 lb/ft^3 was assumed.

(a)

(b)

(c)

Figure 3.9 (a) 60 KPa Tensile-Compression Machine (B) Overburden Pressure Applied to the Sample (c) Prepared Sample

3.4.4 Particle Size Distribution

Particle size analysis of MSW was done using dry sieve (Figure 3.10). The samples were prepared in accordance with ASTM D2217 and the analysis was conducted in accordance with ASTM D422-63. For the analysis first the samples were dried once again at 105°C to a constant weight. The oven dried samples from each depth were passed through a series of sieves (4-in, 1-in, 3/8-in, No.4, No.8, No 10, No. 20, No. 40, No. 80, and No. 100). The particles retained on each sieve were collected and weighed. The percentage passing through each sieve was then calculated by dividing the weight of sample retained on each sieve by the total weight of the sample. The grain size distribution curve was plotted for all the samples.

Figure 3.10 (a) Oven Dried Sample (b) Weighed Empty Sieve (c) Retaining Samples on the Sieve (d) Weight of the Sieve with the Sample Retaining on It

3.4.5 Hydraulic Conductivity

To determine the hydraulic conductivity of collected samples, a constant head permeability test was performed. The standard procedure of ASTM D 2434-68 was followed. As permeability is a function of unit weight and overburden pressure, all the tests were conducted at the estimated overburden pressure and calculated unit weight of the samples.

The compaction permeameter is a 6 inch diameter mold with a volume of 1/15 cubic feet. To compact the samples in the mold in the desired density, compaction effort was provided by the “60 KPa Tensile-Compression machine”. Then the compacted sample in the permeameter mold was screwed to a base plate with built in porous stone at the bottom. A porous stone was also placed on the top (as shown in Figure 3.11 and Figure 3.12) before the top cap was screwed with the mold. O-ring was placed on both top and bottom of the mold between the mold and base plate, and between the porous stone and the top cap. O rings are used to seal the system to avoid any leakage.

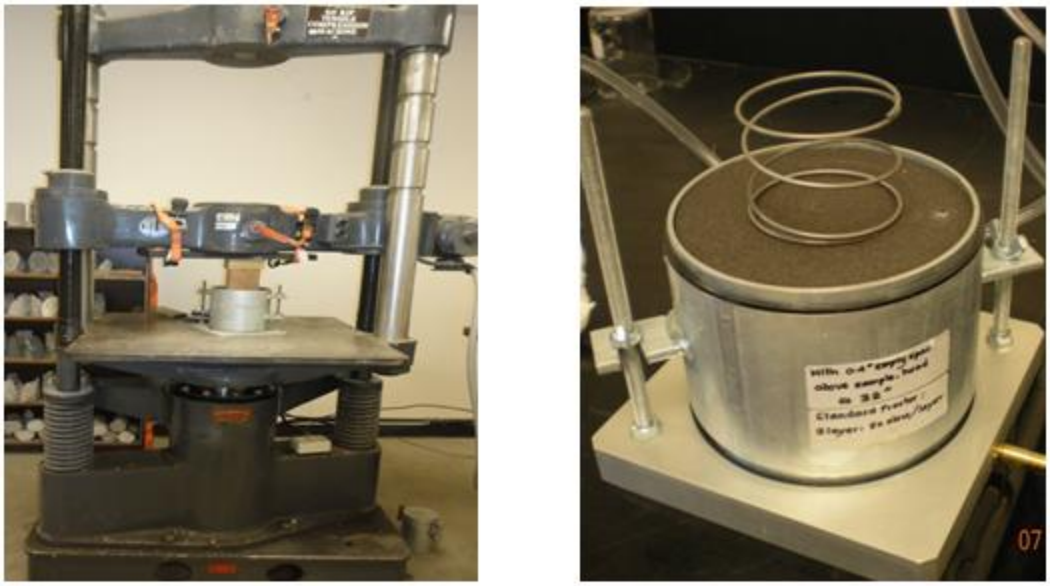

(a) (b)

Figure 3.11 (a) Sample Preparations (b) Partial Permeability Setup

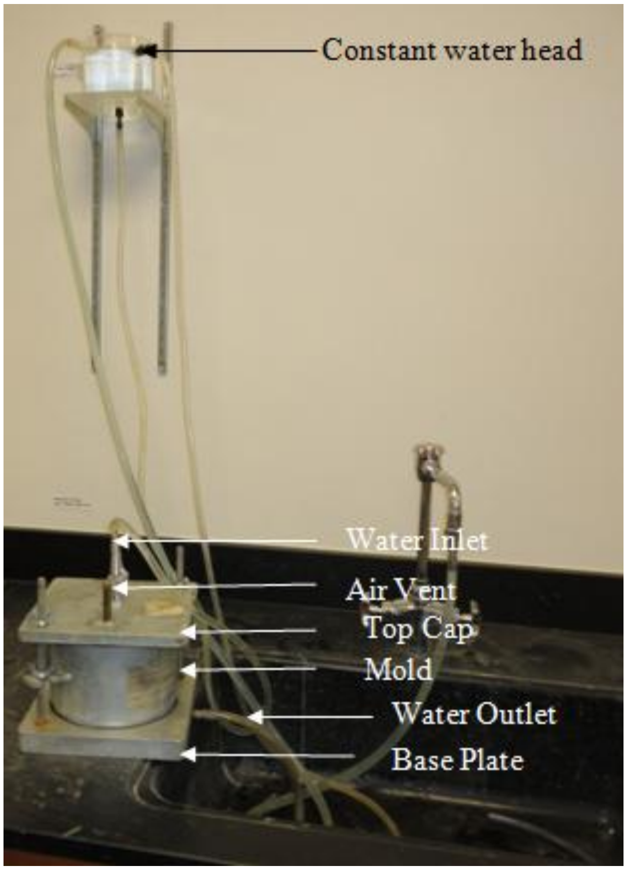


Figure 3.12 Permeability Setup

3.5 Evaluation of Landfill Gas Generation Potential

The decomposition of organic components of MSW produces gas. The decomposition process may continue for 20 to 100 years, depending on the operational practices of the landfill. The prediction of gas generation potential is important for the optimization of the energy recovery and estimation of the greenhouse gas emissions from the landfill.

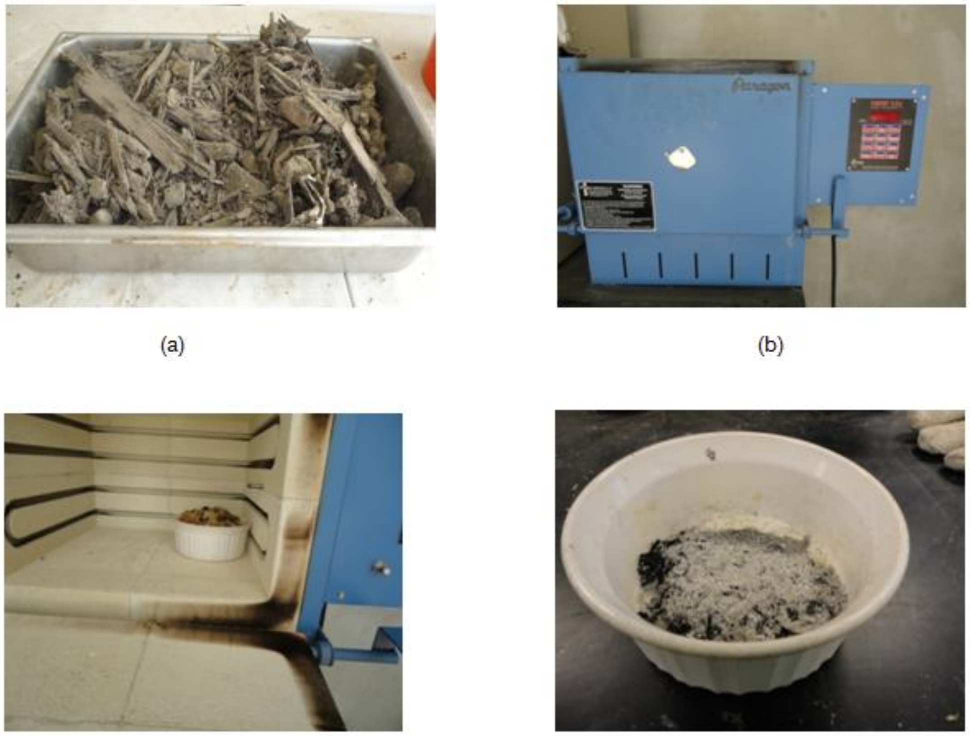
Landfill gas production results from chemical reactions and microbes acting upon the waste as the putrescible materials begins to break down in the landfill. The rate of production is affected by waste composition and rainfall rate and temperature. The spatially heterogeneous nature of most landfills means that there will be a wide range of physical conditions and biological ecosystems co-existing simultaneously within most sites. This heterogeneity, together with the frequently unclear nature of the contents, makes landfill gas production more difficult to predict.

To evaluate the gas potential of landfill, direct lab tests are performed to determine the availability of organic component present by volatile solids test of Biodegradable Organic Fraction (BDOF). EPA recommended gas model LandGEM was also used to determine the gas potential left of the closed section of the City of Denton landfill.

3.5.1 Test Methodology for Volatile Solids of Municipal Solid Waste

The volatile solids procedure followed a modified version of Standard Methods APHA Method 2440-E. Samples were dried once again at 105°C to a constant weight and held in a desiccator. Approximately 50 gm of dried MSW were placed in pre-weighed porcelain crucibles and inserted into a muffle furnace at 550°C for 2 h. Equation 3.4 illustrates how to calculate volatile solids of solid waste. Figure 3.13 illustrates the sample preparation for volatile solids determination.

$$Volatile\ Solids = \frac{Weight\ Loss\ after\ burnt}{(Dry\ weight\ of\ sample\ before\ burnt)} x100\% \tag{3.4}$$



(a) (b)

(c) (d)

Figure 3.13 (a) Oven Dried Sample, (b) Muffle Furnace Set at 550°C, (c) Sample Placed in the Oven, (d) Burnt Sample

3.5.2 First Order Gas Model for Gas Generation Prediction

The Landfill Gas Emissions Model is an estimation tool with a Microsoft Excel interface that can be used to estimate emission rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds, and individual air pollutants from municipal solid waste landfills. For a landfill with a constant or unknown year-to-year solid waste acceptance rate, the annual gas generation rate can be calculated using EPA's gas modeling equation (USEPA, 1997),

$$Qt = 2\ L_0\ m_0.\ (e^{-k.c} - e^{-k.t}) \quad \text{(3.5)}$$

where, Qt = expected gas generation rate in the t^{th} year, ft^3/yr or m^3/yr

L_0 = methane generation potential, ft^3/lb or m^3/Mg

m_0 = constant or average annual solid waste acceptance rate, lb/yr, Mg/yr

k = Methane generation rate constant, yr^{-1}

t = Age of the landfill, yr

c = time since closure, yr (For active landfill, $c = 0$; hence, $e^{-k.c} = 1$)

According to different period of landfill operations, it can be stated that,

For active landfill period,

$Qt = 2\ L_0\ m_0.\ (1\text{-}e\text{-}k.t)$ .... (3.6)

For closed landfill period,

$Qt = 2\ L_0\ m_0.\ (e^{-kta} - 1)\ .\ e^{-kt}$ .... (3.7)

where, Qt = expected gas generation rate in the t^{th} year, ft^3/yr or m^3/yr

L_0 = methane generation potential, ft^3/lb or m^3/Mg

m_0 = constant or average annual solid waste acceptance rate, lb/yr, Mg/yr

k = Methane generation rate constant, yr^{-1}

t = Age of the landfill, yr

ta = total years of active period of landfill, yr.

According to USEPA (1997), the expected gas generation rate from any waste mass, M_i, in the t^{th} year can be calculated by,

$(Q_i)_t = 2\ .\ k\ .L_0\ .\ M_{i.}\ e^{-kti}$ .... (3.8)

where, $(Qi)t$ = expected gas generation rate for waste mass, Mi, in the t^{th} year, ft^3/yr or m^3/yr

L_0 = methane generation potential, ft^3/lb or m^3/Mg

M_i = mass of solid waste filled in the i^{th} year, lb or Mg

k = Methane generation rate constant, yr^{-1}

t_i = Age of the waste mass, Mi, in the t^{th} year, yr

For a landfill with a known and changed year-to-year solid waste acceptance rate, annual gas generation rate can be calculated using EPA's modeling equation, (USEPA, 1997):

$(Q)_t = 2\ .\ k\ .L_0\ .\ M_{i.}\ e^{-kt}$ .... (3.9) where, Q_t = expected gas generation rate in the t^{th} year, ft^3/yr or m^3/yr

L_0 = methane generation potential, ft^3/lb or m^3/Mg

M_i = mass of solid waste filled in the i^{th} year, lb or Mg

k = Methane generation rate constant, yr^{-1}

t = Age of the landfill, yr

ta = total years of active period of landfill, yr.

3.5.3 Model Parameters Considered for Estimation

Gas model mainly relies on:

- ☐ Methane generation rate (k_0),
- ☐ Potential methane generation capacity (L_0),

The Methane Generation Rate, k_0, determines the rate of methane generation for the mass of waste in the landfill. The higher the value of k_0, the faster the methane generation rate increases and then decays over time. The value of k_0 is primarily a function of Moisture Content, availability of nutrients, pH and temperature of waste. EPA recommends using site specific k_0 values. For conventional or dry tomb landfill typical k_0 considered is 0.02-0.04 yr^{-1} and for wet or bioreactor landfill it is considered to be in between of 0.2-0.7 yr^{-1}.

The Potential Methane Generation Capacity, L_0, depends only on the type and composition of waste placed in the landfill. The higher the cellulose contents of the waste, the higher the value of *Lo*. For conventional or dry tomb landfill typical Lo considered is 100 m^3/ Mg.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The landfilled samples were collected from the City of Denton landfill's closed section. MSW is heterogeneous material and the physical properties are expected to change with degradation of the waste, along with other environmental conditions. The estimated age of collected MSW samples ranged from 9 to 25 years. The change in physical characteristics with decomposition may contribute to change in the engineering characteristics of MSW. Therefore, there is a need to understand the MSW characteristics with decomposition. The first order gas generation model was used to predict generation of gas of the closed landfill section for City of Denton landfill. In the following subsections, a brief discussion of various physical and engineering characteristics is presented.

4.2 Test Results

The test results for the physical composition, moisture content, unit weight, hydraulic conductivity, particle size distribution, and volatile solids are presented in the subsections below.

4.2.1 Physical Composition

The physical composition of the collected landfilled samples from boring B-70 and B-72 were determined by manual sorting. For each boring six samples were collected from 10 ft, 20 ft, 30 ft, 40 ft, 50 ft and 60 ft. depth of landfill. Approximately 25 lbs to 30 lbs. of sample was collected from each depth. Physical compositions of the collected samples are listed in the Table 4.1 and Table 4.2. The samples are also separated into degraded and non-degraded portions, given in Table 4.3.

