## ABSTRACT

## BIODEGRADATION AND LANDFILL SETTLEMENT

**by**
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The most widely used method for the final disposal of solid waste is landfilling, which is also economical and simpler than most other disposal systems. Long term settlement in a landfill occurs mainly due to biodegradation of the refuse which is a very slow microbiological process. However, if the rate of biodegradation is enhanced, it may be possible to achieve early stabilization, faster settlement, consequently more capacity of the landfill to handle waste.

The objective of this research is to study the effects of enhanced biodegradation on settlement and to compare these results to other models used for predicting landfill settlement. To accomplish this, a laboratory scale confinement cell was set up using a typical municipal solid waste to study settlement and biodegradation. Results from this study indicate that secondary settlement is linear with respect to logarithm of time and that biodegradation does not have any effect on settlement over a short duration of time, but is predominant over extended periods.

# BIODEGRADATION AND LANDFILL SETTLEMENT

by
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To my beloved family

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# CHAPTER 1

# INTRODUCTION

Scarcity of land is not a new problem because of the kind of development we are experiencing in the last few decades of this century. Municipal landfills usually occupy large spaces of land, when there already is a crunch of available land. Also, the amount of waste needed to be disposed off seems to be endless. Landfilling in probably the most inexpensive way of handling Municipal Solid Waste (MSW). Hence the capacity of a landfill needs to be increased.

The municipal refuse in a landfill settles initially because of the expulsion of air and/or water in the pore spaces of the waste, and over a longer period because of biotransformation of the waste into gases and leachate, which results in settlement. The settlement due to biodegradation goes on up to 40 years after the closure of the landfill. If it is possible to accelerate the biodegradation, more landfill capacity could be achieved for the landfill. The landfill can be considered as an anaerobic bioreactor. By studying how biodegradation occurs fastest, such conditions can be applied to a landfill and early settlement could be achieved. Settlement values as a function of time can be predicted, and this gives an estimate about landfill capacity.

Another advantage of accelerated biodegradation is to prevent groundwater pollution problems because of fractured and leaking liner systems in a landfill worn out by time. If boidegradation is achieved early, the gases and leachates can be removed effectively from the landfill when the venting and liner system is still young.

In this study, a landfill test cell developed using typical MSW composition. The aim was to study landfill behavior patterns and to obtain experimental data of settlement and biodegradation. The test cell was kept in simulated landfill conditions and provision was made for accelerated biodegradation. The data obtained from the test cell was compared with various other landfill settlement prediction models. The gas generated from the test cell was monitored and analyzed. Calculations were performed to study biodegradation using the data obtained from the test cell. The organic mass lost was studied as a first order equation and the rate constant for the process was determined. Various geotechnical parameters of the refuse were determined and compared with the existing studies for municipal refuse.

## 1.1 Research Objectives

The objective of this research was to relate the techniques for describing landfill settlement and biodegradation and then apply such techniques to available data obtained using experimentation. Experiment was done on a refuse typically found in MSW using prefabricated test cell and simulated landfill conditions. The data obtained were analyzed and compared to check their corroboration with various settlement models. Hence, the purpose was to study the biodegradation and settlement in landfills. The proposed research had the following goals:

1. To study the effect of accelerated biodegradation on landfill settlement using simulated landfill conditions in a laboratory.
2. To estimate typical geotechnical parameters of the refuse and compare them with existing literature data.
3. To determine landfill settlement with respect to time and compare this data with various other models predicting the same.

4. To measure the total gas production as a surrogate parameter to quantify biodegradation.

# CHAPTER 2

## BACKGROUND AND LITERATURE REVIEW

The theory of landfill settlement was originally thought of as similar to soil settlement. But studies in field and lab show that biodegradation is one of the most important aspects of landfill settlement which makes it different from soil settlement. Studies done by Wall and Zeiss (1995) indicate that settlement due to biodegradation alone can range from 10-25% and total settlement from 25-50%. The idea of designing a landfill as a anaerobic reactor to simulate actual landfill conditions can be used to study landfill settlement and gas behavior patterns. The main idea behind this is to enhance settlement using conditions most favorable for biological decomposition of municipal refuse. Biodegradation of MSW results in the formation of leachates and landfill gases, mainly carbon dioxide and methane, which are taken out from the landfill using proper venting and drainage systems. This causes a gradual settlement of the landfill. If, by some means, the biodegradation is accelerated, the settlement will occur at a faster rate. The intention behind the enhanced biodegradation is to increase the capacity of the landfill. While designing it as a bioreactor, acceleration and stabilization of the landfill can be achieved in a better way since we have more control over the landfill in terms of microbes, leachate and gas systems.

As the land becomes more expensive in densely populated areas, it is tempting to develop structures over landfills. But construction of foundations in not safe because of several reasons like production of poisonous gases, excessive settlement and low inherent bearing capacity of the soil. Hence it is of utmost importance to study the settlement of landfill properly.

## 2.1 Biodegradation

Approximately 25-40% of the MSW is available for biodegradation (Barlez *et al.*, 1989). If this amount is removed from the landfill, it will cause considerable amount of settlement. 44.8% of solid weight on a dry weight basis is decomposable organic matter (Tchobanoglous *et al.*, 1977).

The potential of a waste to biodegrade depends on the amount of solid carbon that decomposes, rate of decomposition and relation between mass lost and settlement (Wall and Zeiss, 1995). Studies done by Barlez show that a MSW usually contains 40-50% cellulose, 10-15% lignin, 12% hemicellulose and 4% protein on a dry weight basis. Studies indicate that more the amount of cellulose-plus-hemicellulose, greater is the scope for biodegradation. This biodegradable portion of the organic fraction can be converted under anaerobic conditions as represented below (Tchobanoglous *et al.*, 1993) :

$$\text{Organic matter} + H_2O + \text{Nutrients} \xrightarrow{\text{microbial action}} \text{New cells} + \text{Resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{heat}$$

Roughly 80% of the waste is organic matter (Tchobanoglous *et al.*, 1993). They also predict that around 19.7% of solid waste transforms to gas. It was proposed that 90% of the process will occur in the first 40 years of the life of the landfill (Disbrow, 1988).

The generation of landfill gas due to biodecay has been classified in five different phases (Tchobanoglous *et al.,* 1993). The first phase is the *initial adjustment phase* in which aerobic decomposition is predominant because of the presence of the entrapped air in the waste. In phase II, anaerobic conditions begin to generate because of the depletion of oxygen. This phase marks the beginning of the conversion of the complex organic material to organic acids and other products. The leachate (if any) pH drops and $CO_2$ concentrations elevates in this phase. Phase III, the *acid phase* shows further enhancement of phase II with production of higher amounts of organic acids and lesser hydrogen. Acetic acid and $CO_2$ are the two major products of this phase. Also, BOD and COD of the leachate rise significantly. Phase IV is the methane fermentation phase in which the acetic acid and hydrogen gas are converted to $CO_2$ and $CH_4$. The methanogenic bacteria play a major role here. Both methane and acid formation occur in this phase, but the acid is formed at a lower rate. Due to conversion of acid to $CO_2$ and $CH_4$, the pH gradually rises, which results in lower concentrations of heavy metals in leachates. Phase V is when the availability of biodegradable material starts to cease. The gas generation rate also lowers down in this phase. There is a lack of moisture, nutrients and readily biodegradable substrate.

## 2.2 Landfill Settlement

Total settlement of landfills range from 25-50% (Wall and Zeiss, 1995). Decomposition of organic material results in loss of weight from the landfill in the form of gas and leachate, and thus the landfill settles. Construction of new cells over old ones and transport of water in and out of the landfill are some of the important factors to be considered while calculating settlement.

Settlement of waste fills occurs through four mechanisms ( Edil *et al.*, 1990):

1. Mechanical : This is due to distortion, bending, crushing and reorientation of materials; may be due to self weight and/or imposed loads on the landfill.
2. Ravelling : The smaller particles in the waste occupy the voids between the larger particles.
3. Physico-Chemical change : Attributed to corrosion, oxidation and combustion of the waste.
4. Bio-Chemical decay : Microbiological fermentation/decay of waste (aerobic/anaerobic).

Settlement can be classified into three distinct stages :

1. Initial Compression : This type of rapid settlement due to application of load is initial compression. When a load is applied or increased, a comparatively sudden reduction of volume takes place, which is primarily due to the expulsion and compression of air in the voids. The initial compression is estimated using :

$$S_i = \rho\, b\, I\, (1 - \nu^2) / E \qquad (2.2.1)$$

where

$S_i$ = initial compression ( m )

$\rho$ = average stress on soil surface (kg/m$^2$)

b = width of the loaded area (m$^2$)

I = shape factor (depending upon the shape and rigidity of the load )

$\nu$ = Poisson's ratio (unit less)

E = Undrained modulus (kg/m$^2$)

It is generally not possible to determine the value of initial settlement for municipal refuse (Oweiss and Khera, 1990). This is attributed mainly to the fact that it is difficult to find the values of Poisson's ratio and the Modulus of Elasticity. The pattern of stress - strain diagram cannot be found out for initial settlement.

2. Primary Compression : If the equilibrium is not attained after initial consolidation, further reduction in volume continues which is mainly due to squeezing out of water and gas from the voids. This reduction due to this process is called as primary compression. In completed landfills, it takes around 30 days for the primary settlement to occur, after the application of the external load (Sowers 1973). If the waste is saturated or nearly saturated, the major part of volume change is due to primary consolidation, whereas, if the degree of saturation is very low, volume change occurs mainly due to expulsion and compression of air in the voids with little or no removal of water. Even after the reduction of all excess hydrostatic pressure to zero, some consolidation of soil takes place at a very slow rate, which is called secondary consolidation.

The empirical equation is (Holtz and Kovacs, 1981):

$$S_p = H_i \, CR \log(\sigma_f/\sigma_o) \qquad (2.2.2)$$

where,

$S_p$ = primary compression (m)

$H_i$ = Height after initial compression (m)

CR = Compression ratio for primary compression (unit less)

$\sigma_f$ = Final stress (kg/m$^2$)

$\sigma_o$ = Initial stress (kg/m$^2$)

3. Secondary Compression: Secondary compression is mainly due to creep and biodegradation of the waste ( Sowers, 1973). According to Sowers, it is a combination of mechanical secondary compression, physico-chemical action and biological decay; and the secondary compression index $C_\alpha$ is proportional to the initial void ratio and conditions available for decomposition. Sowers also suggested that higher values of $C_\alpha$ can be attained by increasing the rate of degradation. There are several models predicting the secondary settlement of wastes, which are described later in this chapter.

There are two $C_\alpha$ values which can be considered, i.e. two stages of delayed compression (Bjarngard and Edgers, 1990). One phase is by mechanical compression and the second one mainly because of biodegradation. They suggest a range of $C_{\alpha 1}$ from 0.01 to 0.056 for lab study and 0.003 to 0.038 for field data. The $C_{\alpha 2}$, at long time periods showed field values as large as 0.51.