Table 4.1 Physical Composition of Landfilled MSW (Boring B-70)

Boring 70 @ depth, ft	Year of Waste Deposition	Age, Years	Physical Composition (% by weight)										
			paper	plastic	food waste	textile + leather	yard waste + wood	metals	glass	Styrofoam sponge	C & D debris	Degraded particles	others (small objects)
10	2001	9	49.52	15.16	0	2.65	24.97	0.72	0.36	0.06	0.00	0.00	6.56
20	1997	13	23.33	8.42	0	0.09	14.47	2.02	0.22	7.76	11.45	3.87	28.37
30	1994	16	12.72	4.29	0	4.52	1.17	0.65	0.31	0.22	0.00	15.76	60.37
40	1991	19	64.43	12.85	0	6.46	0.18	1.46	6.46	0.67	0.18	0.00	7.31
50	1988	22	69.55	4.29	0	0.36	7.40	0.81	0.24	0.20	0.08	6.43	10.63
60	1985	25	43.68	1.12	0	0.48	1.74	3.30	2.49	0.78	0.61	18.18	28.53
Average			43.87	7.69	0	2.43	8.32	1.49	1.68	1.62	2.05	7.37	23.63
Standard Deviation			22.39	5.46	0	2.62	9.76	1.03	2.50	3.02	4.61	7.86	20.61
Maximum			69.55	15.16	0	6.46	24.97	3.30	6.46	7.76	11.45	18.18	60.37
Minimum			12.72	1.12	0	0.09	0.18	0.65	0.22	0.06	0.00	0.00	6.56

Table 4.2 Physical Composition of Landfilled MSW (Boring B-72)

Boring 72 @ depth, ft	Year of Waste Deposition	Age, Years	Physical Composition (% by weight)										
			paper	plastic	food waste	textile + leather	yard waste + wood	metals	glass	Styrofoam sponge	C & D debris	Degraded particles	others (mixed small objects)
10	2001	9	0.00	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.0
20	1999	11	2.91	8.41	0	0.62	11.19	1.81	0.80	2.97	5.73	28.96	36.55
30	1997	13	12.72	4.29	0	4.52	1.17	0.65	0.31	2.97	0.00	58.47	17.66
40	1994	16	21.40	16.02	0	0.15	7.49	1.75	1.66	0.21	0.27	18.17	30.42
50	1991	19	1.81	0.38	0	1.04	22.89	0.32	0.49	0.04	35.93	0.00	37.08
60	1989	21	40.35	32.82	0	0.00	0.14	18.53	0.41	0.09	0.00	0.00	7.66
Average			13.20	10.32	0	1.06	7.15	3.84	0.61	1.05	6.99	17.60	38.23
Standard Deviation			15.58	12.52	0	1.75	8.95	7.23	0.58	1.49	14.36	23.36	32.37
Maximum			40.35	32.82	0	4.52	22.89	18.53	1.66	2.97	35.93	58.47	100.0
Minimum			0.00	0.00	0	0.00	0.00	0.00	0.0	0.0	0.0	0.0	7.66

Table 4.3 Degradable Composition of Landfilled MSW (Boring B-70 and B-72)

	Boring 70 @ depth, ft	Year	Age, Year	Physical Composition (By degradability)			Boring 72 @ depth, ft	Year	Age, Year	Physical Composition (By degradability)	
				Degradable	Non-Degradable					Degradable	Non-Degradable
B-70	10	2001	9	77.14	22.86	B-72	10	2001	9	0	100
	20	1997	13	37.89	62.11		20	1999	11	14.73	85.27
	30	1994	16	18.41	81.59		30	1997	13	17.92	82.08
	40	1991	19	71.07	28.93		40	1994	16	29.77	70.23
	50	1988	22	77.32	22.68		50	1991	19	25.75	74.25
	60	1985	25	45.49	54.51		60	1989	21	40.49	59.51
	Average			56.37	43.63		Average			25.73	74.27
	Standard Deviation			26.78	26.78		Standard Deviation			10.2	10.2
	Maximum			77.32	81.59		Maximum			40.49	85.27
	Minimum			18.41	22.68		Minimum			14.73	59.51

4.2.2 Moisture Content

To determine the moisture content, 1.5 to 2 lbs. of landfilled samples were randomly taken prior sorting of the samples. The moisture content results are presented in Table 4.4.

Table 4.4 Moisture Content of Landfilled MSW

	Boring 70 @ depth, ft	Age, Years	Moisture Content (%)			Boring 72 @ depth, ft	Age, Years	Moisture Content (%)	
			Before sorting (uncompacted)					Before sorting (uncompacted)	
			Wet Wt. Basis	Dry Wt. Basis				Wet Wt. Basis	Dry Wt. Basis
B-70	10	9	29.51	41.86	B-72	10	9	11.38	12.84
	20	12	17.38	21.03		20	11	24.37	32.22
	30	15	28.61	48.07		30	13	15.52	18.38
	40	21	31.32	45.6		40	16	26.39	35.86
	50	23	32.16	47.41		50	19	11.94	13.55
	60	25	33.94	51.37		60	21	23.15	30.72
	Average		28.82	42.56		Average		20.27	26.15
	Standard Deviation		5.92	11		Standard Deviation		6.22	9.63
	Maximum		33.94	51.37		Maximum		26.39	35.86
	Minimum		17.38	21.03		Minimum		11.94	13.55

4.2.3 Unit Weight

Landfilled samples were compacted with standard proctor compaction effort and using tensile compression machine, as presented in Table 4.5 and Table 4.6, respectively.

Table 4.5 Compacted Unit Weight of Landfilled MSW (Standard Proctor Test)

	Boring 70 @ depth, ft	Year	Age, Year	Compacted Density (pcf)	Compacted unit weight (KN/m^3)		Boring 72 @ depth, ft	Year	Age, Year	Compacted Density(pcf)	Compacted unit weight (KN/m^3)
B-70	10	2001	9	28.45	4.47	B-72	10	1998	9	132.6	20.84
	20	1998	13	44.65	7.02		20	1997	11	94.25	14.81
	30	1995	16	94.65	14.87		30	1995	13	110.45	17.36
	40	1989	19	24.1	3.79		40	1993	16	56.15	8.82
	50	1987	22	40.08	6.3		50	1991	19	68.2	10.72
	60	1985	25	57.2	8.99		60	1989	21	28.15	4.42
	Average			48.19	7.57		Average			71.44	11.226
	Standard Deviation			25.64	4.03		Standard Deviation			32.25	5.07
	Maximum			94.65	14.87		Maximum			110.45	17.36
	Minimum			24.10	3.79		Minimum			28.15	4.42

Table 4.6 Compacted Unit Weight of Landfilled MSW from B-70 (using Tensile-Compression Machine)

Borehole	Fill depth	Age	Total over burden Pressure	Load Applied	Unit Weight	Comment	Borehole	Fill depth	Age	Total over burden Pressure	Load Applied	Unit Weight	Comment
	ft	Year	psf	lb	pcf			Ft	Year	psf	lb	pcf	
B 70	10	9	1200	240	27.6	Partially degraded	B 72	10	9	1200	240	136.35	Cover soil
	20	13	1650	330	33.48	Partially Degraded		20	11	2025	405	68.46	Mostly Degraded
	30	16	2100	420	80.95	Mostly Degraded		30	13	2475	495	87.96	Mostly Degraded
	40	19	2550	510	27.53	Mostly non degraded		40	16	2925	585	51.06	Mostly Degraded
	50	22	3000	600	35.37	Mostly non degraded		50	19	3375	675	62.35	Partially degraded
	60	25	3450	690	32.75	Mostly non degraded		60	21	3825	765	33.08	Partially degraded
Average					39.61		Average					60.58	
Standard Deviation					20.5		Standard Deviation					20.38	
Maximum					80.95		Maximum					87.96	
Minimum					27.53		Minimum					33.08	

Table 4.7 Permeability of Borehole B-70 and B-72 from Different Depths

Boring	Fill depth	Age	Permeability	Unit Weight	Boring	Fill depth	Age	Permeability	Unit Weight
	ft	Yr	cm/sec	pcf		ft	Yr	cm/sec	pcf
B-70	10	9	1.26E-04	27.6	B-72	10	9	8.08E-05	136.35
	20	13	2.84E-04	33.47		20	11	1.62E-05	68.46
	30	16	4.65E-04	80.94		30	13	1.48E-04	87.96
	40	19	4.48E-04	27.53		40	16	3.69E-04	51.06
	50	22	3.17E-04	35.37		50	19	1.11E-04	62.35
	60	25	3.67E-04	32.75		60	21	3.60E-05	33.08
	Average		3.34E-04			Average		1.36E-04	60.58
	Standard Deviation		0.000124347			Standard Deviation		0.000128	20.38
	Maximum		4.65E-04			Maximum		3.69E-04	87.96
	Minimum		1.26E-04			Minimum		1.62E-05	33.08

4.2.4 Hydraulic Conductivity

The permeability of landfilled waste is dependent on unit weight of the samples. Test specimens of landfilled samples were prepared applying overburden pressure, using tensile compression machine. To determine the permeability samples were compacted to the density determined (Table 4.6) previously, and constant head permeability tests were conducted. The permeability results are presented in Table 4.7

4.2.5 Particle Size Distribution

The particle size distribution curve is a good indicator of the degradation level of the MSW. The particle size distribution curves of landfilled wastes are illustrated in Figure 4.1 and Figure 4.2.

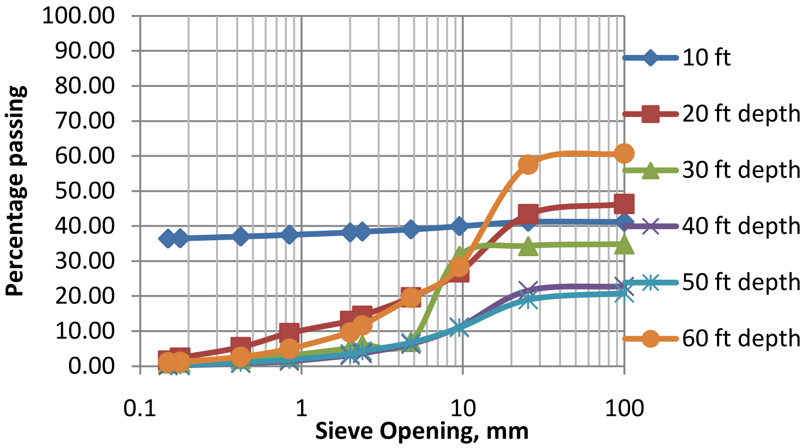


Figure 4.1 Particle Distribution Curves at Different Depth for B-70

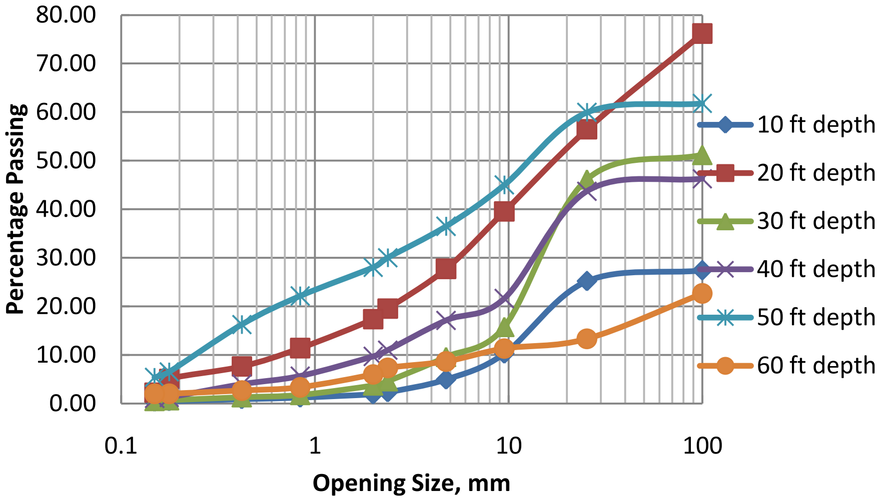


Figure 4.2 Particle Distribution Curves at Different Depth for B-72

4.2.6 Volatile Test Results

According to ITRC (2006), volatile solid test is the most inexpensive measurement of the amount of biodegradable material that is remaining in the waste mass. Volatile solid of landfilled MSW have been correlated linearly with cellulose and cellulose/lignin data (Ham, 1987). Correlation between methane potential (BMP test results) with Volatile Solids was recently developed by Kelly et al. (2006). The volatile solids test results for the landfilled samples are listed below in Table 4.8.

Table 4.8 Organic Content of Landfilled MSW from Boring 70

Bore hole	Boring 70 @ depth, ft	Year	Age, Year	Volatile Solids (%)	Bore hole	Boring 72 @ depth, ft	Year	Age, Year	Volatile Solids (%)
B-70	10	2001	9	85.79	B-72	10	2001	9	5
	20	1997	13	45.3		20	1999	11	20.2
	30	1994	16	59.28		30	1997	13	42.61
	40	1991	19	86.84		40	1994	16	83.9
	50	1988	22	82.57		50	1991	19	77.69
	60	1985	25	73.95		60	1989	21	82.8
	Average			72.29		Average			61.44
	Standard Deviation			16.73		Standard Deviation			34.45
	Maximum			86.84		Maximum			83.9
	Minimum			45.3		Minimum			20.2
Average=63.08									

4.3 Analysis and Discussion

The composition of the MSW, moisture content, organic matter, permeability, particle size distribution and unit weight are important MSW characteristics that influence the characteristics of the landfill. The physical properties of waste are expected to change with degradation. Reliable knowledge of geotechnical properties of these waste materials is required for the evaluation and prediction of actual behavior of landfill.

4.3.1 Physical Composition

Composition of the MSW varies within the landfill. With time, the degradable constituents in the MSW decrease with decomposition, thereby resulting in variation of the overall composition of the waste within the landfill. Composition of MSW for boring B-70 and B-72 is presented as percentage of weight of individual waste components to the weight of total waste in Figure 4.5, 4.7, 4.10 and 4.11.

From visual inspection for B-70, the cover soil was approximately 8 ft. Samples collected from 10 ft depth were relatively fresh. Samples from 20 ft and 30 ft depth were partially degraded and the rest of the samples collected were mostly non-degraded. The degradation of MSW is enhanced by the presence of moisture to the waste. The closed landfill section was operated as a conventional landfill; therefore, no water was added to the landfill. There was no permanent cover provided on top of the closed section of the landfill except for cover soil. The higher degradation at 20 ft and 30 ft might be due to water intrusion from the top through the cover soil. From the composition, it was observed that the percentage of paper was low and the percentage of soils and degraded fines were high in these two MSW samples. Figure 4.3 and 4.4 present the MSW samples collected from boring B-70.

Figure 4.3 Degraded Samples from 20 ft and 30 ft Depth of Boring B-70

Figure 4.4 Partially-Degraded Samples from 40 ft, 50 ft and 60 ft Depth of Boring B-70

The landfilled samples are anticipated to be more degraded with increasing age and depth. The compositions for the collected samples do not follow this trend, as illustrated in Figure 4.5. Moisture is not added in a traditional landfill. The moisture content of waste varies with the composition of waste. However, absence of final cover in the landfill might also lead to unanticipated water intrusion in the waste mass. Hence the presence of less degraded samples for B-70 after 30 ft of the landfill may be due to absence of moisture in landfilled waste. It can be summarized that the unavailability of moisture to the landfilled waste may result in less degradation to no degradation of landfilled waste.

No food waste was obtained from any of samples from boring B-70 as presented in Figure 4.6. Based on the figure, the paper content decreased at 20 ft and 30 ft depth, where the degradation was higher. Paper content increases after 30 ft depth, where the collected samples were relatively fresh.

The average composition of B-70 as presented in Figure 4.7 illustrates paper as 44%, plastic 8%, textile + leather 2%, yard and wood waste 8%, metals 1%, glass 2%, styrofoam and sponge 2%, C & D debris 2%, degraded particles 7% and soil 24%. Presence of higher paper content indicates that the landfilled waste is yet to be degraded. Therefore it can be summarized that large portion of degradable waste was available during the time of sample collection.