## 2.3 Models for Predicting Settlement

There are two different approaches reported to predict settlement (Edil *et al.*, 1990). Settlement due to external surface loading can be plotted as strain versus logarithm of effective stress. The magnitude of settlement is given by the slope of this curve. But there are few problems in this method. In case of old landfills, the original height of the waste is unknown. Secondly, effective stress being a function of refuse density, cannot be determined accurately for a heterogeneous material like municipal refuse. Thirdly, the strain versus log stress curve never turns out to be a straight line, indicating that the settlement coefficient varies as the stresses within the landfill.

The second way to calculate settlement rate as the settlement magnitude per time interval. The settlement data should be available over a long period of time to get satisfactory values. Usually, the strain versus log time curve is plotted for this method and $C_\alpha$ is found as the slope of this curve.

There are three types of models for predicting settlement of landfills:

1. Rheological models based on stress - strain - time relationships.
   a.) Gibson and Lo model.
   b.) Power Creep law.
2. Empirical models based on field data:
   a.) Sowers Model
   b.) Yen Scanlon Model.
3. Model based on Gas emission:
   a.) Arntz and Rahgu (NJIT) model.

All these models are briefly described below:

### 2.3.1 Gibson and Lo model

This model was originally proposed for the long term compression of soils. It can also be used for predicting primary and secondary settlement of municipal refuse (Edil *et al.*, 1990). The primary and the secondary settlement can be represented by one single equation as :

$$S_s = H\ \varepsilon(t) = H\ \Delta\sigma(t)\ \{\ a + b(\ 1 - e^{-(\lambda/b)t})\ \} \qquad (2.3.1.1)$$

where

$H$ = original height of the refuse (ft)

$\varepsilon$ = strain

$\Delta\sigma$ = compressive stress (kPa)

$a$ = primary compressibility parameter ($kPa^{-1}$)

$b$ = secondary compressibility parameter ($kPa^{-1}$)

$\lambda/b$ = rate of secondary compression ($day^{-1}$)

$t$ = time since load application (days)

The ranges of these parameters as studied by Edil *et al.* are:

$\Delta\sigma$ = 45 kPa to 276.4 kPa

$b = 1 \times 10^{-4}$ to $5.87 \times 10^{-3}$ $kPa^{-1}$

$\lambda/b = 9.2 \times 10^{-5}$ to $4.3 \times 10^{-3}$ $day^{-1}$

$a = 5.11 \times 10^{-7}$ to $3.8 \times 10^{-4}$ $kPa^{-1}$

### 2.3.2 Power Creep Law

Time dependent deformation under constant stress is widely used for studying the transient creep behavior of a lot of materials. Edil applied the same law to municipal refuse, which is given as (Edil *et al.*, 1990):

$$S(t) = H \,.\, \varepsilon(t) = H \;\Delta\sigma(t)\; m\,(t/t_r)^n \qquad (2.3.2.1)$$

where,

$m$ = reference compressibility ($kPa^{-1}$)

$n$ = rate of compression (unit less)

$t_r$ = reference time ( usually 1 day)

Edil *et al.* also suggest values of m and n based on field study of three different landfills and lab study:

$m = 7.52 \times 10^{-8}$ to $1.38 \times 10^{-4}$ $kPa^{-1}$

$n = 0.297$ to $1.17$ (unit less)

### 2.3.3 Yen and Scanlon model

Yen and Scanlon studied several landfill sites in California (Yen and Scanlon, 1975). They suggest the following set of empirical equations:

$$m = 0.0268 - 0.0016 \log t_1 \text{ (for fill heights of 12 - 24 m )} \quad (2.3.3.1a)$$

$$= 0.038 - 0.0155 \log t_1 \text{ (for fill heights of 24 - 30 m )} \quad (2.3.3.1b)$$

$$= 0.0433 - 0.0183 \log t_1 \text{ (for fill heights greater than 30 m )} \quad (2.3.3.1c)$$

where m is in m/month

$t_1$ = median fill age in month, which is :

$t_1 = t - t_c/2$

t= time from beginning of landfill (months)

$t_c$ = time for completion of landfill (months)

It is to be noted that as the height of fill increases, the m value also increases.

### 2.3.4 Sowers Model

This is probably the most widely used model for predicting landfill settlement because of its accuracy and simplicity. This is also another empirical model based on study of several full scale municipal landfills. It is the first model to predict secondary compression in the landfills (Wall and Zeiss, 1995). It is based on Buisman's theory of secondary compression of soils. According to Sowers, it is assumed in this model that the secondary portion of the settlement curve is linear with respect to the logarithm of time. The equation is given as :

$$S_s = H_p \ C_{\alpha e} \ \log (t/t_p) \qquad (2.3.4.1)$$

where

$S_s$ = Settlement due to secondary compression (meters)

$C_{\alpha e}$ = slope of strain versus log time curve

t = time after landfill closure (years)

$t_p$ = time for primary compression to occur (years)

$H_p$ = Height after primary compression (meters)

Also,

$$C_{\alpha e} = C_\alpha/(1 + e_o) = \Delta\text{strain} \ / \ \Delta\log t \qquad (2.3.4.2)$$

where $C_\alpha$ is the slope of the void ratio versus log time curve. The relationship between $C_{\alpha e}$ and initial void ratio of the waste is as given below (Sowers, 1973) :

$$C_{\alpha e} = \frac{(0.03 \text{ to } 0.09)\, e_o}{(1 + e_o)} \qquad (2.3.4.3)$$

The values of 0.03 corresponds to unfavorable conditions while 0.09 corresponds to unfavorable conditions for biodegradation.

### 2.3.5 Arntz and Raghu (NJIT) Model

Arntz and Raghu correlated the rate of gas production, the resulting loss of volume and the settlement observed settlement (Arntz and Raghu, 1993). This model is based on the SIMCON model proposed by C. S. Holling that the rate of settlement is in inverse proportion with the exponential of time. This is proposed to be a two phase model. The first phase is shown by the equation below :

$$\frac{dV}{dt} = a\,t \quad ( 0 =< t =< t_1) \qquad (2.3.5.1)$$

where

V = Volume of gas produced ( $ft^3$ of gas per $ft^3$ of waste per year )

a = average amount of gas per year for $t_1$ ($ft^3$)

$t_1$ = time required for phase 1 ( 10 years recommended )

The second phase is described by the equation below:

$$\frac{dV}{dt} = a\ t_1\ e^{-K(t - t1)} \qquad (2.3.5.2)$$

where,

K = a constant

t = time for total gas production (years)

Settlement is calculated using volumetric strains. It is assumed that the volumetric strain is equal to the vertical strain.

# CHAPTER 3

# METHODOLOGY

The methodology adopted for this study was to link techniques for describing landfill settlement and biodegradation and applying them to available data obtained using experimentation. The experimental setup included characterizing a waste stream, fabricating and operating landfill test cell in simulated landfill conditions. The data obtained was analyzed and compared to check it's compatibility with various settlement models.

## 3.1 Experimental Set Up

For this study, an incubator (Lab Line Instruments Inc., Model 703AP) was used to simulate landfill temperature most adequate for landfill biodegradation. Peak gas production occurs at 35 $^{0}$C, which is optimum for anaerobic mesophilic digestion (DeWalle *et al.*, 1978). The test cell was filled with a typical MSW composition given by Tchobanoglous *et al.*, as shown in Table 3.2. The waste consisted of 70% fresh waste and 30% old waste obtained from Elizabeth landfill, Elizabeth, NJ, primarily as a seed for bacteria. The old waste obtained from Elizabeth landfill was 20 years old degraded municipal refuse. Anaerobically degraded waste can serve as a seed of bacteria acclimatized to anaerobic refuse decomposition (Barlez *et al.*, 1986). As per Barlez *et al.*, the addition of such bacteria to the reactor should decrease the time for the onset of methane production. Fresh soil could also be used as a source of anaerobic bacteria (Tchobanoglous *et al.*, 1993).

Higher level of initial moisture content provides acceleration for methane production (Rowers and Farquhar, 1973). In this study, a combined moisture content (fresh waste and old degraded waste ) was kept around 53.3% (wet weight basis), and the Total Volatile solids were 58.5 %. Anaerobic condition was maintained by purging the whole system with nitrogen and thus removing oxygen. This will enhance the activity of the anaerobic bacteria present in the old degraded refuse.

Pohland suggests that methane production can be enhanced by leachate recirculation (Pohland, 1975). The idea is to maintain the nutrients and the bacteria within the system. This feature was incorporated by recirculating the leachate produced on a continual basis, as shown in Figure 3.1.

It has been suggested that if the refuse particle size is reduced to a characteristic particle below 20% of the cell diameter, cells of smaller dimensions can be designed (Wall and Zeiss, 1995). Studies show that larger sized particles are not favorable for gas production (DeWalle *et al.*, 1978). So, for this study, the particle size was chosen as 0.75 inch by proper shredding. This was done by passing the material through ASTM sieve of 0.75 inch. The cell height was chosen as 15 inches and diameter of 6.299 inches, providing a cross section area of 31.16 inch square or 0.2164 feet square.

The waste was of unit weight 40 $lb/ft^3$ . It was filled to an original height of 14 inch, excluding the porous stones kept at the top and the bottom of the waste to ensure that no solids choke the gas and leachate extraction systems. The porous stone was prepared in the lab using sand and Dow Corning Epoxy in a 3:1 ratio.

The cell was made out of plexiglas, which basically is inert, and will not chemically react with the leachates or gases produced by the reactor. The cell is diagramatically