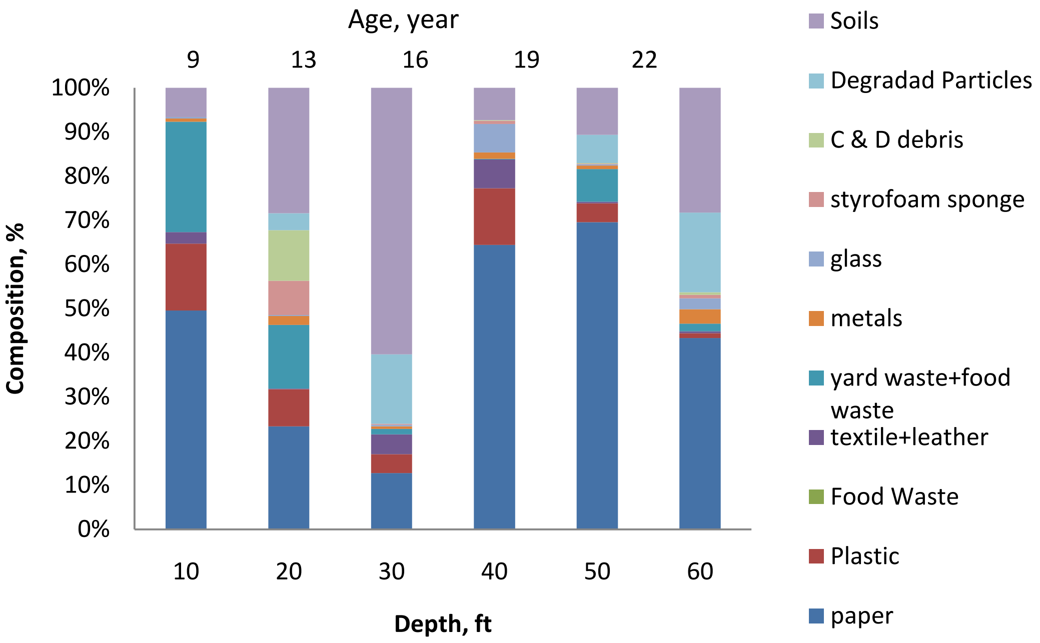


Figure 4.5 Weight Percentages of MSW from Boring B-70 at Different Depth

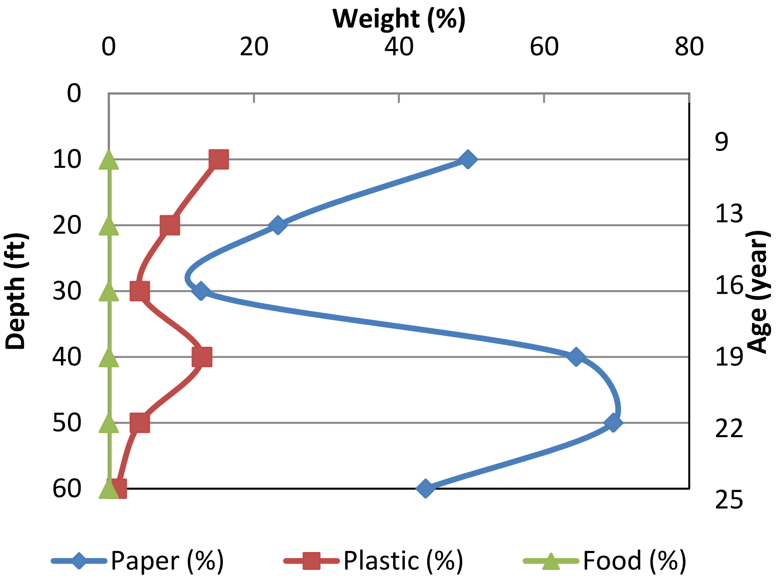


Figure 4.6 Weight Percentages of Paper, Plastic and Food Waste of MSW from Boring B-70 at Different Depth

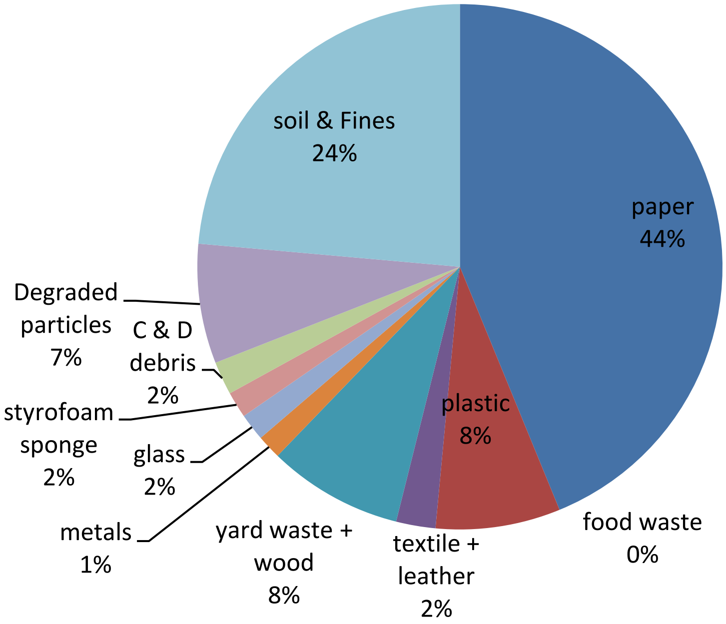


Figure 4.7 Average Weight Percentages of Boring Sample B-70

The landfill cover was approximately 15 ft for B-72. Therefore, sample collected from 10 ft depth was cover soil and was discarded. From visual inspection, the sample collected from 20 ft depth and 50 ft depth of landfill was mostly degraded and black in color, as presented in Figure 4.8. The MSW samples from these two particular depth contained mostly fine components. The samples collected from 30 ft and 40 ft depth were partially degraded, and the sample from 60 ft depth incorporated very less degradation as shown in Figure 4.9.

Figure 4.8 Degraded Samples from 20 ft and 50 ft Depth of Boring B-72

Figure 4.9 Samples with Almost no Degradation from 60 ft Depth of Boring B-72

From the composition illustrated in Figure 4.10, it was observed that the paper content was 2.91% at 20 ft depth for boring B-72. The percentages of plastic components and soils & fines component were high. No food waste was present in any of the samples. At 50 ft depth C & D debris were very high approximately 35%. The paper content was low. Visually the samples were black and degraded. Soil content was also determined high in this sample. The samples from B-72 were more degraded than samples from B-70. It can be explained as uneven distribution of moisture in the landfill and extensively heterogeneous nature of waste. The degradation is a function of moisture availability. Therefore it can be predicted that the waste present in the vicinity of B-72 were in the more saturated zone than B-70. And therefore the samples were mostly degraded and remaining degradable percentage is very low for the particular boring MSW samples.

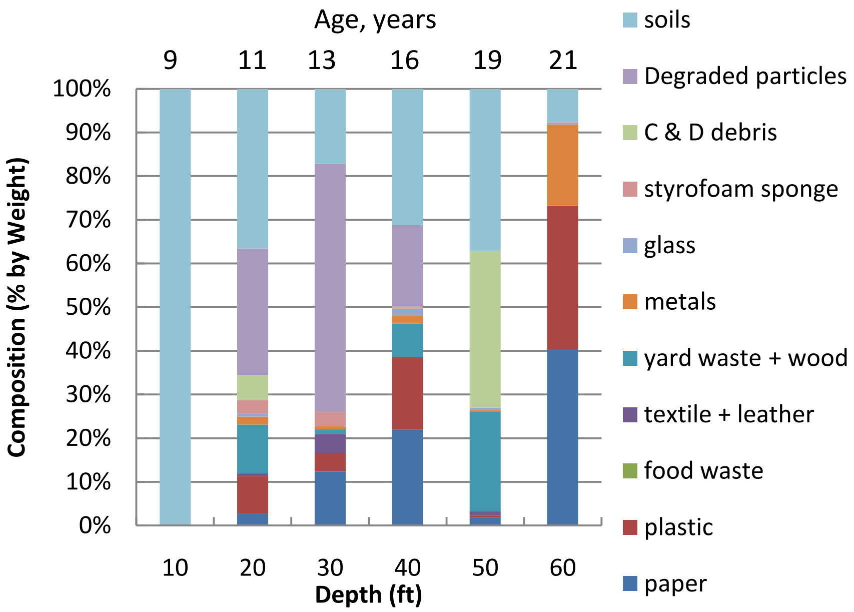


Figure 4.10 Weight Percentages of MSW from Boring B-72 at Different Depth

The average composition of the boring B-72 presented in figure 4.11 illustrates remaining percentage of degradable component was less than non degradable components. The degraded components and soil & fine percentage were approximately 56% of the composition. No food waste was present in the samples.

For the average, the cover soil sample collected from 10 ft depth of boring 72 was discarded. The results indicated that major portion of waste was soil and degraded fines. From the combined average for landfilled MSW samples, the main components of waste other than soils and degraded fines (39%) were paper (31%) and plastics (10%).

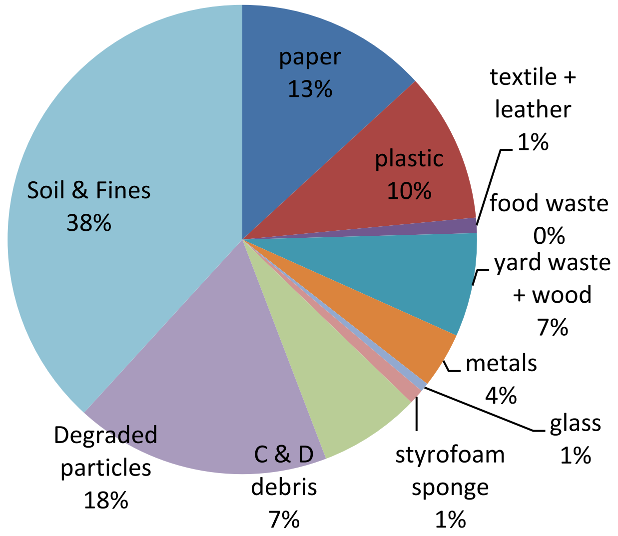


Figure 4.11 Average Weight Percentages of MSW from Boring B-72

The average composition of the landfilled samples, including both borings, is presented in Figure 4.12. The major component of the landfilled waste was determined to be soils and degraded fines (39%). However, paper content was also determined to be 31%, which is relatively high for landfilled waste. Food waste was 0% and plastic was 10% in the total waste mass.

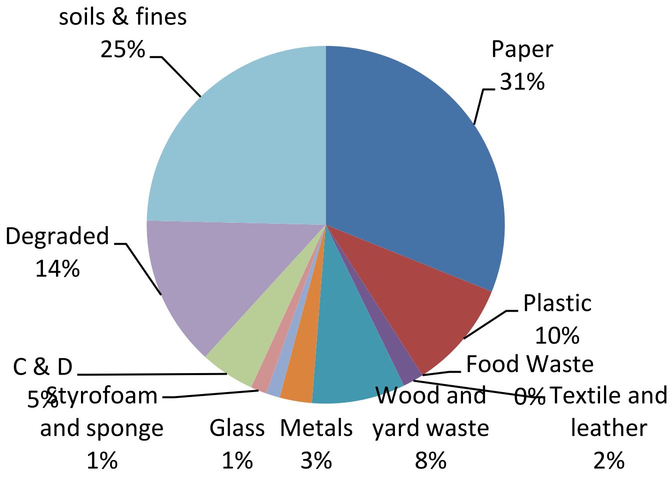


Figure 4.12 Average Composition of Landfilled Waste

The degradable and non-degradable percentages of boring samples B-70 and B-72 is presented in Figure 4.13. For both B-70 and B-72 degradation was higher on top and less in the bottom of the landfill. However, the water intrusion depth was different for the two borings which might be due to heterogeneous nature of waste. The degradable component for B-70 is averaged 56.37% and for B-72 is 25.73% which makes an overall average of 42.44%. The degradable portion of B-70 is much higher than the degradable portion of B-72. This is due to fact that four of the six samples collected for the second boring were mostly degraded.

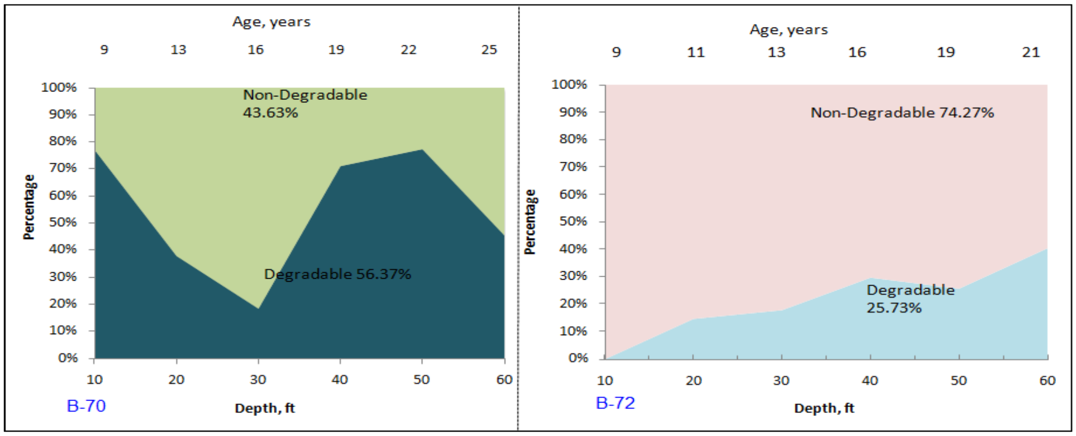


Figure 4.13 Degradable and Non-degradable MSW Components in Boring B-70 and B- 72 at Different Depth

The average composition of the landfilled wastes indicates presence of higher percentage of degradable component in the landfill at the time of sample collection. From the visual inspection and also from the composition from manual sorting, the degradation of waste was determined higher at the top of the landfill. As explained before, this is likely due to water intrusion through the cover soil. The most degraded sample was from 20 ft depth of B-72. For the mostly degraded samples paper content was low, and the fine content was higher. The average paper percentage determined was 31%, and food waste 0%. Food is a readily degradable component which might be an explanation for 0% food in the landfilled waste. Degradation of paper is relatively slower and requires appropriate environment. It can be summarized that the waste mass was partially degraded.

4.3.1.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of composition of landfilled municipal solid waste. Some of the most important ones were discussed in Chapter 2. The values suggested there are summarized in Table 4.9.

From the comparison of test results with previous studies, it can be summarized that for the previous studies of landfilled waste aged 6-30 years, paper percentage was low and percentage of fine was high. For the current study, the percentage of fines was nearly the same as previous studies. However, the paper percentage was very high compared to the previous studies on landfilled waste. The presence of high percentage of paper in the remaining waste may be because of unavailability of moisture for degradation of the wastes. The samples collected from the Denton landfill were partially degraded as presented in Figure 4.14.