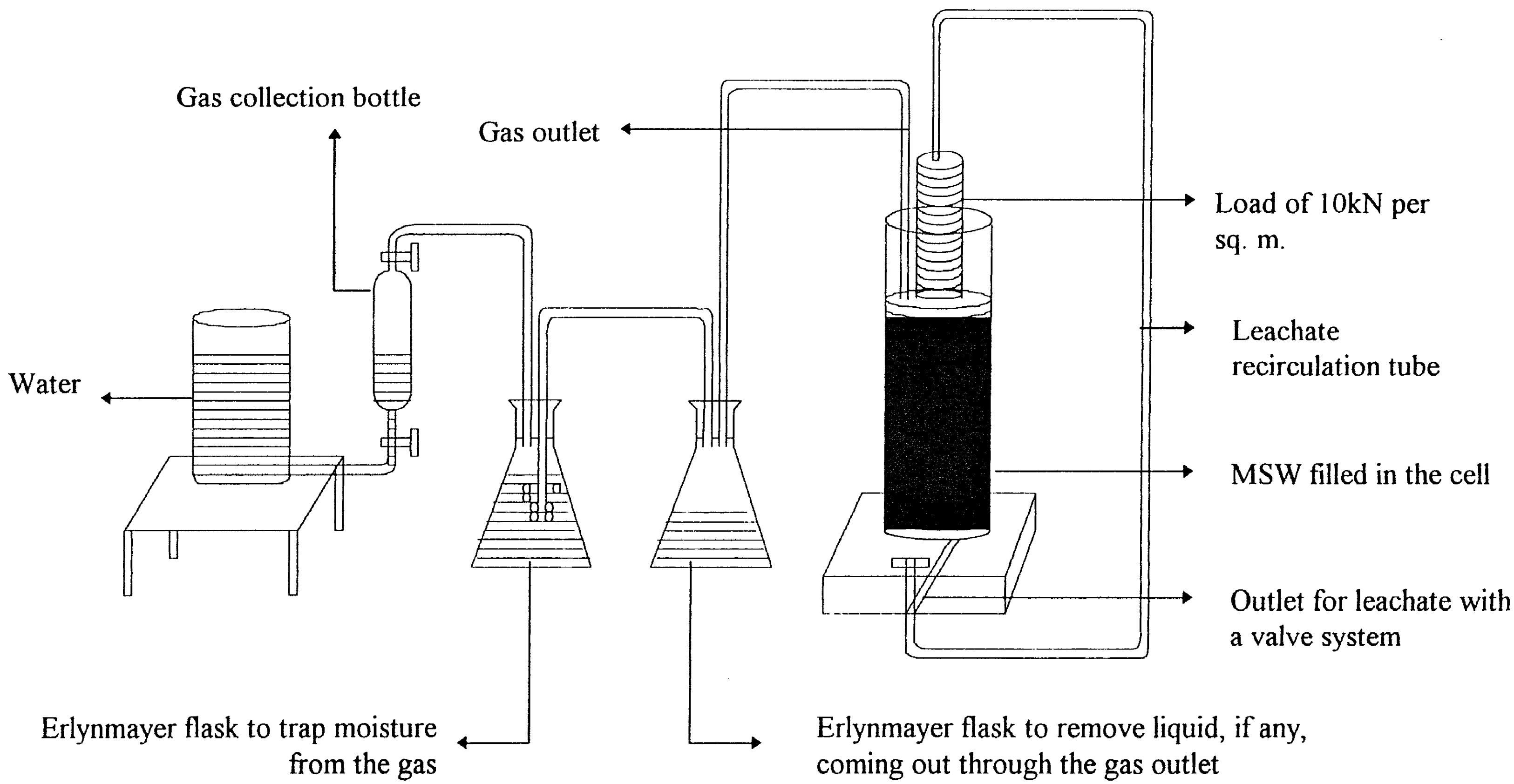


**Figure 3.1** Experimental set up

shown in Figure 3.2. The piston that goes inside the cell was sealed with 'O' rings to ensure that no gas and liquids escape from the reactor. This was tested by pouring soap water in the cell at a certain level, and then the piston was applied a load of 10 $kN/m^2$. The 'O' ring itself had some resistance with the inner cell wall. It needs some extra force by itself to go down, other than its self weight. This was measured as 5.4 $kN/m^2$ . Thus a total load of 32 kg was applied to the system. Out of this, 21 kg went towards the 10.5 $kN/m^2$ condition of the landfill, simulating 2-3 meter layer of waste as an overburden for the cell. The remaining 11 kg formed the 5.4 $kN/m^2$, which takes care of the friction between the piston and the inner cell wall.

The gas collection system was basically a liquid displacement method. The gas outlet was at the top of the cell, and was connected to a gas collection bottle using tygon tubing. Before the gas could enter the gas collection bottle, a trap was used to capture the moisture ( if any ) coming along with the gas. The volume of gas produced was measured by noting the change in the liquid level in the collection bottle whose dimensions are known. The gas collection bottle also had a septum so that it was possible to collect gas samples using syringe for composition analysis. Gas composition was analyzed using a Gow-Mac Gas Chromatograph, Thermal Conductivity Detector, Series 580. Leachate samples were analyzed using a Perkin Elmer Series II CHNS/O -2400 Analyzer. The reactor was kept in a floor type incubator (Lab Line Instruments Inc., Model 703AP) maintained at $35^0$ C. This anaerobic reactor was setup on January 17, 1996.

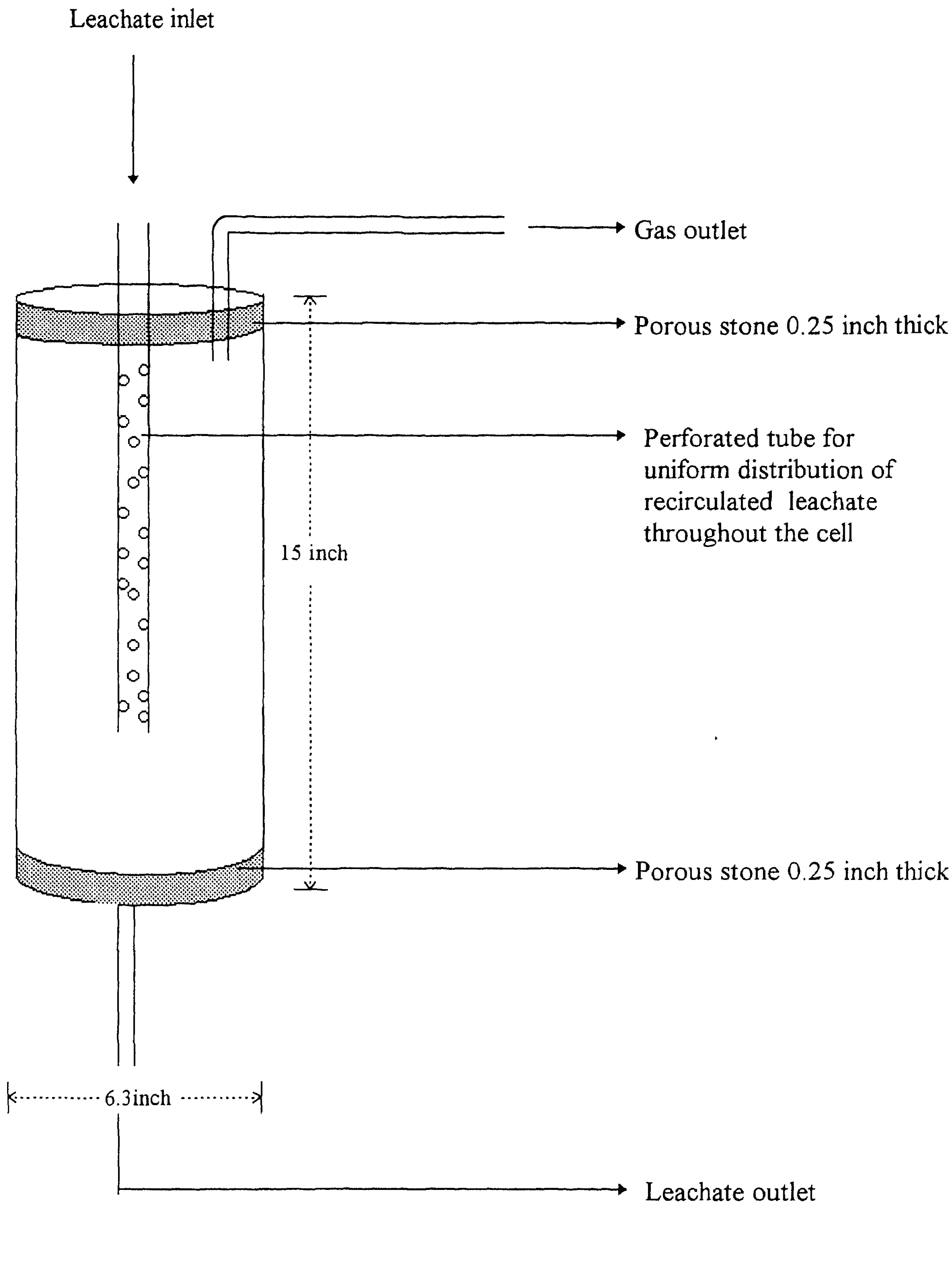


**Figure 3.2** Details of the cell.

## 3.2 Properties of the Waste

Some of the most commonly parameters used to characterize a waste are described in Table 3.1 below. All the details of the calculations are detailed in Appendix A.

**Table 3.1** Properties of waste

| | |
|---|---|
| Specific Gravity, G | 1.45 |
| Degree of Saturation, $S_r$ | 0.42 |
| Initial Void Ratio | 3.93 |
| Compression ratio for primary settlement, CR | 0.43 |
| Rate of secondary settlement, $C_{\alpha\varepsilon}$ | 0.0714 |
| Moisture Content (Wet weight basis) | 53.3% |
| Total Volatile solids (Dry weight basis) | 58.5 % |

## 3.3 Waste Composition of the Combined Waste

As mentioned before, a 70% fresh waste and a 30% old waste were used for this study. The composition of the 70% fresh waste was taken as the typical MSW composition according to Tchobanoglous *et al.*, and is shown in Table 3.2. The composition of the old waste was assumed based on literature study.

The high moisture content of the combined waste (53.3%) is attributed to the fact that the old waste obtained from Elizabeth landfill was in the form of a slurry and had an extremely high water content. Since we were aiming at an accelerated biodegradation, this percentage was thought to be appropriate.

**Table 3.2** Waste Composition

| Component | % fresh waste | Fresh wt. (kg) | % old waste | Old wt. (kg) | Combined wt. (kg) | Combined % |
|---|---|---|---|---|---|---|
| **Organics** | | | | | | |
| Food | 9 | 0.287 | 0 | 0 | 0.287 | 6.32 |
| Paper | 34 | 1.085 | 5.5 | 0.0752 | 1.1602 | 25.55 |
| Cardboard | 6 | 0.191 | 5.5 | 0.0752 | 0.2662 | 5.86 |
| Plastic | 7 | 0.223 | 9.25 | 0.126 | 0.349 | 7.68 |
| Textile | 2 | 0.063 | 3.7 | 0.0506 | 0.1136 | 2.5 |
| Rubber | 0.5 | 0.015 | 9.25 | 0.126 | 0.141 | 3.1 |
| Leather | 0.5 | 0.015 | 3.7 | 0.0506 | 0.0656 | 1.44 |
| Yard waste | 18.5 | 0.590 | 0 | 0 | 0.59 | 13.0 |
| Wood | 2 | 0.063 | 0 | 0 | 0.063 | 1.38 |
| **Inorganics** | | | | | | |
| Glass | 8 | 0.255 | 18.51 | 0.25 | 0.505 | 11.12 |
| Tin Cans | 6 | 0.191 | 18.51 | 0.25 | 0.441 | 9.71 |
| Aluminum | 0.5 | 0.0159 | 18.51 | 0.25 | 0.2659 | 5.85 |
| Other Metal | 3 | 0.095 | 3.7 | 0.0506 | 0.1456 | 3.2 |
| Ash, misc. | 3 | 0.095 | 3.7 | 0.0506 | 0.1456 | 3.2 |
| **Totals** | **100** | **3.1839** | **100** | **1.3548** | **4.5387** | **100** |

# CHAPTER 4

## OBSERVATIONS MADE FOR THE CELL

### 4.1 Settlement

The settlement data is as shown in Table 4.1. The total settlement observed after 130 days was 4.95 inches. This is about 35.5% settlement, including primary and secondary settlement. This value is comparable to the data obtained using various models used for settlement prediction of landfills, which is presented in the later sections. The settlement versus time data is diagramatically displayed in Figure 4.1. It is observed that a rapid settlement of 2.95 inches occurred within 5 days. This is called settlement due to primary compression. The Root Time method was adopted to find the duration of primary settlement for the data obtained. The root time method requires compression readings for a shorter period of time, compared to the other method used, namely, the log time method. The details of this method are presented in Appendix D.

As observed from the time - settlement curve (Figure 4.1), it is noticed that the earlier rapid settlement gradually lowers down and results into another type of settlement, the secondary settlement. At the end of 130 days, a total settlement of 4.95 inches was observed. This implies that an effective settlement of 2 inches occurred due to secondary settlement. The log time (days) versus strain curve, which is shown in Figure 4.2, is used to determine the rate of secondary settlement, $C_{\alpha e}$ . The value of $C_{\alpha e}$ was determined to be 0.0714 and it is the ordinate value difference for the straight line portion of the log time - strain curve for one log cycle. From Figure 4.2, it is observed that there is a sharp dip in the curve at the far end of the settlement versus time curve.

**Table 4.1** Settlement data obtained from the experiment

| Time (days) | Settlement (inch) | Time (days) | Settlement (inch) | Time (days) | Settlement (inch) |
|---|---|---|---|---|---|
| | | 43 | 4.14 | 86 | 4.5 |
| 1 | 1.7 | 44 | 4.15 | 87 | 4.511 |
| 2 | 2 | 45 | 4.16 | 88 | 4.511 |
| 3 | 2.5 | 46 | 4.17 | 89 | 4.515 |
| 4 | 2.73 | 47 | 4.19 | 90 | 4.521 |
| 5 | 2.95 | 48 | 4.199 | 91 | 4.528 |
| 6 | 3.15 | 49 | 4.2076 | 92 | 4.533 |
| 7 | 3.3 | 50 | 4.2157 | 93 | 4.561 |
| 8 | 3.4 | 51 | 4.223 | 94 | 4.578 |
| 9 | 3.48 | 52 | 4.2307 | 95 | 4.591 |
| 10 | 3.52 | 53 | 4.2484 | 96 | 4.593 |
| 11 | 3.55 | 54 | 4.2461 | 97 | 4.6 |
| 12 | 3.6 | 55 | 4.2538 | 98 | 4.603 |
| 13 | 3.62 | 56 | 4.2615 | 99 | 4.606 |
| 14 | 3.65 | 57 | 4.2692 | 100 | 4.61 |
| 15 | 3.7 | 58 | 4.2769 | 101 | 4.619 |
| 16 | 3.72 | 59 | 4.2845 | 102 | 4.623 |
| 17 | 3.77 | 60 | 4.2922 | 103 | 4.64 |
| 18 | 3.8 | 61 | 4.2999 | 104 | 4.651 |
| 19 | 3.82 | 62 | 4.3076 | 105 | 4.683 |
| 20 | 3.85 | 63 | 4.3153 | 106 | 4.697 |
| 21 | 3.88 | 64 | 4.323 | 107 | 4.713 |
| 22 | 3.9 | 65 | 4.3307 | 108 | 4.719 |
| 23 | 3.92 | 66 | 4.3384 | 109 | 4.722 |
| 24 | 3.94 | 67 | 4.3461 | 110 | 4.725 |
| 25 | 3.96 | 68 | 4.3538 | 111 | 4.732 |
| 26 | 3.97 | 69 | 4.3615 | 112 | 4.745 |
| 27 | 3.99 | 70 | 4.3692 | 113 | 4.755 |
| 28 | 4 | 71 | 4.3769 | 114 | 4.763 |
| 29 | 4.01 | 72 | 4.3849 | 115 | 4.769 |
| 30 | 4.02 | 73 | 4.3922 | 116 | 4.75 |
| 31 | 4.03 | 74 | 4.3999 | 117 | 4.789 |
| 32 | 4.04 | 75 | 4.4076 | 118 | 4.8 |
| 33 | 4.05 | 76 | 4.4153 | 119 | 4.823 |
| 34 | 4.06 | 77 | 4.423 | 120 | 4.837 |
| 35 | 4.07 | 78 | 4.41 | 121 | 4.85 |
| 36 | 4.08 | 79 | 4.412 | 122 | 4.869 |
| 37 | 4.09 | 80 | 4.415 | 123 | 4.875 |
| 38 | 4.1 | 81 | 4.419 | 124 | 4.887 |
| 39 | 4.105 | 82 | 4.421 | 125 | 4.895 |
| 40 | 4.11 | 83 | 4.443 | 126 | 4.918 |
| 41 | 4.12 | 84 | 4.471 | 127 | 4.929 |
| 42 | 4.13 | 85 | 4.489 | 128 | 4.945 |