Table 4.9 Comparison of Composition of MSW found in Literature and Present Study

Components	Landfilled Waste in San Tirso landfill in Brazil	Landfilled Waste in USA	landfilled waste in Japan	Present Study
	Gomes et al., 2005	Gabr and Valero, 1995	Suthatip et al., 2006	City of Denton Landfill
Age	6-7 years	15-30 years	20 years	25 years
Paper products	0.9	0	1.1	31.13
Plastic, rubber	38.7	13	6.2	9.82
Food waste/ organics	0.1	--	--	0
Garden refuse	2.8	--	--	Considered with Wood
Textiles	33.3	23	0.7	1.9
Wood	2.8	9	16.2	8.44
Metal products	10.2	10	5.4	2.91
Glass & ceramics	2.8	10	0.4	1.25
Ash, rock & dirt	11.2	19	7.5	24.65
C & D			20.8	4.93
Others and fines		14	41	13.62

Figure 4.14 Partially Degraded Landfilled Samples

4.3.1.2 Comparison of Fresh and Landfilled Waste Composition

The MSW is highly heterogeneous and consists of many degradable of components. Therefore, landfilled waste is expected to be degraded with time. However, the degradation rate of the components is different. Food waste is readily degradable and therefore in landfilled waste food waste may not be present. Paper, textile, wood and yard waste are the degradable components. The decomposition of waste is expected to reduce the mass of degradable component like paper, textile, and wood and yard waste. In contrast, the mass of non-degradable components remain same in the MSW. Therefore the percentage of degradable components may be less for degraded waste, than for fresh waste. The percentage of non-degradable components may even increase. The average composition of the landfilled waste collected from the closed section of the landfill was compared to the annual average of fresh MSW from the working phase of city of Denton landfill (Taufiq,T., 2010), as illustrated in Table 4.10 and Figure 4.15.

Table 4.10 Comparison of Fresh and Landfilled Waste Average Composition

Composition type	Fresh (%)	Landfilled (%)
Paper	40	31.13
Plastic	18	9.82
Food Waste	2	0
Textile and leather	4	1.9
Wood and yard waste	9	8.44
Metals	5	2.91
Glass	1	1.25
Styrofoam and sponge	1	1.45
C & D	2	4.93
Degraded	0	13.62
Soils & fines	18	24.65

The figure 4.14 illustrates the comparison between paper, plastic, textiles, wood and yard waste and, soils and fines percentage of fresh and landfilled waste.

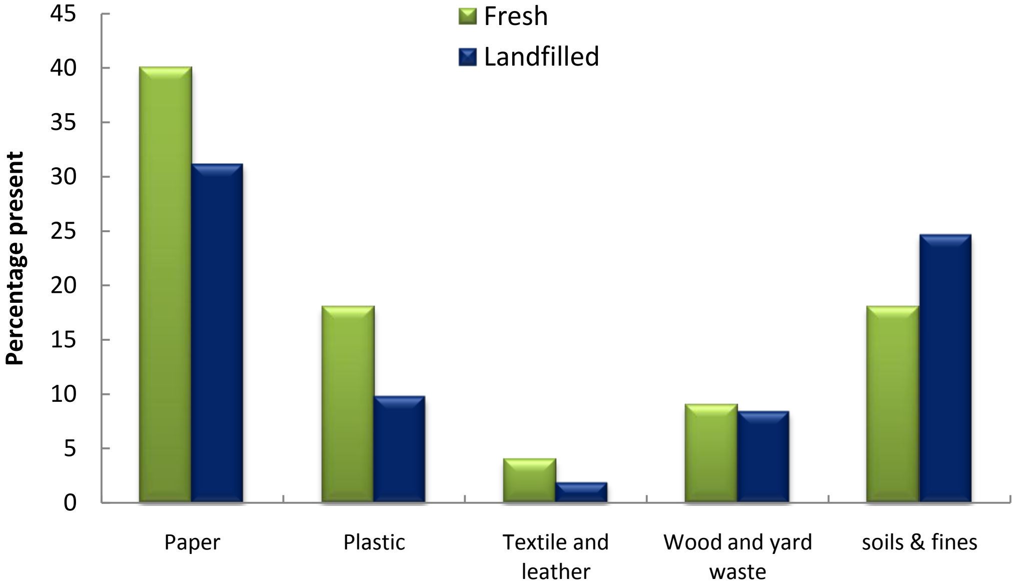


Figure 4.15 Comparison of Fresh and Landfilled Waste

The paper percentage for landfilled waste was less than fresh waste as expected due to degradation of landfilled waste. Plastic percentage was determined less than fresh. The landfilled waste is approximately 25 years old and plastic packaging was not widely used until 1990's. Therefore it might be a possible explanation for less plastic percentage in landfilled waste compared to fresh. The soils and fines were higher in landfilled waste than fresh MSW. A possible explanation might be the presence of degraded fines and lot of cover soil mixture, which is totally absent in fresh waste samples.

It should also be noted that at different times of the year, the material in the waste varies. Year of deposition also plays a very important role in the composition of the landfill. Hence, fresh waste composition of 2009-2010 might be different than the initial composition of the landfilled waste in 1985. Therefore the changes of waste composition due to degradation may not be reflected when compared to the fresh waste collected in 2009-2010. But the compared data provides a good understanding of changes in composition of waste with depth, age and degradation of MSW.

4.3.2 Moisture Content

The moisture content of MSW is extremely important, as it influences the decomposition behavior and all other engineering properties. The moisture contents of B-70 and B-72 on dry weight and wet weight basis are presented in Figure 4.16. The moisture content of the boring B-70 averaged 28.82% (wet weight basis) and for B-72 moisture content averaged 20.27% (wet weight basis). The average moisture content of the B-72 samples was lower than the B-70 samples. Paper percentage was very high in the B-70 samples that might have been the reason of higher moisture content in B-70 samples. With higher degradation, the organic components of waste decreases. According to Landva and Clark (1990) presence of high organic content in MSW increases moisture content of the waste. Therefore, with degradation moisture content might be reduced. The B-72 samples were comparatively more degraded than the B-70 samples that might be reason of low moisture content of wastes collected from B-72.

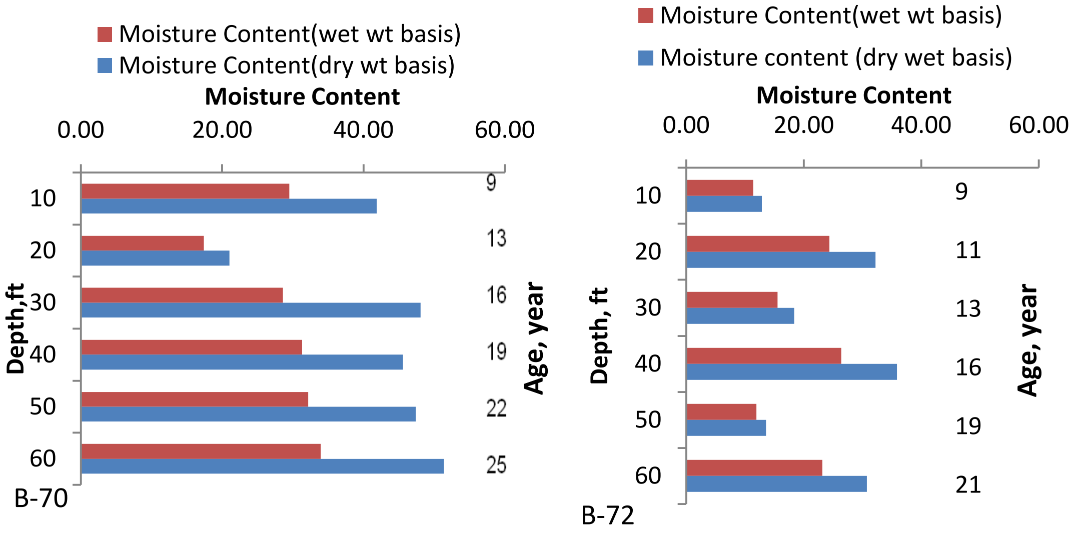


Figure 4.16 Moisture Content of MSW of Boring B-70 and B-72

4.3.2.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of moisture content of landfilled municipal solid waste. Some of the most important ones were discussed in Chapter 2. The values suggested there are compared with the current study in Table 4.11.

The moisture content determined for the landfilled waste was close to the previous studies. From the previous studies the moisture content of landfilled waste was around 110%-130% (dry weight basis). For the current study, the average moisture content was determined as 128% (d/w). The moisture content determined from Hossain et al (2008) was higher than the other values obtained from the literature. This might be due to the effect of moisture recirculation on the waste in that particular study.

Table 4.11 Comparison of Moisture Content of MSW Found in Literature and Present Study

Source	Moisture Content	Condition	Remarks
Gabr & Valero (1995)	30 (d/w)	at surface	15 to 30 years old waste
	130(d/w)	at greater depth	
Gomes et al(1994)	117(d/w)	3 years old waste	Portugal
Landva & Clark (1990)	120 (d/w)		Canada
Zekkos et al. (2006)	10-50	2-15 years old	
Hossain et al. (2008)	55% (w/w)	Phase I	Simulated ELR in Laboratory
	64.7%(w/w)	Phase IV	
Manassero et al. (1997)	55%	1-6 years old waste	USA
Present Study	128% (Average, d/w)	25 years old waste	City of Denton Landfill, Texas
	25% (Average, w/w)		

4.3.2.2 Comparison of Moisture Content of Fresh and Landfilled Waste

The moisture content of landfilled waste from City of Denton landfill was compared to the annual average of fresh samples collected from the Denton landfill. The moisture content in four quarters and their average is presented in Table 4.12 and Figure 4.17. The moisture content for boring B-70 and B-72 and their average is also presented in the table.

The moisture content for fresh MSW ranges from 30% to 40% on wet weight basis. Moisture content for landfilled waste was less than the moisture content for fresh waste, as illustrated in Figure 4.16. The average moisture content for landfilled waste was 24.55 (w/w) and for fresh 36.39% (w/w). The reason for higher moisture content for fresh waste might be the presence of higher organic components in the waste mass. Since no moisture was added to the landfilled waste of the closed section and moisture requirement for waste degradation, the initially available moisture from the waste mass itself might be reduced during the decomposition process.

Table 4.12 Comparison of Moisture Content of Fresh and Landfilled MSW

Fresh MSW	Moisture content (%)		Landfilled MSW	Moisture content (%)	
	Before sorting (un-compacted)			Before sorting (un-compacted)	
	Wet Wt. Basis	Dry Wt. Basis		Wet Wt. Basis	Dry Wt. Basis
Q-1	40.88	69.29	B-70	28.82	42.56
Q-2	34.57	53.74			
Q-3	30.37	49.87	B-72	20.27	46.15
Q-4	39.75	68.41			
Average	36.39	60.33	Average	24.55	44.36

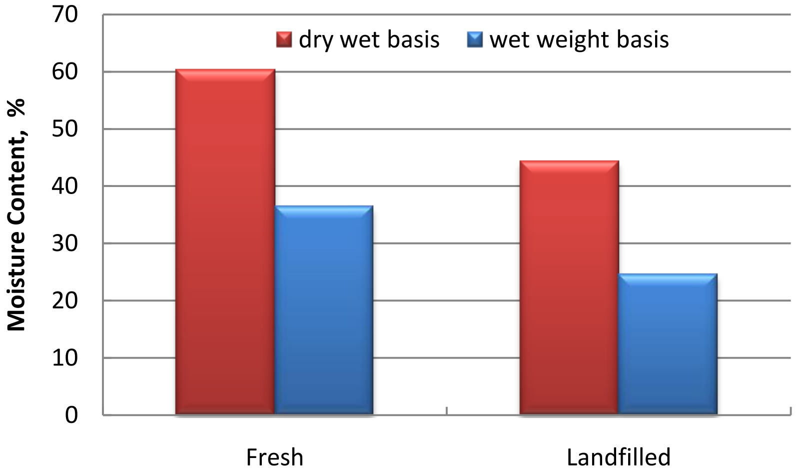


Figure 4.17 Comparison of Moisture Content of Fresh and Landfilled Waste

4.3.3 Compacted Unit Weight

Unit weight of solid waste is considered to be an important factor in estimating the stability of landfills. It is directly influenced by the type of waste, degree of decomposition, degree of compaction, volume of daily cover, compaction degree, quantity of leachate produced, and the depth from which sample is taken.

Results for unit weight of landfilled MSW using standard proctor compaction are presented in Figures 4.18 and 4.19. For B-70 the average unit weight is 48.19 pcf and for B-72 is 71.44 pcf. Unit weight for B-72 was higher due to presence of more degraded components in B-72.

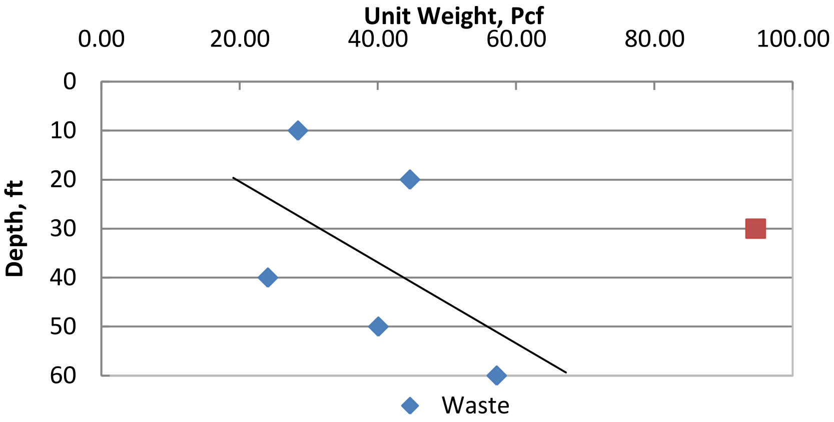


Figure 4.18 Compacted Unit Weight of Landfilled MSW (using Standard Proctor Test) from Boring B-70

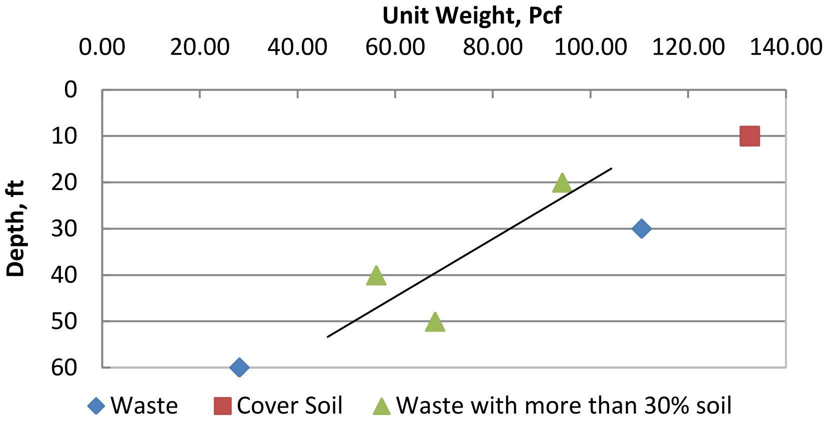


Figure 4.19 Compacted Unit Weight of Landfilled MSW (using Standard Proctor Test) from Boring B-72

The degraded components are finer than the fresh MSW. As the particle size decreases, voids between the waste mass decreases, which increases the unit weight. The unit weight depends on the presence of soil and degraded fine components. Figure 4.20 illustrates the increase of unit weight of MSW with the increase in soil and degraded fines percentage. It can be summarized that the unit weight values increased with the degree of decomposition, and with the increasing percentage of soil and fines in the MSW.