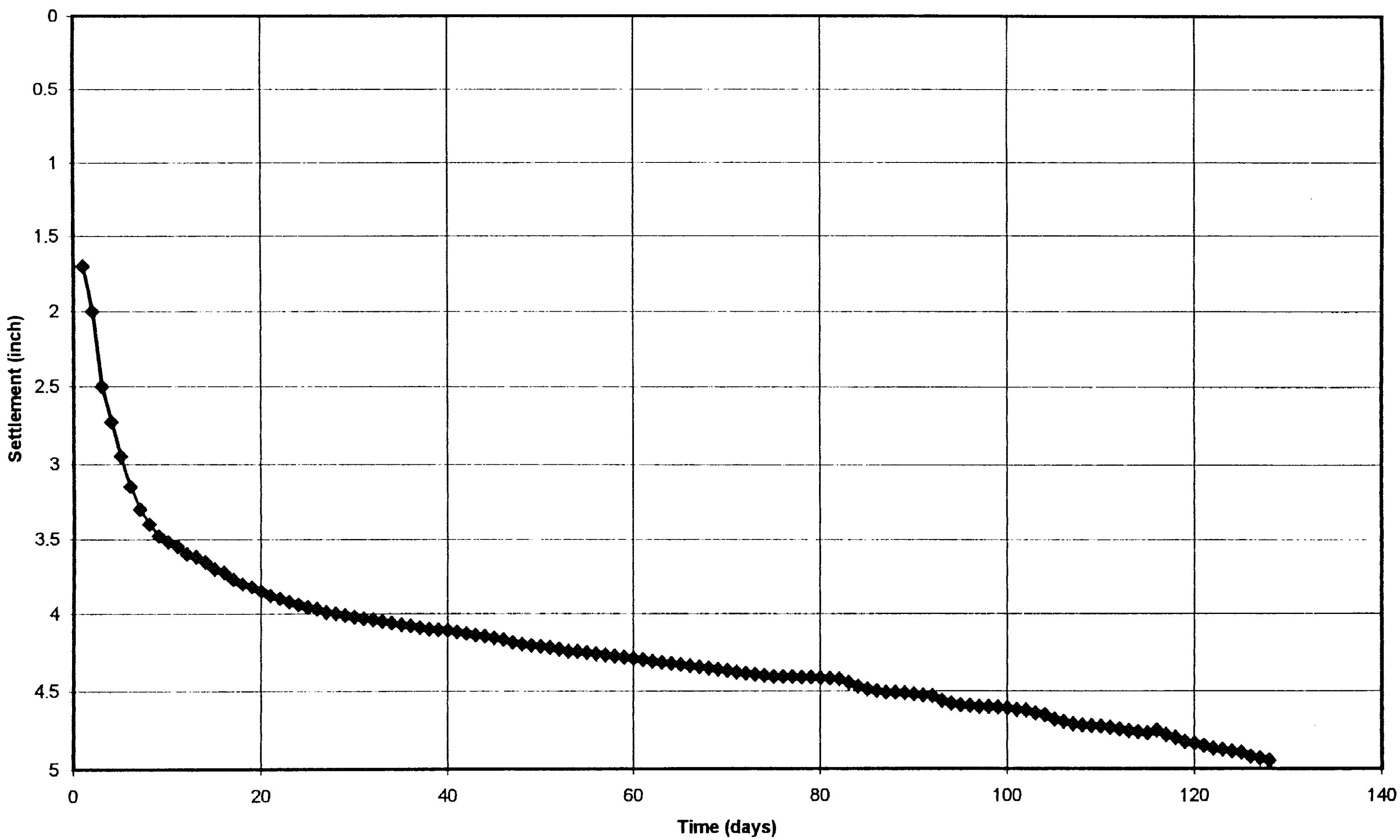


**Figure 4.1** Experimental data plotted against time.

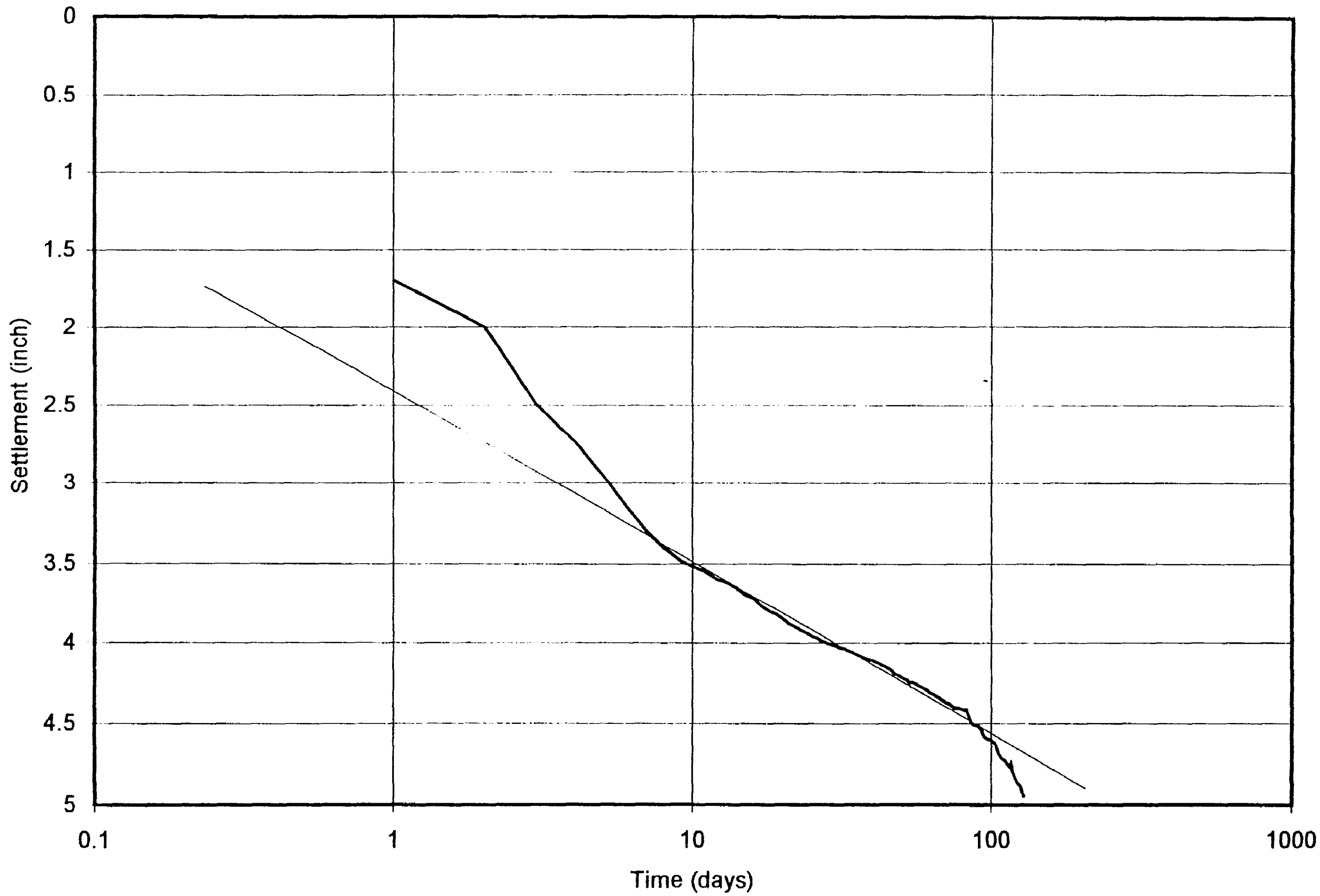


**Figure 4.2** Log time-strain curve used to determine the rate of secondary settlement.

## 4.2 Gases

The cumulative gas production at the end of 133 days was observed to be 2365 ml. The gas production curve with respect to time is shown is Figure 4.3. This curve follows an exponential behavior, nearly fitting to the curve, $y = 24.97 * e^{0.0343x}$. The daily gas production is shown in Figure 4.4. Methane gas was first traced on day 51. Methane percentage at this stage was found to be 7.93%. It should be noted that the methane generation might have started a little earlier, but could not be detected due to the unavailability of the Gow-Mac Gas Chromatograph till that time. The maximum methane production was 57.97% on day 114, and after that it was around the same till the end of the experiment. The methane gas production curve is as shown is Figure 4.5. Table 4.2 gives the amount of methane gas generated as a percentage of the total gas as well as the volume of the gas generated.

## 4.3 Leachates

After the application of external load of 10 $kN/m^2$, moisture in the pore spaces began to seep out through the leachate outlet. The pH of this was noted to be 6.2 to 6.5. It gradually dropped to its lowest of 5.1 on 3.13.96, i.e. day 56. A very slow increase in pH was observed in the later period. A buffer solution of sodium bicarbonate was added to the reactor, which increased the pH to 6.5. All the leachate produced was recycled back into the system.

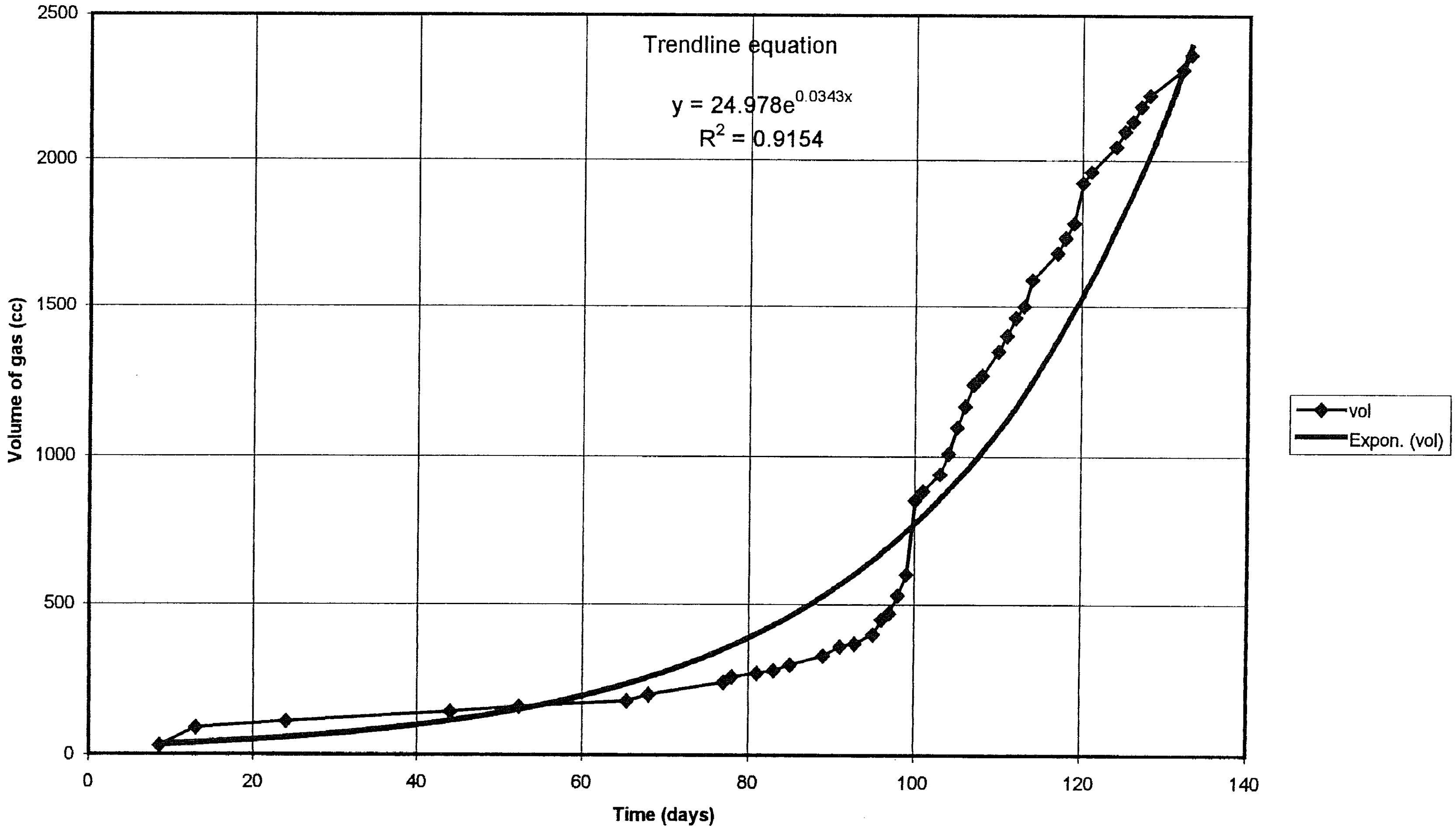


**Figure 4.3** Cumulative gas production for the test cell.

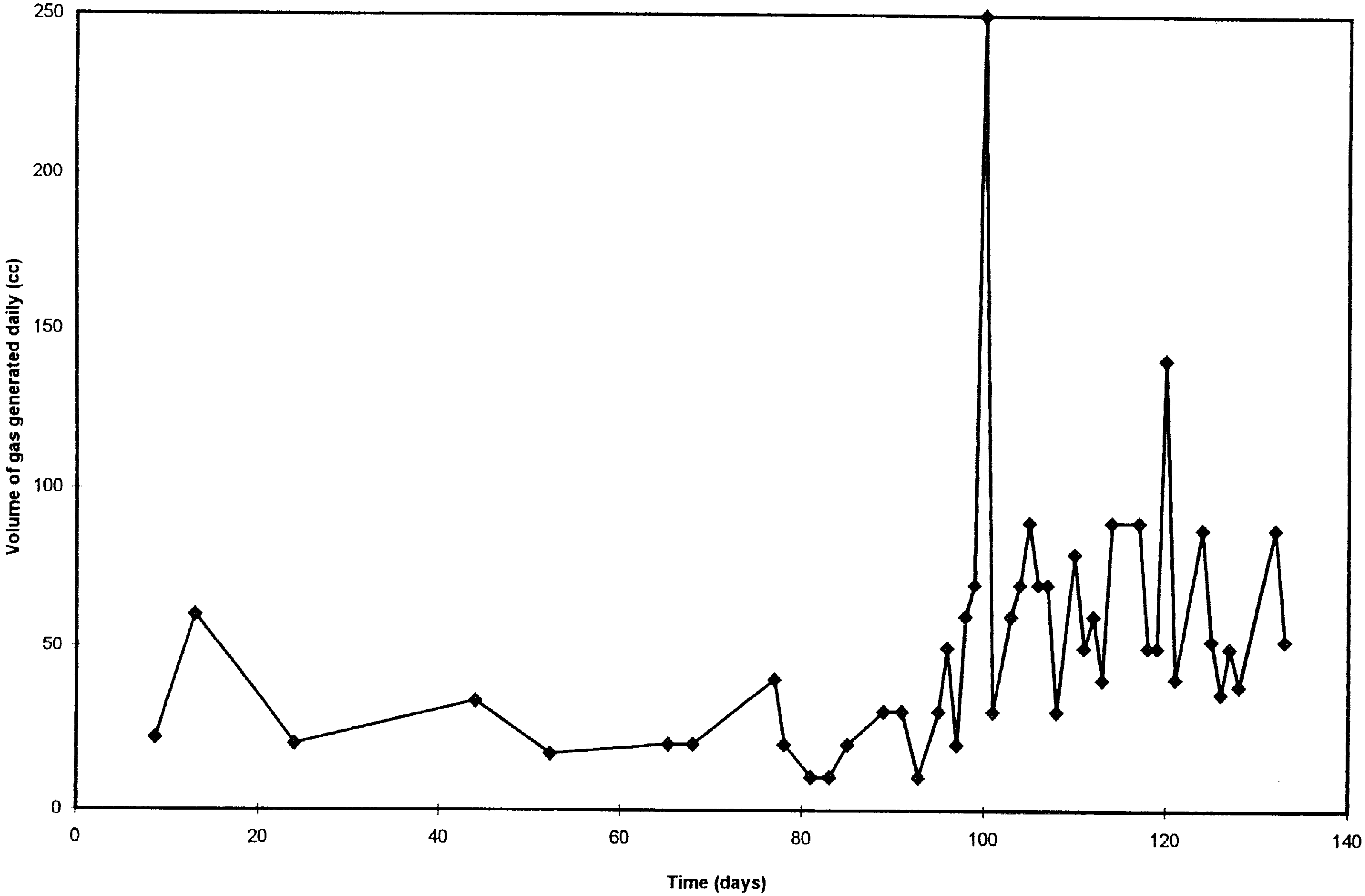


**Figure 4.4** Daily gas production from the test cell.

**Table 4.2** Details of Methane produced from the test cell.

| Time (days) | Methane gas % | Total gas | Methane (mls) |
|---|---|---|---|
| 55 | 7.93 | 240 | 19.05 |
| 56 | 11.06 | 250 | 27.66 |
| 57 | 11.65 | 260 | 30.30 |
| 62 | 19.70 | 290 | 57.13 |
| 64 | 20.76 | 300.5 | 62.40 |
| 65 | 15.62 | 310 | 48.42 |
| 68 | 19.53 | 331.38 | 64.74 |
| 69 | 20.89 | 340 | 71.03 |
| 77 | 23.73 | 419.29 | 99.52 |
| 78 | 20.87 | 507.29 | 105.89 |
| 86 | 22.83 | 1110 | 253.44 |
| 112 | 53.30 | 1657.1 | 883.27 |
| 113 | 52.36 | 1704.61 | 892.65 |
| 114 | 57.97 | 1752.12 | 1015.87 |

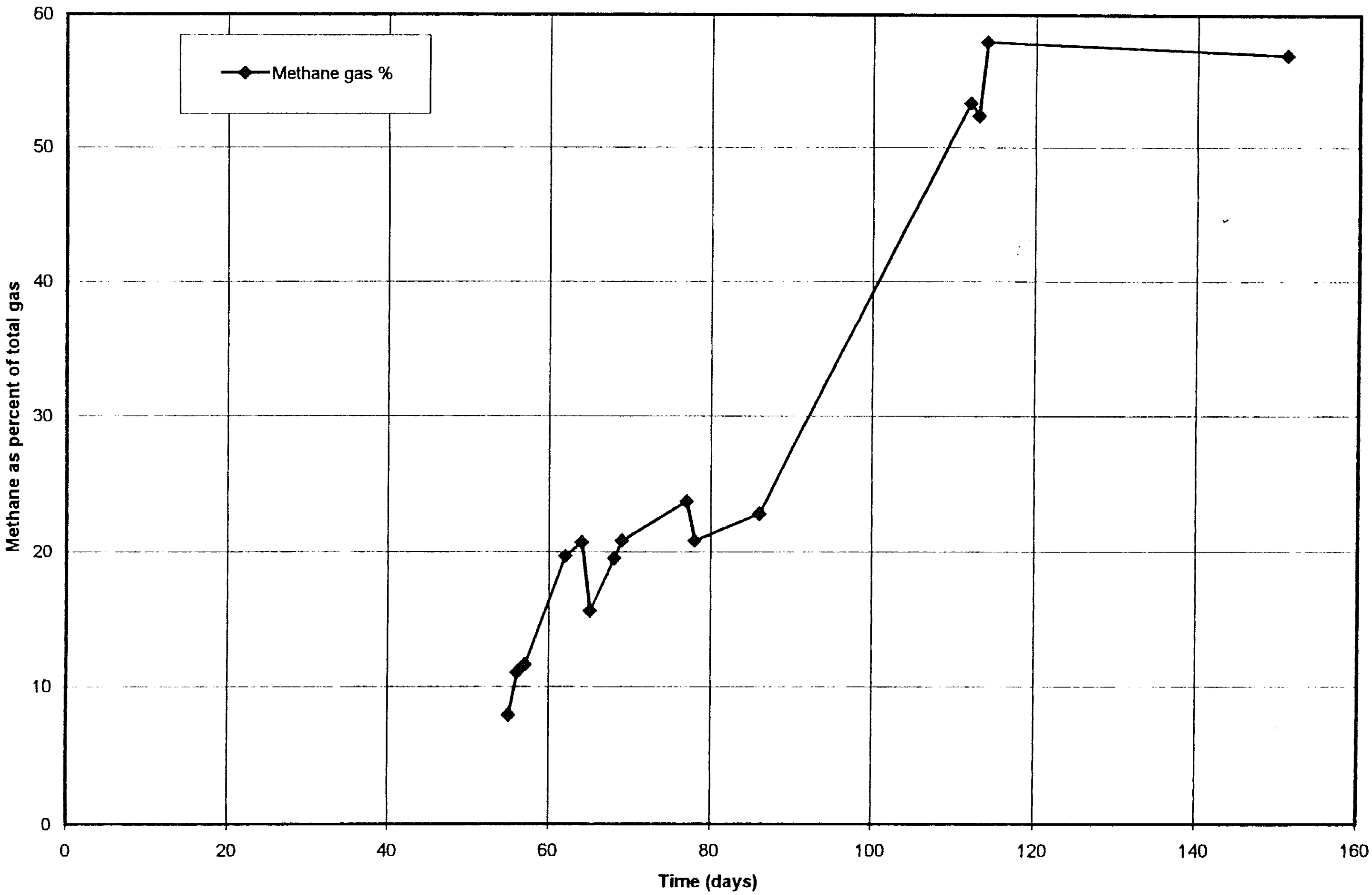


**Figure 4.5** Methane generation pattern from the test cell.

# CHAPTER 5

# SETTLEMENT CALCULATIONS USING VARIOUS MODELS

The models for predicting landfill settlements were introduced in the earlier chapters In this chapter, a summary of settlement according to these models is presented, and the details of the calculations are presented in Appendix B. Figure 5.1 compares the settlement data obtained from different models.

## 5.1 Gibson and Lo Model

As mentioned earlier, the parameters used in this model have a wide range and can vary upto four orders of magnitude. The secondary compressibility factor varied from 0.0001 $kPa^{-1}$ to 0.0058 $kPa^{-1}$. An attempt was made to find out the minimum and maximum values for settlement using the extreme conditions. Using low end parameters, the total settlement was $1.057 \times 10^{-3}$ inches, and for high end parameters, the value was 11.06 inches. The settlement value for the average values of the parameters used is 2.09 inch. Here, a difference of four orders of magnitude was observed between the minimum and the maximum values. This again shows that this model does not really represent the processes going on in the landfill. Figure 5.1 graphically shows the settlement values for this model as a function of time, and the values are computed and compared with other models in Appendix E.

## 5.2 Power Creep Law

This time dependent settlement model of the Power Creep Law is also based on the studies done by Edil *et al.* as described before. This model also suffers from the same problem of having very large range of parameters used in the calculations, as in the Gibson and Lo model. For the minimum values of m and n, the two empirical parameters used in this model, the settlement value was determined to be 4.45 x $10^{-5}$ inches. For the average values of m and n, settlement was calculated as 0.34 inch and for the maximum values. It was 5.64 inches. Thus the wide range of the value of the results make it difficult predict exactly the landfill settlement. Figure 5.1 and Appendix E show the settlement according to this model.

### 5.3 Yen and Scanlon Model

Although this model has a lot of limitations as mentioned before, an attempt has been made to calculate the settlement data and compare with the test fill results. The calculations yielded a value of 3.27 inch of settlement after 130 days. Even though this value is not very far from the actual result of 4.95 inches as observed for the test fill (within 66% of the observed value), some researchers claim that it does not reliably model a landfill. This is because, in equation 2.3.3.1a, if 'm' is set equal to zero, i. e. the settlement has stopped, the time required for this to happen can be calculated. This calculation indicates that the settlement will stop after 6130 days or 17 years. But studies indicate that the landfill settlement can easily go up to 30 years. This is one of the major contradictions this model has with the existing data. Appendix E shows the settlement trends according to this model.

## 5.4 Sowers Model

As discussed earlier, Sowers model for the calculation of secondary settlement depends on the rate of secondary compression and the time after the closure of the landfill. The rate of secondary settlement $C_{\alpha e}$ was determined using the log time versus strain method as described earlier. This value, the slope of log time versus the strain curve was determined as 0.0714 for the experimental data. Based on the initial void ratio, Sowers suggests an alternative method to find $C_{\alpha e}$. For this, 0.09 is the factor used to represent most favorable conditions for biodegradation (see equation 2.3.4.3). For the experimentally determined initial void ratio of 3.93, the $C_{\alpha e}$ value was calculated as 0.0717. It should be noted that the $C_{\alpha e}$ values obtained experimentally using the test cell and by the method suggested by Sowers are appreciably close. Using the Sowers equation 2.3.4.1, the secondary settlement was calculated as 1.11inchs, for a primary settlement of 2.95 inches. Thus the total settlement is 4.06 ( = 2.95 + 1.11 ) inches at the end of 128 days. Appendix E shows the settlement for this model.

It is to be noted that the settlement predicted by the Sowers model is closest to the settlement obtained from the test fill amongst all the other models.

## 5.5 NJIT Model

This model was not used in this study because of the following reasons:

1. The NJIT model, which is a two phase model as described earlier, assumes a first phase up to 10 years, which is out of the scope of the study. Because of time constraints, the model cannot be studied for such a long duration of time.

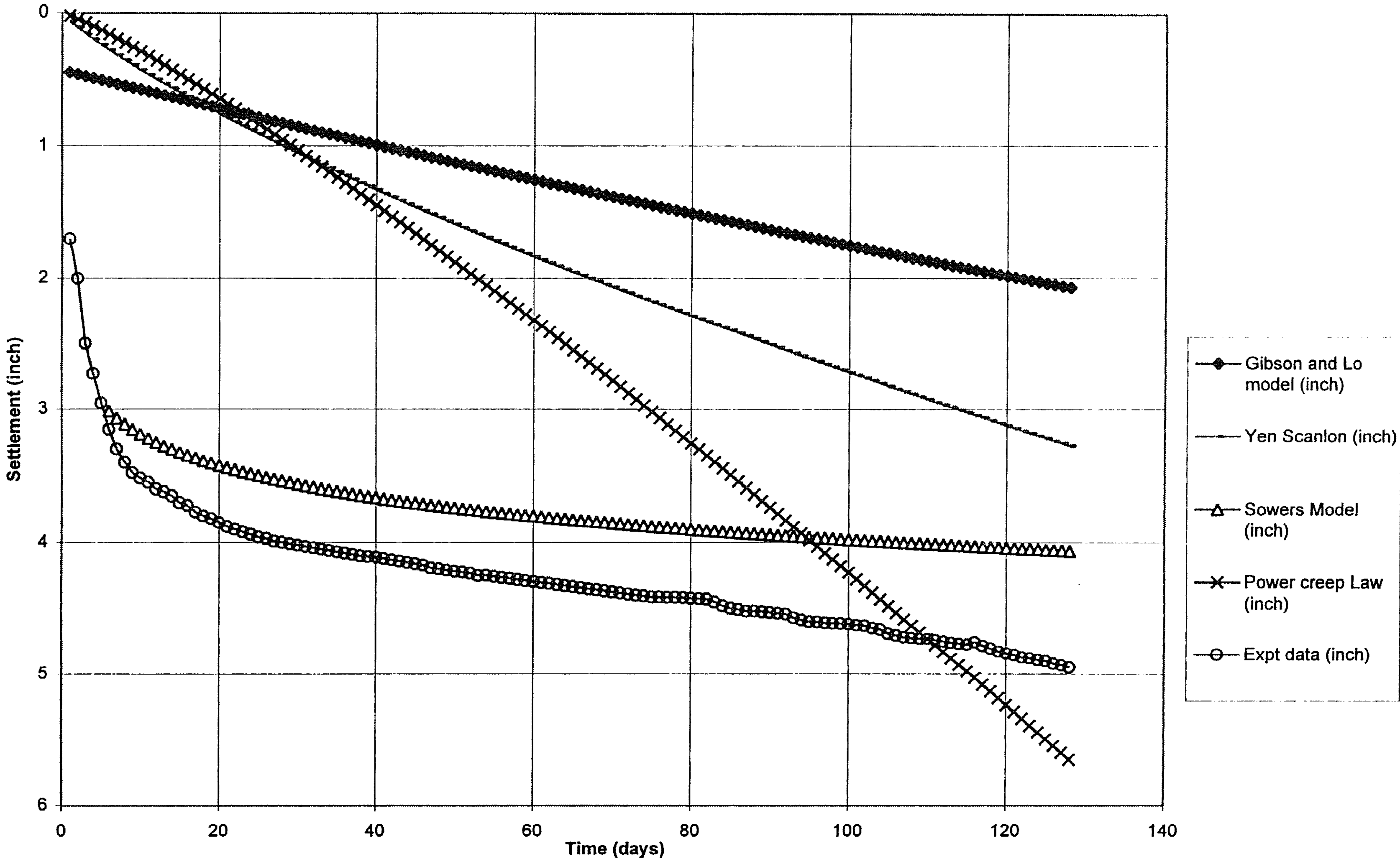


**Figure 5.1** Comparison of settlements determined from various models with the experimental data.

2. The settlement prediction in this model can be done only after the gas production for a period of the life of the landfill is known. This means that first the gas production has to be predicted, and based on that prediction, the waste settlement could be predicted. As per the studies done by different researchers, there is no reliable model for gas production. Although the triangular model is used, it is not a correct estimate of the gas production.