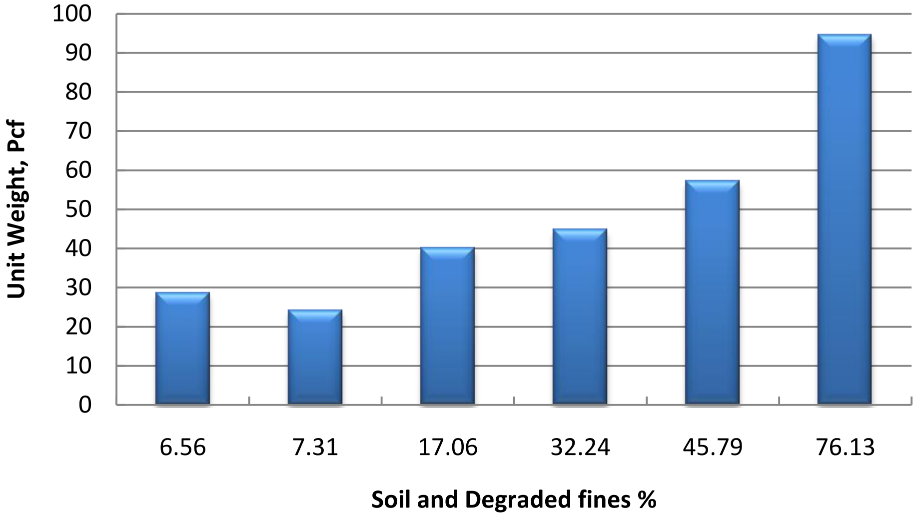


Figure 4.20 Relation between Unit Weight and Soil and Degraded Fines Percentage

The standard proctor method for compacted unit weight determination does not take into account the overburden pressure on the samples present in the actual landfill. To simulate the field unit weight of the samples collected from different depths, unit weight was determined using tensile compression machine (as described in section 3.6.3). The results are presented in Figure 4.21.

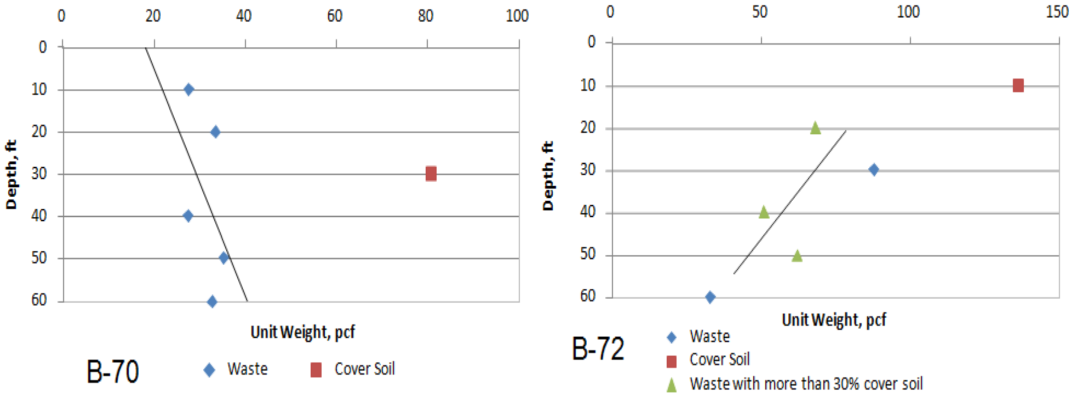


Figure 4.21 Compacted Unit Weight of Landfilled MSW from B-70 and B-72 (using Tensile-Compression Machine)

Figure 4.22 illustrates the unit weight of B-70 was increased with depth. The overburden pressure on the top is less and increases with depth. Since unit weight is directly influenced by the degree of compaction, the unit weight was increased as the overburden pressure increased with depth. The unit weight of B-72 was high near the surface and decreased with depth. Due to higher overburden pressure with depth, the unit weight was expected to increase for landfilled MSW. The cover soil of boring B-72 was 15 ft depth, which leads to higher unit weight on top. The MSW was degraded at 20 ft depth and cover soil was mixed at 30 ft depth samples. At 40 ft the waste was partially degraded and 50 ft depth the waste was degraded. From 60 ft depth, collected waste was relatively fresh. The high degradation of sample produced more fines on top and less degradation of sample at the bottom. The unit weight was dependent on the presence of soils and fines percentage, which reflected a trend of decreasing unit weight of depth for boring B-72.

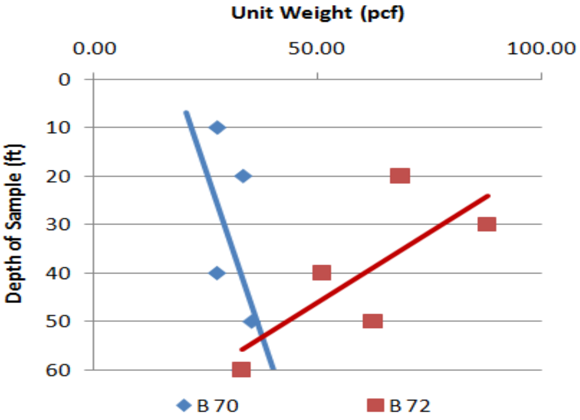


Figure 4.22 Unit Weight of Landfilled MSW from B-70 and B-72 (using Tensile-Compression Machine)

4.3.3.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of unit weight of landfilled municipal solid waste. Some of the most important ones have been discussed in Chapter 2. The values are compared with the present study in Table 4.13.

Table 4.13 Comparison of Unit Weights of MSW Found in Literature and Present Study

Reference	Unit Weight		Conditions	Source
	lb/ ft^3	KN/m^3		
Gabr & Valero (1995)	7.09 to 52.18	7.4 to 8.2	14 to 30 years old waste	
Reddy et.al. (2009)	37.46 to 38.71	5.89 to 6.08	Working face	Orchard Hills Landfill
Landva & Clark	43.27 to 103.1	6.8 to 16.2		Canada
Chen et al. (2009)	31.82 to 95.46	5 to 15	Increases with depth	Qizhishan Landfill, China
Kavazanjian (1995) (From Zekkos et al. (2006))	38.18	6	At surface	
	82.73	13	At 45 m depth	
Manassero (1990)	50.91 to 63.64	8 to 10		
ZHU Xiang-rong et	50 to 108	7.86 to 16.98	13 years old	Tianziling
(standard Proctor Test)	27.53 to 87.96	4.32 to 13.83	Range for Landfilled MSW	City of Denton Landfill
(Tensile Compression Machine)	24.10 to 71.44	3.78 to11.23	Average	
(standard Proctor Test)	58.76	9.23	Average	
(Tensile Compression Machine)	49.14	1.13		

The unit weight data available from studies had a wide range of values for unit weight. The heterogeneity of waste composition with location, age and depth is likely the major reason for this wide variation of unit weight results.

4.3.3.2 Comparison of Unit Weight of Fresh and Landfilled Waste

The unit weight of fresh samples collected from working phase was compared to the landfilled waste in Table 4.14 and Figure 4.23. The standard proctor test results might be more comparable with fresh waste unit weight. Average unit weight for fresh samples was 37.20 pcf and for landfilled samples 59.82 pcf. The average unit weight for landfilled samples was high due to presence of more fines and higher compaction effort in the field. The average unit weight determined using Tensile Compression test (50.10 pcf) for landfilled sample was higher than fresh waste but less than unit for landfilled determined using standard proctor method (59.82 pcf). The lower unit weight determined from tensile compression test might be due to variable overburden pressure for different samples. The overburden pressure on the samples from top was less than standard compaction effort.

Table 4.14 Comparison of Unit Weight of Fresh and Landfilled MSW

Quarter	Compacted Density(pcf)	Compacted unit weight (KN/m^3)	Landfilled MSW		Compacted Density(pcf)	Compacted unit weight (KN/m^3)
1	33.88	5.32	B-70	Standard Proctor	48.19	7.57
2	37.83	5.94		Tensile Compression Test	39.61	6.22
3	39.96	6.28	B-72	Standard Proctor	71.44	11.22
4	37.13	5.83		Tensile Compression Test	60.58	9.51
Average	37.20	5.84	Average	Standard Proctor	59.82	8.63
				Tensile Compression Test	50.10	8.89

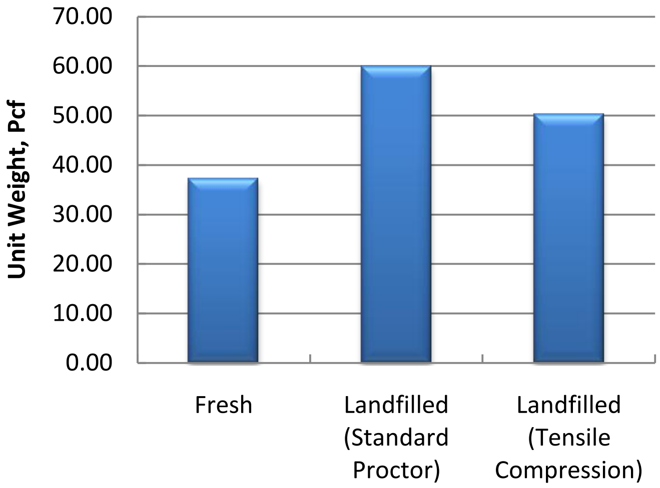


Figure 4.23 Comparison of Unit Weight of Fresh and Landfilled Waste

4.3.4 Permeability

Permeability depends on the pore space. It is a function of unit weight. The permeability tests were conducted at the corresponding unit weight of the samples determined for the field condition. The test results are shown in Figure 4.24. The average permeability of B-70 is 3.34X10^{-4} cm/sec and for B-72 is 1.27X10^{-4} cm/sec. Some of the samples have very low permeability, on the range of 10^{-5}, due to presence of higher soil and fine contents. For B-72 at 20 ft depth the permeability was very low and from the visual inspection this sample was the most degraded sample. The average permeability of B-72 samples were less due to its being more degraded than B-70 samples.

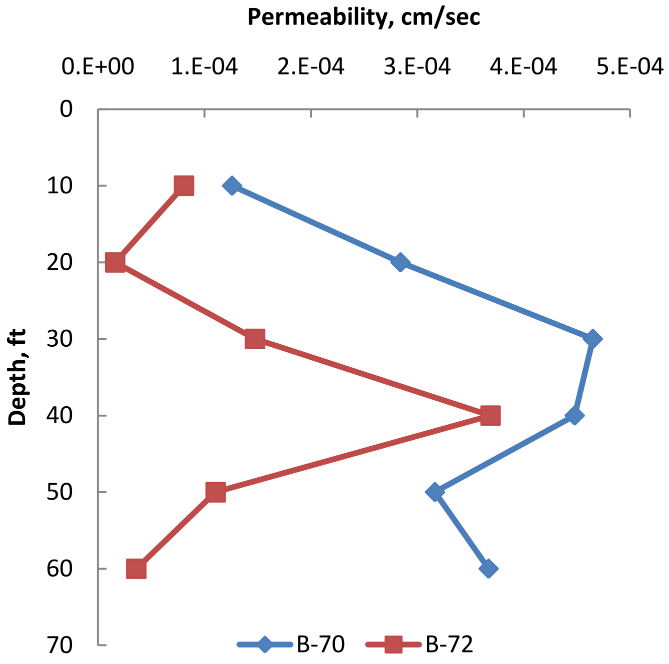


Figure 4.24 Permeability of Borehole B-70 and B-72 from Different Depths

4.3.4.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of permeability of landfilled municipal solid waste. Some of the most important ones were discussed in Chapter 2. The values from literature review and comparison with present study are illustrated in Table 4.15.

The average permeability was determined for landfilled samples to be 2.3E-4 cm/sec. From the previous studies, the range of landfilled waste permeability was 10^{-3} to 10^{-5}. For the current study, the range was 10^{-4} to 10^{-5} cm/sec. From Hossain et al., (2009) for lab scale ELR bioreactor permeability for different phase of degradation was determined as illustrated in Figure 4.25. From phases I to IV, permeability decreased from 10^{-2} to 10^{-4} cm/sec.

Table 4.15 Comparison of Permeability of MSW Found in Literature and Present Study

Source	Permeability	Condition	Remarks
	cm/sec		
Gabr & Valero (1995)	10^{-3} to10^{-5}		15 to 30 years aged waste
Durmusoglu et al. (2006)	$4.7x10^{-4}$ to$1x10^{-3}$		Large scale test, 10 years old waste
	$2.35x10^{-4}$ to $1.24x10^{-2}$		Small scale test, 10 years old waste
Chen & Chynoweth (1995)	$9.6x10^{-2}$	10 pcf	
	$7.3x10^{-4}$	20 pcf	
	$4.7x10^{-5}$	30 pcf	
Landva & Clark (1990)	$1x10^{-3}$ to $4x10^{-2}$	Excavation Pit	Canada
Hossain et al. (2009)	10^{-2} to 10^{-4}	Decreases with decomposition	Lab Scale Bioreactor
Reddy et al. (2009)	$0.6x10^{-3}$ to $3.0x10^{-3}$	Landfilled waste at unit weight of 4.5-5.5 KN/m^3.	
Present study	10^{-4} to 10^{-5}	Range	City of Denton landfill
	$2.3X10^{-4}$	Average	

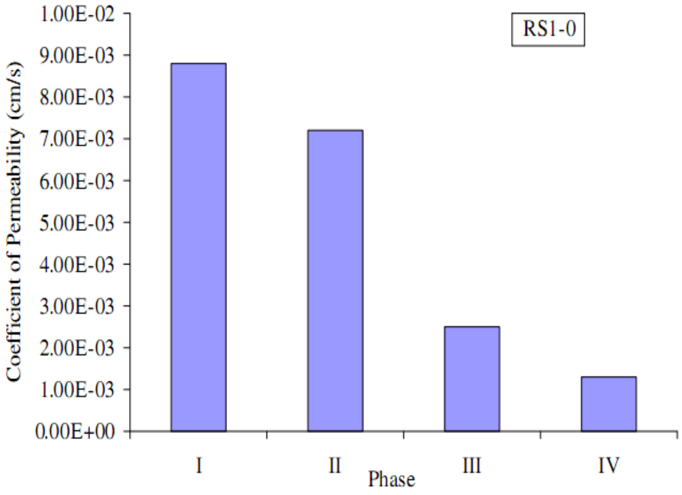


Figure 4.25 Permeability at Different Phase of Degradation

4.3.4.2 Comparison of Permeability of Fresh and Landfilled Waste

The permeability of landfilled waste was determined to be less than permeability of fresh waste as presented in Table 4.16 and Figure 4.26. Permeability is a function of unit weight. With increasing unit weight, pore space in the waste mass reduces. The degradation of waste increases fine contents in the waste composition which reduces void space thus reduces the permeability of MSW.

Table 4.16 Comparison of Permeability of Fresh and Landfilled MSW

Fresh MSW	Permeability (cm/s)	Unit Weight (pcf)	Landfilled MSW	Permeability (cm/s)	Unit Weight (pcf)
Q-1	4.62-03	33.33	B-70	3.34E-04	39.61
Q-2	2.35E-03				
Q-3	1.55E-03		B-72	1.36E-04	60.58
Q-4	2.45E-03				
Average	2.12E-03	33.33	Average	2.35E-04	50.10

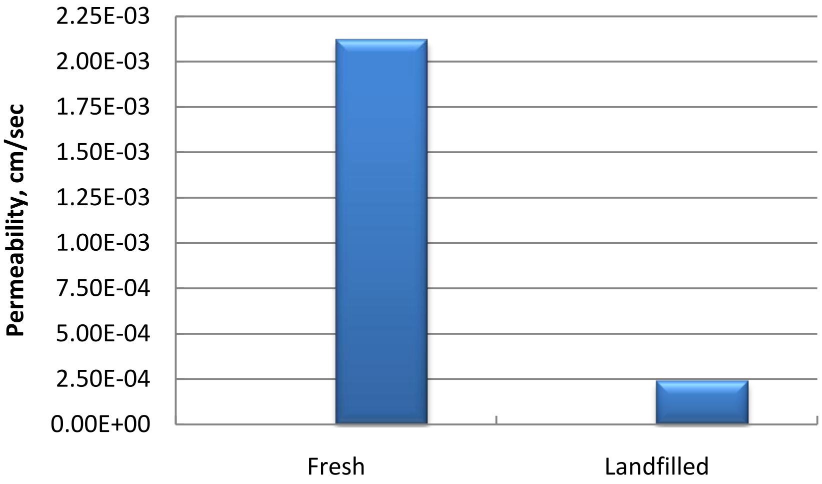


Figure 4.26 Comparison of Permeability of Fresh and Landfilled Waste

4.3.5 Particle Size Distribution

According to a previous study by Haque and Hossain (2007), the particle size distribution for phase I and Phase IV was plotted on the same graph to observe the current degradation level of the collected waste samples, as illustrated in Figures 4.27 and 4.28.The samples collected from B-70 mostly correspond to the phase I condition of the landfill. The samples from 20 ft depth shows similar gradation as phase IV. For the samples from 30 to 60 ft depth the gradation curve indicates the condition as phase I. From the composition and percentage of degradable portion of the landfill for B-70, it was observed that for samples collected form 20 ft was mostly degraded.

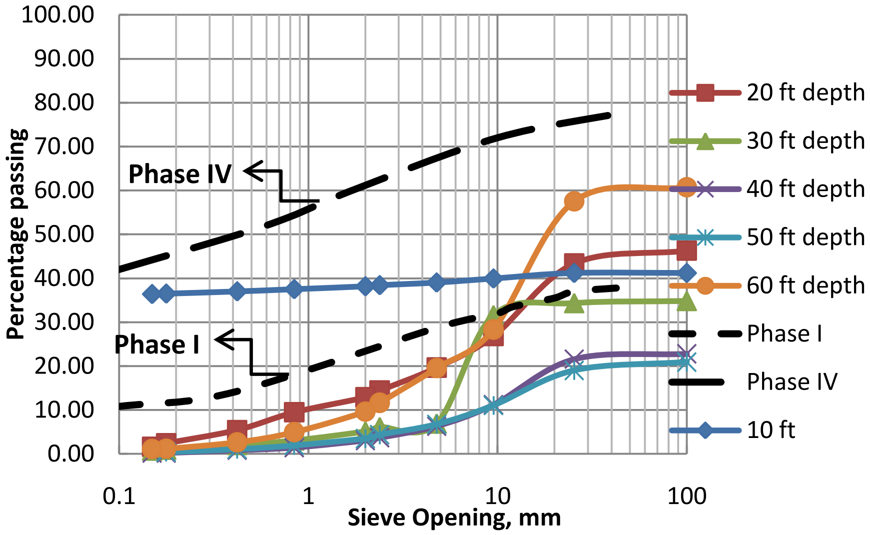


Figure 4.27 Particle Size Distribution of Borehole B-70 from Different Depths

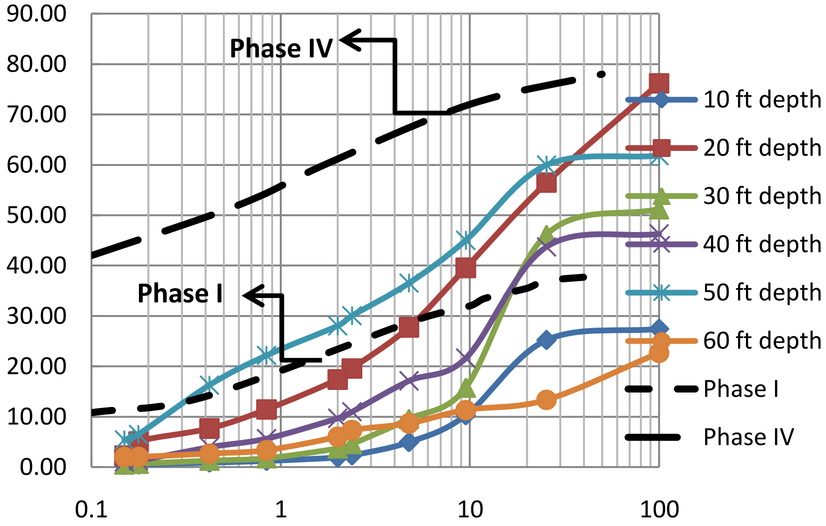


Figure 4.28 Particle Size Distribution of Borehole B-72 from Different Depths

4.3.6 Volatile solids

Volatile solids test results provide a good indication of the degradation level of the waste mass. From the test results, an increasing trend of volatile solid with depth was observed. The waste samples collected from B-70 and B-72 were mostly degraded on top and less degraded on bottom of the landfill. The average volatile solid for the samples from B-70 was

72.29% and for B-72 was 61.44%. The sample collected from 10 ft depth of B-72 was discarded as it was only cover soil. The average for B-72 is less than the average for B-70. The samples collected from B-72 were mostly degraded, which is reflected in lower volatile solids. The volatile solid for different depths of B-70 and B-72 are presented in Figure 4.29 and Figure 4.30.

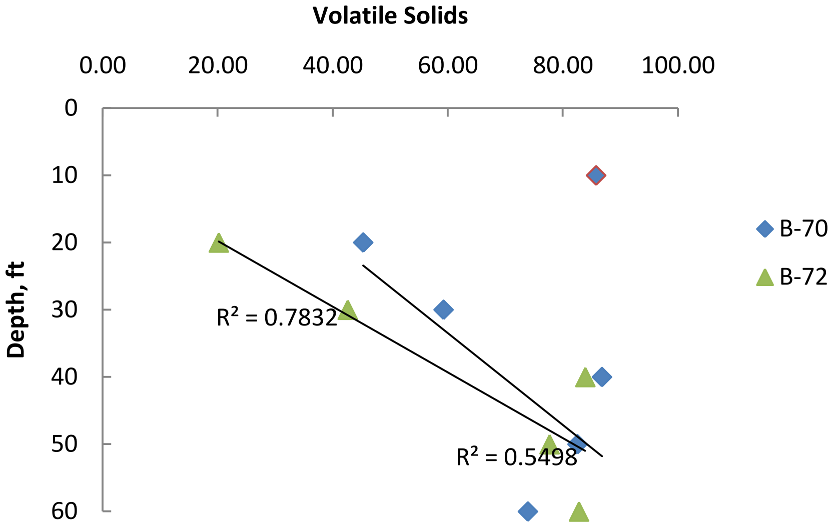


Figure 4.29 Volatile Solids of Boring B-70 with Depth

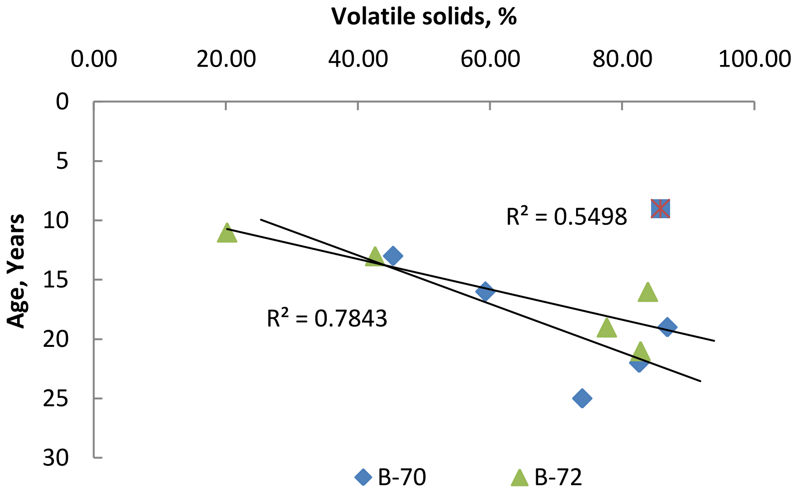


Figure 4.30 Volatile Solids of Boring B-72 with Depth

Food and paper are two most major degradable components in the waste. The percentage of food waste is very low for USA. According to US EPA (2008), food waste generation was 12.7% for USA. Therefore, volatile solids may be directly dependent on the paper percentage in the waste stream. Figure 4.31 illustrates paper percentage present in the samples of B-70 shows a similar trend with volatile solids at different depths. For B-72 the trend was almost similar except at 50 ft depth. At that specific depth, due to the presence of high amount of C & D waste, percentage of paper from that sample could be misleading.

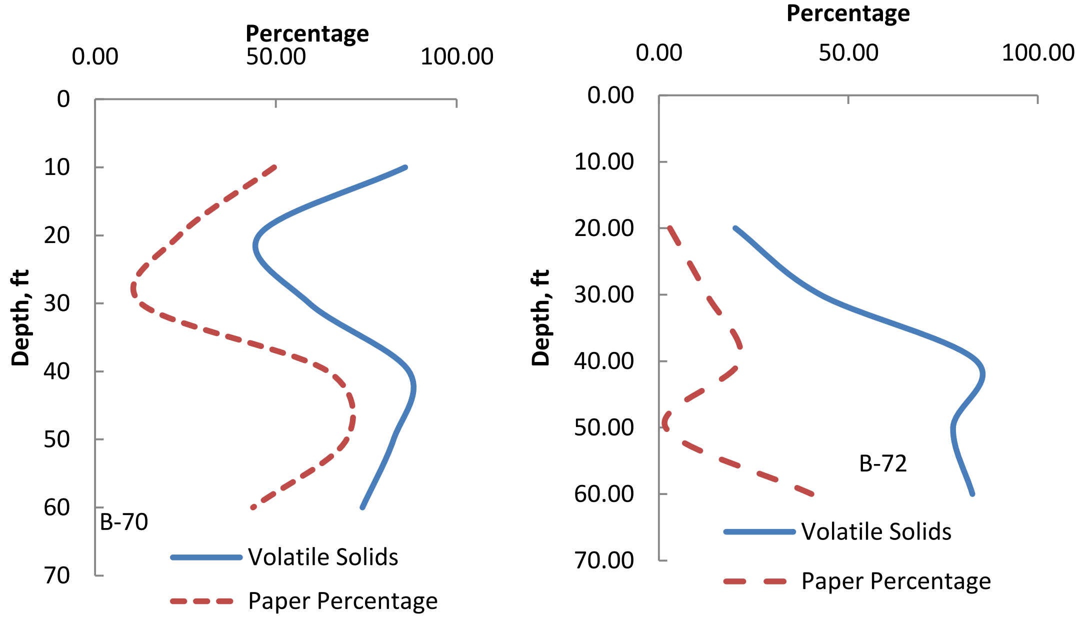


Figure 4.31 Paper Percentage and Volatile Solids with Depth

4.3.6.1 Comparison of Volatile Solids of Fresh and Landfilled Waste

The annual average of volatile solids for fresh solid waste collected from the working phase of City of Denton landfill (2009-2010) was determined 76.96%. Average volatile solids for landfilled waste discarding the cover soil sample were 66.87%. The comparative results of fresh and landfilled waste volatile solids test were presented in Table 4.17 and Figure 4.32. Volatile solids of landfilled samples were less than volatile solids of fresh waste. However, the volatile solids from landfilled samples were close to fresh waste. It can be summarized that the samples were partially degraded, hence, there was probability of future gas generation for these samples.

Table 4.17 Comparison of Volatile Solids of Fresh and Landfilled MSW

Fresh	VS	Landfilled MSW	VS
Annual average	76.96	B-70	72.29
		B-72	61.44
Average	76.96	Average	66.87

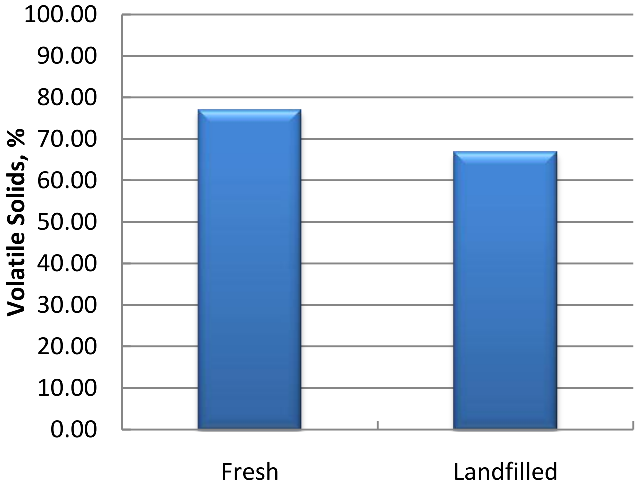


Figure 4.32 Comparison of Fresh and Landfilled MSW

In general, gas production is a function of waste composition. Cellulose and hemicelluloses comprise 45-60% of the dry weight of MSW and are its major biodegradable constituents (Barlaz et al., 1989). The decomposition of these compounds produces methane (CH_4) and carbon dioxide (CO_2) in landfills (Barlaz et al., 1990).

Kelly et al. (2006) developed correlations between Cellulose and VS, Lignin and VS, BMP and VS; and Cellulose + Lignin and VS. Based on the correlations and test results BMP, Cellulose, Lignin and C/L were estimated as illustrated in Table 4.18, Table 4.19 and Figure 4.34. C/L ratio was less than or equal to 1 for samples from 20 ft and 30 ft of B-70 and B-72.

The C/L ratio for sample from 10 ft depth of B-70 was 2.36. C/L ratio or (C+H)/L ratio is directly related to degradation of waste. Hossain et al., (2002) presented a correlation between (C+H)/L ratio with compression index that is directly proportional to the settlement of waste. Therefore, C/L ratio provides a good indication of decomposition level of waste.

According to Hossain et al., (2002) the (C+H)/L ratio decreases with the degradation of landfilled wastes. The (C+H)/L ratio for different phases of sample is illustrated in Figure 4.33. The (C+H)/L ratio for bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower decrease in this ratio in the traditional landfill samples. The (C+H)/L ratios of traditional samples were higher than those of the bioreactor samples at the same time point. It was documented that at the time when bioreactor samples had completed all phases of degradation, the traditional samples were still in early Phase 3.

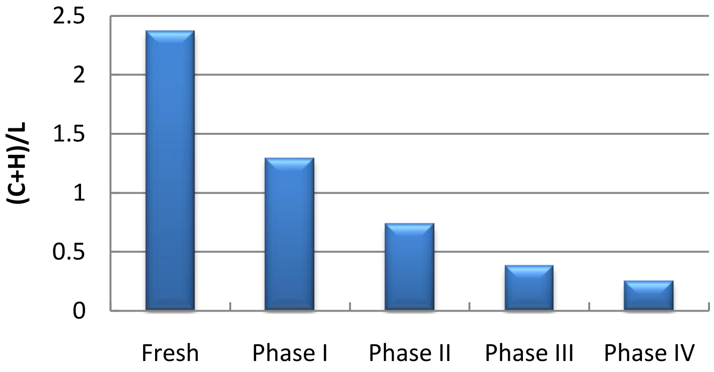


Figure 4.33 (C+H)/L Ratio with Phases of Decomposition of MSW (Hossain et al., 2002)

The closed section of the landfill was operated as traditional landfill and for most of the samples C/L ratio was more than 1. Therefore it might be assumed the degradation for the landfilled waste was not complete at the time of sample collection. Based on a previous study (Hossain et al., 2002) the degradation phases of the samples were determined from the estimated C/L ratio. The C/L ratio indicated the samples were between phase I and IV as presented in Table 4.18 and Table 4.19.