The author believes that the landfill settlement predictions cannot be estimated accurately using this model. Hence, it is not discussed further.

# CHAPTER 6

# DECOMPOSITION RESULTS AND DISCUSSIONS

## 6.1 Decomposition of Waste

There are two different approaches considered here to look at biodegradation. The first one is based on the amount of gas generated, while the second one is related to the change of TVS (total volatile solids).

### 6.1.1 Decomposition Based on Amount of Gas Generated

As mentioned before, a 70% fresh waste and a 30% old waste was used for this study. Since the fresh waste was created in the laboratory, it's composition was known. However, the waste obtained from the Elizabeth Landfill was a 20 years old waste and most of the organic contents in this waste can be presumed to have degraded over 20 years. Hence the item-wise composition (food, paper, cardboard, wood, etc.) of this waste cannot be determined. Also, the moisture content for each of the items cannot be determined, which is the key factor to determine the chemical formula of the waste. Hence, in this study a chemical formula for the combined waste could not be found out.

It was decided to assume a chemical formula as $C_{68}H_{111}O_{50}N_1$, which is the formula for rapidly biodegradable waste (Tchobanoglous *et al.*, 1993). The decision to choose this as the chemical formula is based upon the fact that it is for a rapidly biodegradable waste which is very near to the waste under study because of the accelerated biodegradation conditions (like high moisture content, optimum temperature conditions and supply of acclimatized bacteria). The amount of gas generated was determined to be 14.4 $ft^3$/lb of dry weight. See Appendix C for detailed calculations of gas production. Thus the amount of gas liberated from one pound of waste in known. Therefore, if we know the amount of gas generated from the cell, the amount of waste used up can be back-calculated.

The first order kinetics was used for the carbon mass balance data and the rate constants were calculated:

$$C_t = C_0 \ e^{-kt} \qquad (6.1.1.1)$$

where,

$C_t$ = Carbon mass in the waste at time t

$C_0$ = Initial carbon mass in the waste

t = time in years

k = Rate constant ( $year^{-1}$ )

After lab studies in several test fills, Wall and Zeiss (1995) obtained the values of rate constant in the range of 0.0383 $year^{-1}$ to 0.0478 $year^{-1}$. Golueke (1972) studied the behavior of organic carbon in municipal refuse and suggested the fraction of organic carbon present in the waste to be 56% of the refuse. Wall and Zeiss (1995) suggest an improvement to this method by first removing the moisture content from the waste, and then finding out the total volatile solids (TVS). The initial organic carbon will be 1/1.8th of the TVS corresponding to the 56% as mentioned before.

Thus the initial organic carbon is

$$C_0 = 4.54 \text{ (kg)} \times \frac{(100 - 53.3)}{100} \times \frac{58.5}{100} \times \frac{1}{1.8}$$

$C_0$ = 0.689 kg.

The total gas production at the end of 133 days is 2365 cc. So the mass lost can be back calculated as :

$$C_0 - C_t = 2365\ (cc) \times \frac{1}{14.4(ft^3/lb)} \times \frac{1}{28317\ (cc/ft^3)}.$$

$$C_0 - C_t = 0.005799\ lb.\ \text{or}\ 0.01275\ kg$$

Now, the rate constant is found out using the initial carbon and the final carbon amount at t = 133 days as 0.0512 per year, using equation 6.1.1.1. This value of 'k' is comparable to the studies done by previous researchers.

As mentioned in the review section, settlement due to biodegradation is predominant in the delayed secondary compression period. Biodegradation does not really play a major role in settlement during the early period immediately after the primary compression. An attempt has been made to justify this for the test cell under consideration. When the known amount of organic matter lost is subtracted from the original mass of the system, the amount of settlement taking place can be theoretically found out. The organic mass lost till day 133 was 15.3 gm, which is a mere 0.72% of the total solids. The secondary settlement occurred till then was 9% . This significant difference in these two values imply that decomposition did not have much of an effect on settlement so far. But over a period of time, the biodegradation can start affecting the settlement rate.

It is interesting to find out approximately how long it will take for the amount of mass lost and the amount of settlement to be comparable to each other. The calculations for settlement (using Sowers model) and the mass lost (using the first order kinetics with a rate constant of 0.0512 year $^{-1}$) is extended over a period of 1800 days (see Figure 6.1 for the five year prediction). It should be noted that after around 5 years, the organic matter lost becomes 0.153 kg, which is 22% of the initial organic mass. The secondary settlement occurring in the cell after 5 years amounts to 18% of the initial height. Thus it is clear that the settlement takes place at a much faster rate in the beginning than the rate of decomposition. But later on decomposition starts to have a significant effect on settlement. See figure 6.1 for 5 year predictions.

The value of 'k' found out earlier was based on the final amount of gas produced. But there is a variation in the amount of gas produced on a daily basis, so the rate constant might not be the same everyday. Data indicates that the biodegradation can be explained in two phases. The first stage is in the earlier stages of the study and the rate constant obtained for this stage is 0.0102 $year^{-1}$, and in the second stage it increases to 0.151 $year^{-1}$ (see Figure 6.2). Figure 6.3 shows the 5 year prediction using $k = 0.151$ $year^{-1}$ of the second stage for fraction settlement and fraction of mass lost. It shows that approximately after one year, the effect of biodegradation on settlement is predominant. See Appendix F for details of the data obtained for the above calculation.

### 6.1.2 Decomposition Based on Change in Total Volatile Solids

The main products of biodegradation are leachates and gases, as explained in the earlier chapters. Basically, the organic fraction is the part of the total mass which undergoes biodegradation. Thus, any change in TVS will reflect the amount of leachate and gas produced. Here, the final and initial values of the TVS are found out experimentally and a mass balance is done based on the products of decomposition.