Table 4.18 Predicted BMP, Cellulose and Lignin Percentage from Volatile Solids Results for B-70

Depth	Age	VS	BMP	Cellulose	Lignin	C/L	Expected Phase of Degradation
(ft)	(years)	(%)	(ml/g)	(%)	(%)		
10	9	85.79	134.67	41.36	17.50	2.36	Fresh Sample
20	13	45.30	70.69	20.31	20.86	0.97	Between Phase I and II
30	16	59.28	92.78	27.58	27.47	1.00	Between Phase I and II
40	19	86.84	136.33	41.91	26.45	1.58	Phase I
50	22	82.57	129.58	39.69	24.38	1.63	Phase I
60	25	73.95	115.96	35.20	23.98	1.47	Phase I
	Average	72.29	113.34	34.34	23.44	1.47	

Table 4.19 Predicted BMP, Cellulose and Lignin Percentage from Volatile Solids Results for B-72

Depth	Age	VS	BMP	Cellulose	Lignin	C/L	Expected Phase of Degradation
(ft)	(years)	(%)	(ml/g)	(%)	(%)		
10.00	9	5.00					Cover Soil
20.00	11	20.20	31.04	7.25	16.86	0.43	Between Phase II and III
30.00	13	42.61	66.44	18.91	26.77	0.71	Between Phase II and III
40.00	16	83.90	131.68	40.38	25.28	1.60	Phase I
50.00	19	77.69	121.87	37.15	26.50	1.40	Phase I
60.00	21	82.80	129.94	39.81	21.38	1.86	Phase I
Average		61.44	96.20	28.70	23.36	1.23	

According to Figure 4.34, the C/L ratio increases with depth for both of the borings B-70 and B-72. Therefore it specified that the landfilled samples were more degraded on top and less degraded on bottom. The predicted degradation phase of the landfilled samples also conformed to the understanding from the composition and volatile solids of the landfilled waste.

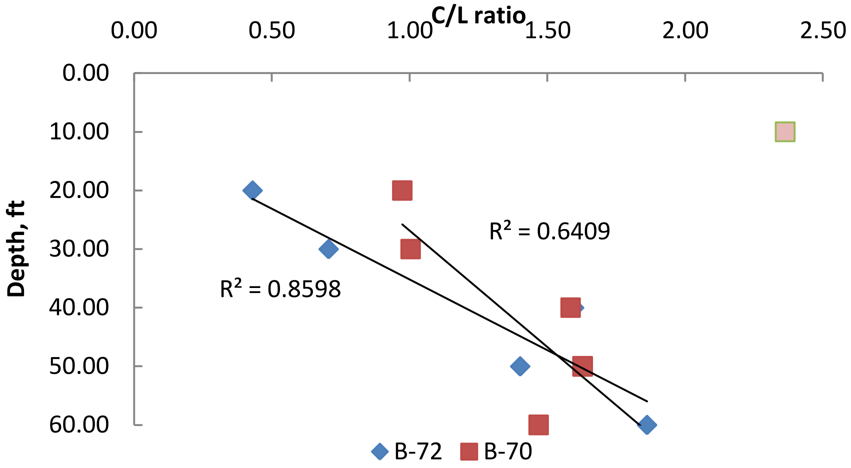


Figure 4.34 C/L ratio for Different depths for Boring B-70 and B-72

The estimated values of BMP for different samples from the previous study of Kelly et al., (2006) were included in the graphs as presented in Figure 4.35 and 4.36 for B-70 and B-72, respectively. The BMP values for most of the sample were more than 100 ml/g. The maximum BMP is 140 m^3/ Mg. From the volatile solids of fresh waste the BMP value was estimated 100 ml/g. The average BMP for the landfilled samples was also close to 100 ml/g. Therefore it is quite reasonable to predict that almost half of the samples have not been degraded until now The BMP values are the methane potential of the MSW. To estimate gas generation, methane potential of waste was assumed 100 ml/g throughout the entire period of gas generation. This BMP values give an idea of the current degradation phase of the landfill.

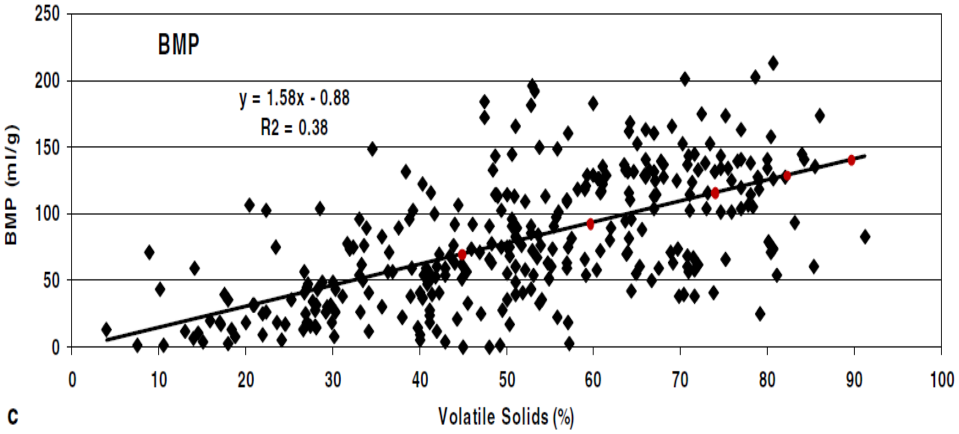


Figure 4.35 BMP prediction from Volatile Solids Test Results for B-70

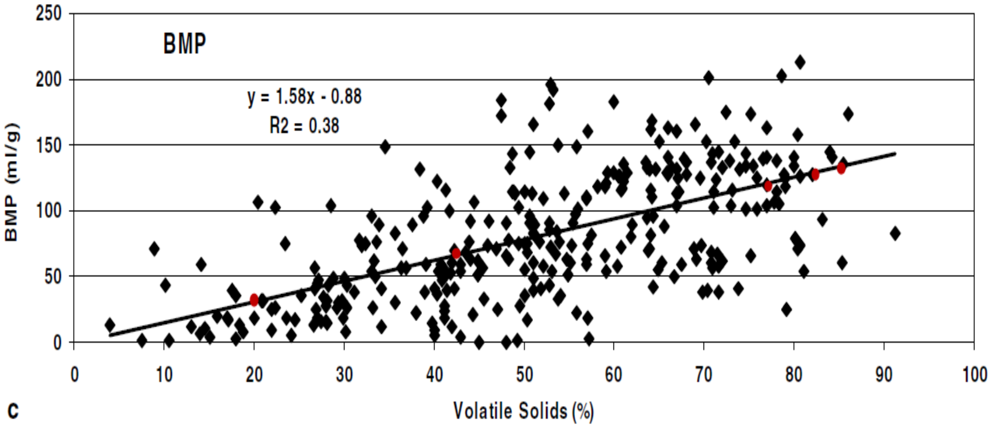


Figure 4.36 BMP Prediction from Volatile Solids Test Results for B-72

4.4 Prediction of Gas Generation Potential

Numerous factors influence the amount and rate of generation in a landfill. The factors are interconnected. The general factors are as follows

- Waste composition
- Local climate (rainfall, temperature)
- Landfill operation practice
- Age of waste
- Cover system

- Life span of Landfill

All these parameters are site specific, therefore, the gas generation volume and rate is unique for each site. Different gas models have been developed to predict the amount and rate of gas generation. The US EPA gas model assumes first order decay model for predicting gas generation. For model analysis for a dry tomb or conventional landfill the reference methane generation value, Lo, is assumed as 100 m^3/Mg, and methane generation rate constant, ko as 0.04 yr^{-1} (LandGEM version 3.02 guide).

To predict the gas generation for the City of Denton landfill, the conventional landfill operating procedure was considered. The landfill started accepting wastes in 1985 and closed at 2001. Gas generation was predicted for 100 years because of the fact that the gas generation becomes almost negligible after 100 years regardless of the gas generation potential and gas generation rate. For methane generation, Lo=100 m^3/Mg and different ko values from 0.02 to 1.0yr^{-1}, gas generation was predicted. For different collection efficiencies, recovery of gas was also estimated, as presented in Table 4.20 and Figure 4.37.

Table 4.20 Gas Generation for Different Methane Generation Rate at a Constant Lo=100 m^3/Mg

Methane Generation rate, K	Total Gas Generation	Predicted Gas Generation until 2010	Total Future Gas Generation	Future Gas Generation as Percentage of total gas generation	Efficiency	Total Future Gas Recovery	Average future gas recovery	Calculated Gas recovery in 2011	Calculated Gas recovery in 2011
yr^{-1}	ft^3	ft^3	ft^3	%	%	ft^3	ft^3/yr	ft^3/yr	ft^3/min
0.02	1.03E+10	3.58E+09	6.69E+09	65.15	50	3.35E+09	4.52E+07	8.57E+07	163
0.04	1.18E+10	6.00E+09	5.80E+09	49.18		2.90E+09	3.92E+07	1.20E+08	228.5
0.06	1.19E+10	7.64E+09	4.31E+09	36.07		2.15E+09	2.91E+07	1.35E+08	256.5
0.08	1.19E+10	8.74E+09	3.12E+09	26.32		1.56E+09	2.11E+07	1.20E+08	229
0.1	1.18E+10	9.49E+09	2.27E+09	19.27		1.13E+09	1.67E+07	1.08E+08	205
0.02	1.03E+10	3.58E+09	6.69E+09	65.15	60	4.01E+09	5.43E+07	1.03E+08	195.6
0.04	1.18E+10	6.00E+09	5.80E+09	49.18		3.48E+09	4.71E+07	1.44E+08	274.2
0.06	1.19E+10	7.64E+09	4.31E+09	36.07		2.59E+09	3.49E+07	1.62E+08	307.8
0.08	1.19E+10	8.74E+09	3.12E+09	26.32		1.87E+09	2.53E+07	1.44E+08	274.8
0.1	1.18E+10	9.49E+09	2.27E+09	19.27		1.36E+09	2.00E+07	1.29E+08	246

Table 4.20-Continued

Methane Generation rate, K	Total Gas Generation	Predicted Gas Generation until 2010	Total Future Gas Generation	Generation as Percentage of total gas generation	Efficiency	Total Future Gas Recovery	Average future gas recovery	Calculated Gas recovery in 2011	Calculated Gas recovery in 2011
yr^{-1}	ft^3	ft^3	ft^3	%	%	ft^3	ft^3/yr	ft^3/yr	ft^3/min
0.02	1.03E+10	3.58E+09	6.69E+09	65.15	70	4.68E+09	6.33E+07	1.20E+08	228.2
0.04	1.18E+10	6.00E+09	5.80E+09	49.18		4.06E+09	5.49E+07	1.68E+08	319.9
0.06	1.19E+10	7.64E+09	4.31E+09	36.07		3.02E+09	4.08E+07	1.89E+08	359.1
0.08	1.19E+10	8.74E+09	3.12E+09	26.32		2.19E+09	2.95E+07	1.69E+08	320.6
0.1	1.18E+10	9.49E+09	2.27E+09	19.27		1.59E+09	2.33E+07	1.51E+08	287
0.02	1.03E+10	3.58E+09	6.69E+09	65.15	80	5.35E+09	7.23E+07	1.37E+08	260.8
0.04	1.18E+10	6.00E+09	5.80E+09	49.18		4.64E+09	6.27E+07	1.92E+08	365.6
0.06	1.19E+10	7.64E+09	4.31E+09	36.07		3.45E+09	4.66E+07	2.16E+08	410.4
0.08	1.19E+10	8.74E+09	3.12E+09	26.32		2.50E+09	3.38E+07	1.93E+08	366.4
0.1	1.18E+10	9.49E+09	2.27E+09	19.27		1.81E+09	2.67E+07	1.72E+08	328

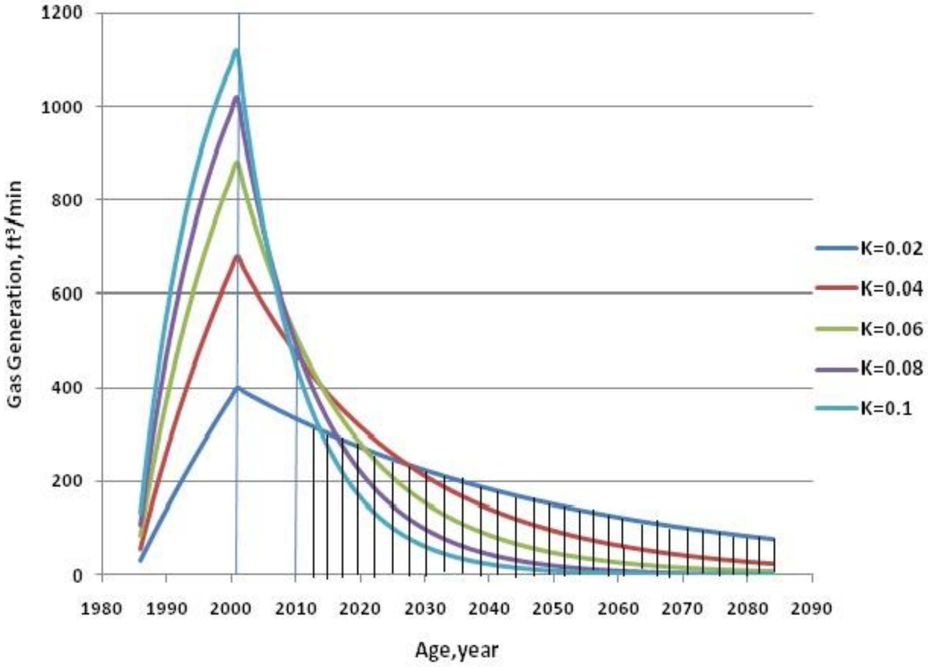


Figure 4.37 Gas Generation for Different Methane Generation rate at a constant Lo=100m^3/Mg

From the estimated gas generation, it was observed that high K values mean increased gas generation during the active landfilling period, and reduced gas generation after closure reduces. For higher decay rates, gas production ceases earlier. The peak of gas generation volume is higher values of for higher decay rate. Therefore, it is evident that for a conventional landfill where gas generation constant is less indicates reasonably high amount of gas generation after closure.

From the physical characteristics of the collected wastes, it was apparent that the landfilled wastes were not fully decomposed and most of the samples were partially degraded or not degraded. The decay rate for a traditional landfill is generally assumed to be 0.04 yr^{-1}. However, from the physical characteristics of the waste, it was noticeable that the decay rate was less than 0.04 yr^{-1} and for estimation, a decay rate of 0.02 yr^{-1} was assumed, as presented in Table 4.21.

Table 4.21 Gas Generation for Different Methane Generation Potential at a constant Ko=0.02 yr^{-1}

Methane Generation Potential, Lo	Total Gas Generation	Predicted Gas Generation until 2010	Total Future Gas Generation	Future Gas Generation as Percentage of total gas generation	Efficiency	Total Future Gas Recovery	Average future gas recovery	Calculated Gas recovery in 2011
m^3/Mg	ft^3	ft^3	ft^3	%	%	ft^3	ft^3/yr	ft^3/yr
80	8.22E+09	2.86E+09	5.35E+09	65.16	50	2.68E+09	3.62E+07	9.59E+07
100	1.03E+10	3.58E+09	6.69E+09	65.16		3.35E+09	4.52E+07	1.20E+08
120	1.23E+10	4.29E+09	8.03E+09	65.16		4.01E+09	5.43E+07	1.44E+08
140	1.44E+10	5.01E+09	9.37E+09	65.16		4.68E+09	6.33E+07	1.75E+08
80	8.22E+09	2.86E+09	5.35E+09	65.16	60	3.21E+09	4.34E+07	1.15E+08
100	1.03E+10	3.58E+09	6.69E+09	65.16		4.01E+09	5.43E+07	1.44E+08
120	1.23E+10	4.29E+09	8.03E+09	65.16		4.82E+09	6.51E+07	1.73E+08
140	1.44E+10	5.01E+09	9.37E+09	65.16		5.62E+09	7.60E+07	2.10E+08
80	8.22E+09	2.86E+09	5.35E+09	65.16	70	3.75E+09	5.06E+07	1.15E+08
100	1.03E+10	3.58E+09	6.69E+09	65.16		4.68E+09	6.33E+07	1.68E+08
120	1.23E+10	4.29E+09	8.03E+09	65.16		5.62E+09	7.60E+07	2.02E+08
140	1.44E+10	5.01E+09	9.37E+09	65.16		6.56E+09	8.86E+07	2.45E+08
80	8.22E+09	2.86E+09	5.35E+09	65.16	80	4.28E+09	5.79E+07	1.53E+08
100	1.03E+10	3.58E+09	6.69E+09	65.16		5.35E+09	7.23E+07	1.92E+08
120	1.23E+10	4.29E+09	8.03E+09	65.16		6.42E+09	8.68E+07	2.54E+08
140	1.44E+10	5.01E+09	9.37E+09	65.16		7.49E+09	1.01E+08	2.80E+08

Figure 4.38 shows the average gas generation rate for different gas generation potential. Gas generation potential of MSW depends on the composition of waste. Gas generation potential is proportional to the degradable waste percentage. Based on Table 4.21, it was observed that total volume of gas varies with methane potential, Lo. However, the percentage of gas production before and after closure remains same irrespective of the methane generation potential.

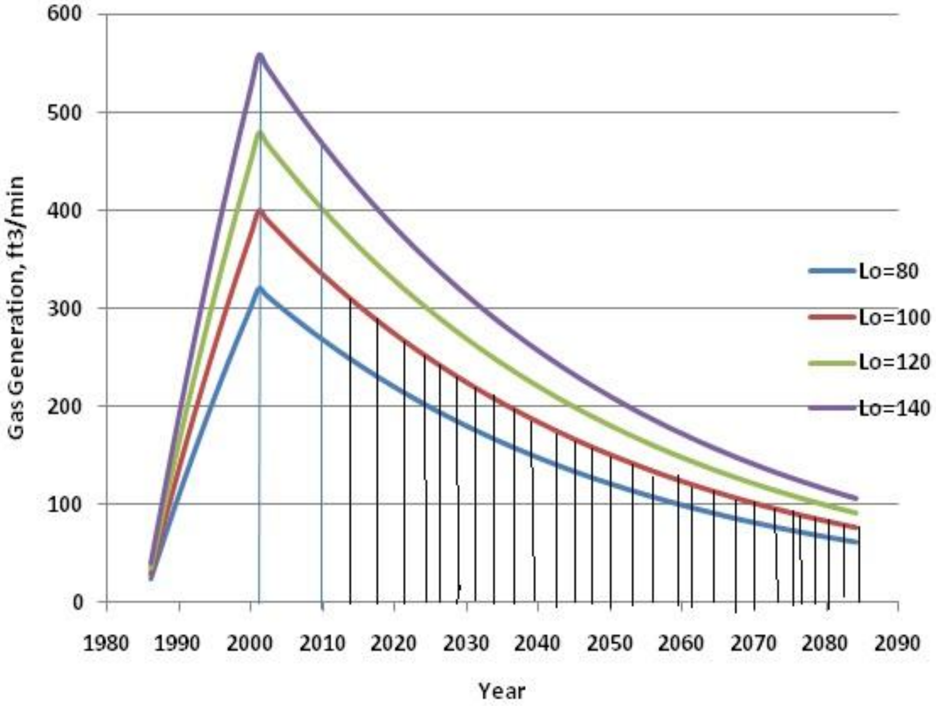


Figure 4.38 Gas Generation for Different Methane Generation Potential at a Constant ko=0.02 yr^{-1}

In a landfill, 100% gas recovery is only theoretically possible with the presence of final cover and with the assumption of there are no surface emissions from the landfill. However, in reality 100% recovery is not a feasible option. A general assumption of 50% recovery of landfill gas is utilized. Based the Figure 4.37, higher the decay rate, the higher the gas production will be in the beginning. Therefore, a higher ‘k’ value will lead to lower remaining methane generation potential. Figures 4.39 and 4.40 illustrates the higher gas generation with higher collection efficiency in field.

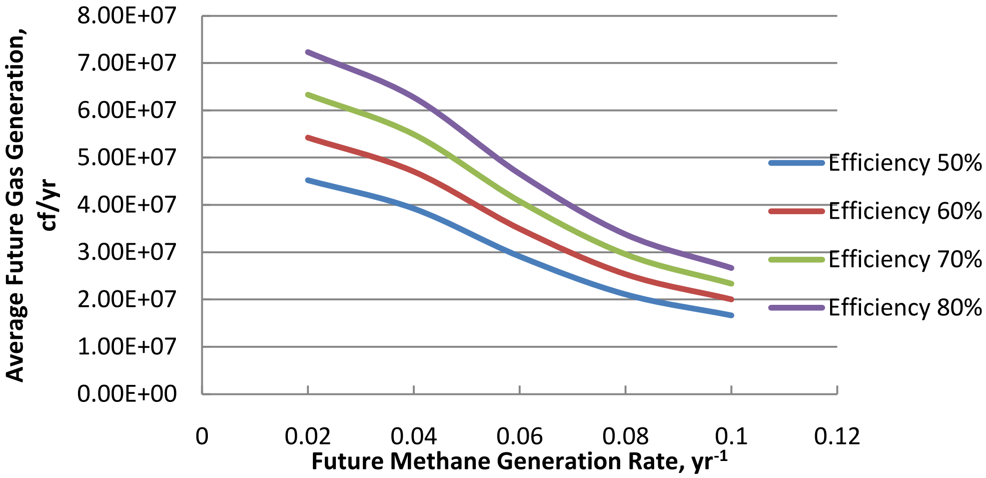


Figure 4.39 Gas Recovery with Increasing Methane Generation Rate

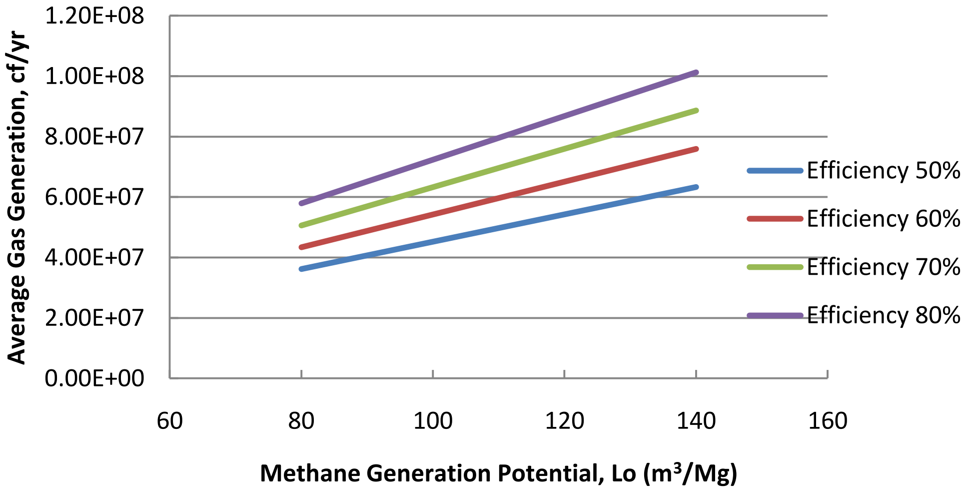


Figure 4.40 Gas Recovery with Increasing Gas Potential

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The main objective of the current study was to determine gas potential of the closed section of city of Denton landfill. A closed landfill might have potential benefits for gas recovery and utilization due to the presence of organic components in the MSW. The decomposition of organic components of MSW produces gas. The decomposition process after landfill closure may continue for 20 to 100 years depending on the operational practice of the landfill. However, to evaluate the methane potential of a closed landfill it is important to have the understanding of the characteristics of the existing or decomposed landfill wastes. The current study presents the characteristics of municipal solid waste samples, collected from a closed section (phase zero) of the City of Denton landfill, Texas. The phase zero section of landfill was operated as a pre subtitle-D conventional landfill. Twelve MSW samples were collected from the landfill using 3ft diameter bucket auger sampler from two boreholes in November, 2010. The collected MSW samples were utilized to determine physical and hydraulic characteristics. These properties are: physical composition, compacted unit weight, moisture content, permeability, volatile solids and particle size distribution. Degradation of landfilled sample depends on degradable waste components, age, presence of moisture and local climate. In a conventional or dry tomb landfill main concept is to prevent the intrusion of moisture in the waste. It is very likely that the wastes placed in a conventional closed landfill is mostly not degraded and have huge potential left for gas generation. Therefore the physical and engineering characteristics of landfilled municipal solid waste and landfill gas potential of landfilled or partially degraded solid waste were determined.

5.1 Summary and Conclusions

The work completed for the present study can be summarized as follows:

1. Landfilled MSW samples have been collected from the City of Denton Landfill closed section. Twelve samples were collected from two borings designated as B-70 and B-72, at ten feet depth interval. Each sample weighed approximately 15 to 20 Lbs.

2. The composition of the sample was determined by manual sorting. The average composition for landfilled waste determined as Paper (31%), Plastic (10%), Food Waste (0%), Textile and Leather (2%), Wood and Yard Waste (8%), Metals (3%), Glass (1%), Styrofoam and Sponge (1%), C & D (5%), Degraded Fines (14%) and Soils (25%).

Paper percentage (31%) determined in the landfilled waste composition was very high compared to the earlier researches on landfilled waste. The percentage of fine (41%) was nearly the same as documented in previous studies (Gomes et al., 2005; Gabr and Valero, 1995; Suthatip et al., 2006). The presence of high percentage of paper and partially degraded components in the landfilled waste may be because of unavailability of moisture for degradation of the wastes.

3. The average composition of the landfilled waste collected from the closed section of the landfill was compared to the annual average of fresh MSW from working phase of city of Denton landfill (2009-2010). As expected for landfilled waste the paper percentage was less than fresh waste due to degradation. Plastic percentage was determined less than fresh. Because of the landfilled rapid use of plastic packaging was not in use until 1990’s, the plastic percentage in the original composition of landfilled waste might have been less. The soils and fines were higher in landfilled waste than fresh MSW. Presence of degraded fines and lot of cover soil mixture increased the percentage of soils and fine in landfilled MSW.

It should also be noted that at different time of the year, the material in the waste varies. Fresh waste composition of 2009-2010 might be different than the initial composition of the landfilled waste in 1985. Therefore the changes of waste composition due to degradation may not be reflected when compared to the fresh waste collected in 2009-2010.

4. The degradable component of landfilled waste was 42.44% and non-degradable was 57.56%. The degradable portion of B-70 was much higher than the degradable portion of B-72. This was due to fact that four of the six samples collected form boring B-72 was mostly degraded. For both B-70 and B-72 degradation was higher on top and less in the bottom of the landfill. Due to absence of permanent cover on the closed section, there might be some water intrusion from top that caused higher degradation on top of the landfill. But the water intrusion depth is different for the two borings which might be due to heterogeneous nature of waste. The average composition of the landfilled wastes indicated presence of high amount of degradable component in the landfill at the time of sample collection.

5. The moisture content of the landfilled samples ranged from 11% to 34%. The average moisture content of the landfilled MSW was determined to be 24.93%.

6. The average compacted unit weight of the samples was determined both using standard proctor method and using Tensile Compression machine applying overburden pressure. From standard proctor method 58.76 lb /ft^3 and from tensile compression machine test results average compacted unit weight was found to be 49.14 lb /ft^3. The unit weights of samples were directly related to soil and fine percentage. Samples from B-72 were mostly degraded and average unit weight was higher than B-70 samples that were partially degraded. Degradation increases finer particles in waste mass. Therefore the unit weights were higher for more degraded samples.

7. The permeability of landfilled waste was determined to be in the range of 10^{-4} to 10^{-5}. The average permeability was determined 2.3E-4. Permeability of waste is a function of pore space. Degradation reduces size of waste particles and hence pore space is decreased. With degradation permeability reduces. (Hossain et al., 2002). The permeability results for fresh (city of Denton landfill, 2009-2010) and degraded samples (collected in 2010) were compared. The permeability of landfilled waste was determined less than fresh samples.

8. The particle size distribution of the samples were determined and compared to previous study that indicated the degradation phase of samples. Samples were compared with previous studies and approximate half of the samples were as phase I degraded samples and other half of the samples were between phase I and phase IV degradation level. (Haque and Hossain, 2007).

9. The volatile solid results were conducted with biodegradable organic portions. The average of volatile solids result was 66.87%. The annual average of volatile solids for fresh solid waste collected from the working phase of city of Denton landfill (2009-2010) was determined 76.96. Volatile solids of landfilled samples were less than volatile solids of fresh waste. However, the volatile solids from landfilled samples were close to fresh waste. It can be summarized that the samples were partially degraded hence the there was probability of future gas generation for these samples.

10. Percentage of Cellulose, Hemicelluloses was estimated from the volatile solids determined. (Kelly et al., 2006). C/L ratio is a good indication of degradation phase of waste. (C+H)/L ratio in the bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower decrease in this ratio in the traditional landfill samples. The (C+H)/L ratios of traditional samples were higher than those of the bioreactor samples at the same time point. (Hossain et al., 2002).

The closed section of the landfill was operated as traditional landfill and for most of the samples C/L ratio was more than 1. Therefore it might be assumed the degradation for the landfilled waste was not complete at the time of sample collection. The C/L ratio indicated half of the samples were at phase I and other half of the samples were between phase I and phase IV degradation level.

11. First order gas model was used to predict gas generation the closed section of the landfill. The average gas generation potential of the sample ranges from 65% to 20% for different gas generation rates and gas potential assumed. In a landfill 100% gas recovery is only theoretically possible with the presence of final cover and with the assumption of there is no surface emission in the landfill. However in reality 100% recovery is not a feasible option. A general assumption of 50% recovery of landfill gas is utilized. Based on the Figure higher the decay rate the gas production will be higher in the beginning. Therefore higher 'k' value will lead to lower remaining methane generation potential. From the physical characteristics of collected wastes it was apparent that the landfilled wastes were not fully decomposed and most of the samples were partially degraded or not degraded. The decay rate for a traditional landfill is generally assumed 0.04 yr^{-1}. However from the physical characteristics of the waste it was noticeable that the decay rate was less than 0.04yr^{-1} and for gas potential estimation decay rate of 0.02 yr^{-1} was assumed.

12. Based on the results the maximum prediction of future gas generation was 65% of the total gas generation.

5.2 Recommendations for Future Studies

To enhance the reliability of the results found and to make the current study even more effective, it is recommended that the work is further continued as mentioned in this section:

1. To monitor the effect of aging on the physical characteristics of MSW, samples can be collected from ELR landfills with reasonably even moisture distribution on the samples.

2. Site specific methane generation rate can be determined from reasonable amount of gas data collection from the landfill site to estimate gas generation.

3. To study the efficiency of gas collection system, surface emission from landfill can be determined.

4. To predict gas generation potential Biochemical Methane potential (BMP) test can be done. BMP was not conducted in the current study due to time constrain.

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BIOGRAPHICAL INFORMATION

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