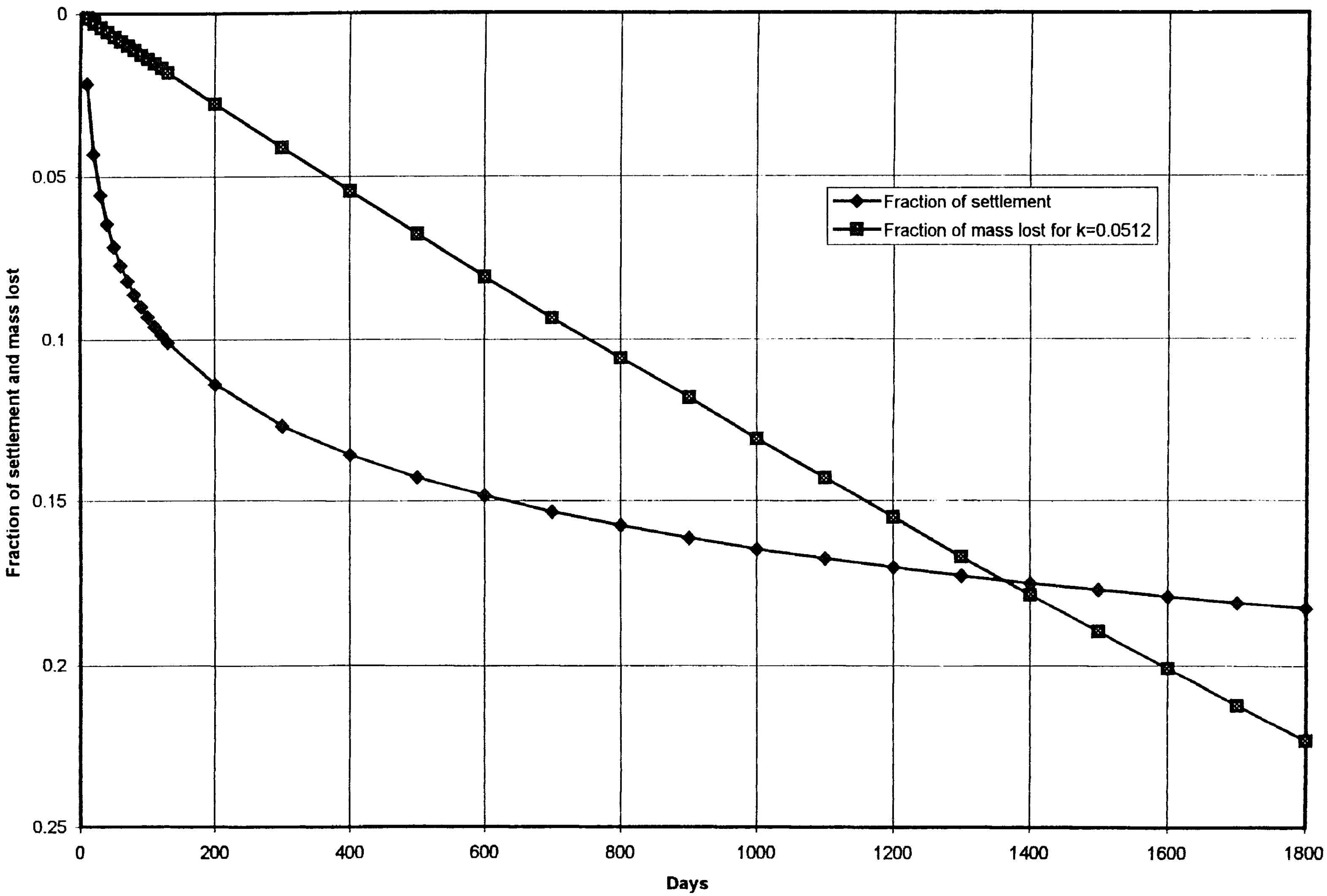


**Figure 6.1** Comparison of first order decomposition and secondary settlement for k=0.0512/yr.

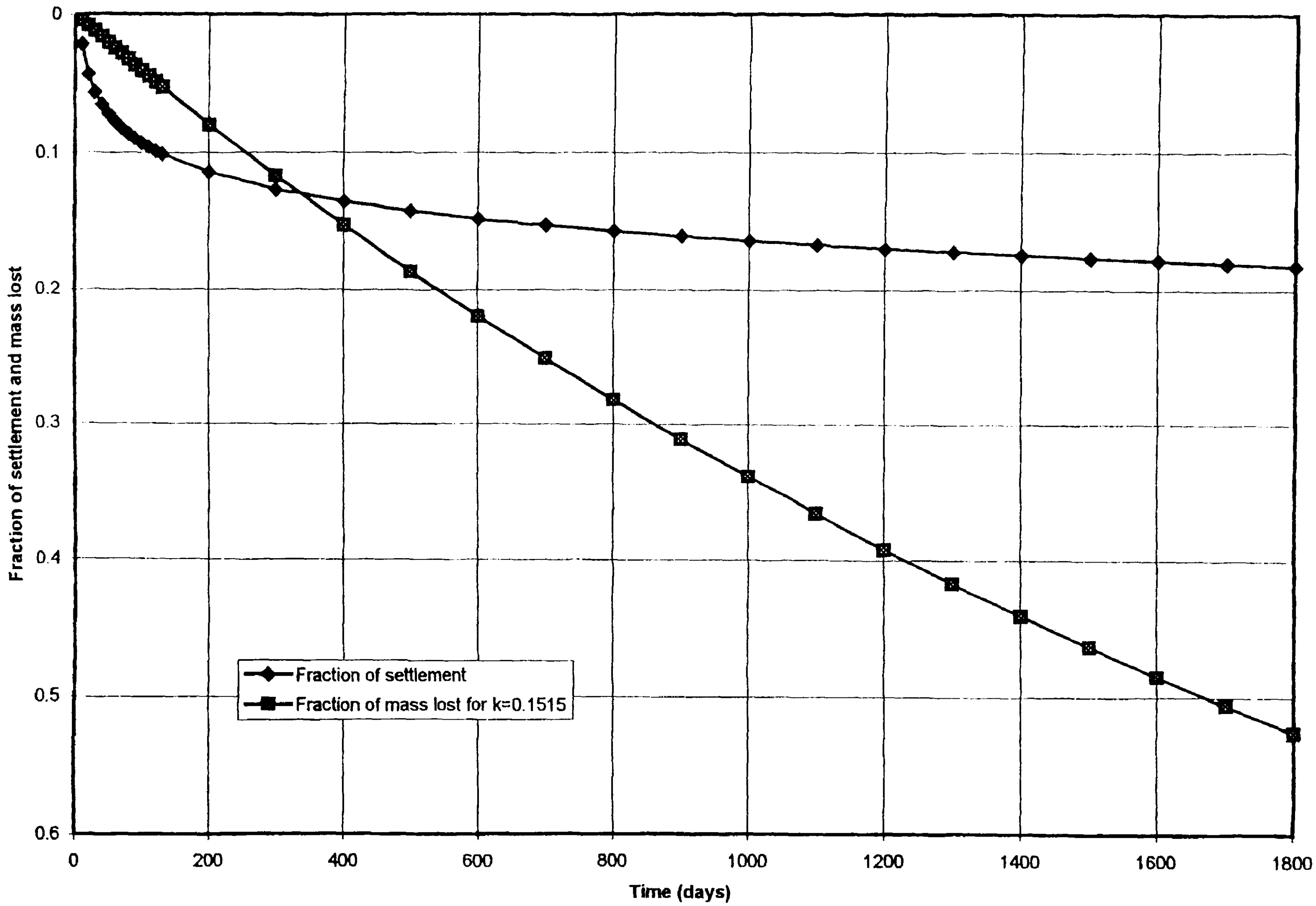


**Figure 6.2** Comparison of first order descomosition and secondary settlement for k=0.151/yr.

**Table 6.1** Comparison of initial and final values of TVS

| | **Initial** | **Final** |
|---|---|---|
| Total weight (gm) | 4545 | 4650.3 |
| Dry weight (gm) | 2122.5 | 2046.13 |
| TVS (gm) | 1241.67 | 1159.13 |
| Organic Carbon (gm) | 689.8 | 643.96 |

Note: The higher final total weight is due to the addition of water to the closed and confined reactor in which the leachate was also recirculated.

As can be seen from the Table 6.1, the change in TVS is 82.54 gm.

Gas production per pound of dry weight is 14.4 $ft^3$

Amount of gas generated in the reactor = 2365 cc = 0.0835 $ft^3$

Equivalent weight of waste converted for gas formation = $5.965 \times 10^{-3}$ lb.

= 2.71 gm

$\Delta$TVS = Wt. of leachate + Wt. of waste converted for gas production

Thus, Wt. of leachate = 82.54 gm - 2.71 gm

= 79.83 gm of leachate.

Assuming density as 1 gm/cc, the weight of leachate will be 79.83 gm.

### 6.2 Settlement Results

Figure 5.1 compares the settlement obtained using various other models used for predicting settlement and compares with the data obtained from the test cell. As can be seen, the Power Creep law shows the maximum settlement, but as discussed previously, the parameters selected in this model has a wide range of values and results vary upto 3 orders of magnitude. So the comparison with model is not done. According to Figure 5.1, the most sensible comparison is done using the Sowers model. The trends observed for the Sowers model and the data obtained are observed to follow a similar trend, though the values obtained for the test cell are somewhat higher than those predicted by Sowers. This is attributed to the favorable conditions provided for the biodegradation to occur. The settlement observed in the test cell is consistently more than the Sowers value by a small amount of magnitude. As mentioned before, a sharp dip is observed at the end of the log time - settlement curve after day 110. It is also observed that the peak gas production was observed at day 114 as 57.97%. This implies that the peak rate of biodegradation is occurring at this stage and a very high rate of settlement is observed. If the experiment were to run for a longer duration of time, a new and higher value of $C_{\alpha e}$ might have been observed.

The value obtained for the rate of secondary compression ($C_{\alpha e}$) for the data obtained from the landfill test cell is 0.0714, and it is well within the typical values as other studies. Using Sowers' (1973) method to determine $C_{\alpha e}$, (see Appendix B.4) a value of 0.0717 is obtained, which is appreciably close to the value obtained from the landfill test cell.

## 6.3 Gas Production Results

The peak methane production was 57.97% on day 114 of the experiment, and the balance was mostly carbon dioxide. This is in agreement with the landfill studies done so far on field evaluation done by other researchers. The first trace of methane was observed on day 51, which proves that an accelerated condition for biodegradation helps achieve gas production, and hence decomposition of waste more efficiently.

Gas during this phase of experimentation was not found to be an accurate indicator of settlement, as biological transformations usually occur during processes of enzymatic hydrolysis which solubilize particulate organic matter (Volatile Solids) before biodegradation can occur.

# CHAPTER 7

# CONCLUSIONS

In this study, the effect of enhanced biodegradation of MSW was studied and based on the results, the following can be concluded:

1. The rate of settlement in the early period of the life of the landfill is higher than the rate of biodegradation, but later on, decomposition and transformation of waste into gases and leachates start to have a significant effect on the settlement.
2. Biodegradation of waste can be achieved by providing favorable conditions for maximum biological activity like provision of acclimatized bacteria, ideal temperature required for biodegradation and leachate recirculation.
3. Sowers model was found to be the most appropriate for prediction of landfill settlement as compared with the data obtained from the experiment.
4. The kinetics for biodegradation in this experiment can be described by a two phase process which may be modeled as first order equation. The first phase indicating slower rates of biodegradation, and the second phase where it is more rapid.

# CHAPTER 8

## SUGGESTIONS AND RECOMMENDATIONS

The following recommendations should be helpful for future researchers:

1. Simulation of a landfill under laboratory conditions need to be studied for a longer period of time to accurately quantify the effect of biodegradation on settlement.
2. Leachate COD needs to be closely examined in order to quantify biodegradation with respect to time. COD of the leachate can serve as a surrogate parameter to estimate the rate and extent of biodegradation.
3. More number of testfills should be used for laboratory study in order to confirm the results of biodegradation and to detect errors in the methodology adopted and to get a better statistical analysis of the results.
4. Temperature changes inside the test cell need to be observed closely for an in-depth understanding of biodegradation process.

# APPENDIX A

## DETERMINATION OF VARIOUS GEOTECHNICAL PROPERTIES OF THE WASTE

The waste sample was analyzed for various geotechnical properties. All this properties are discussed below.

1. Specific Gravity (G) : The specific gravity was determined using the standard pycnometer test in the Soils Lab at NJIT. The worksheet is as given below in Table A.1.

**Table A.1** Pycnometer readings

| Sr. No. | Pycnometer weights | Pycnometer # 1 (gm) | Pycnometer # 2 (gm) | Symbols |
|---|---|---|---|---|
| 1 | Wt. of pycnometer (empty) | 179.86 | 186 | $W_1$ |
| 2 | Wt of pycnometer + waste | 215 | 216 | $W_2$ |
| 3 | Wt. of pycnometer + waste + water | 688 | 694 | $W_3$ |
| 4 | Wt of pycnometer+ water | 678 | 683 | $W_4$ |

G is determined using the following :

$$G = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_2)}$$

G for the first pycnometer is determined as 1.57, and for the second one, it is 1.34. So, the value of G is taken as the average of the two as 1.45.

2. Degree of Saturation The phase diagram for the waste is given as in Figure A.1.

| Weights | | Volume |
|---|---|---|
| 0 gm | AIR | 3360 cc |
| 2421.3 gm | WATER | 2421.3 cc |
| 2124 gm | SOLIDS | 1465 cc |

**Figure A.1** Phase diagram for the waste.

Initial weight (W) = 4545 gm

Moisture Content (dry wt basis ) = 114%

Dry Weight, $W_d = W / (1+w) = 4545 / 2.14 = 2124$ gm

Volume of solids $V_s = \dfrac{W_d}{G \times \gamma_w}$

where $\gamma_w$ = Specific gravity of water (1 g/cc)

$V_s = 2124 / (1.45 \times 1)$

$V_s = 1465$ cc

Now, moisture content, $w = W_w / W_d$

Thus, $W_w = w \times W_d = 1.14 \times 2124 = 2421.3$ gm

$V_{air}$ = total volume of cell - ( Vol of solids + vol of water )

$= 7146 - (1465 + 2421.3)$

$= \quad 3360 \text{ cc}$

Therefore,

$$V_{voids} = V_{air} + V_{water} = 3360 + 2421.3 = 5781.3 \text{ cc}$$

The degree of saturation, $S_r$, is determined as the ratio of volume of water to the ratio of the volume of voids, which is:

$$S_r = V_{water} / V_{voids} = 2421.3 / 5781.3 = 0.42$$

Thus, the degree of saturation is 0.42.

3. VOID RATIO

The initial void ratio ($e_o$) is calculated as

$$e_o = \frac{\text{Moisture content ( dry basis)} \times \text{Specific gravity}}{\text{Degree of Saturation}}$$

$$= \frac{1.14 \times 1.45}{0.42}$$

$$= 3.93$$

Thus the initial void ratio was 3.93, which is typical of MSW.

4. Compression Ratio for primary settlement (CR )

The CR value for the waste of the test cell was determined using the following equation:

$$CR = \frac{C_c}{1 + e_o}$$

The empirical value for $C_c$ as suggested by Oweis and Khera (1990) is

$$C_c = 0.55\ e_o$$

Thus,

$$CR = \frac{0.55\ e_o}{1 + e_o}$$

Knowing the initial void ratio $e_o$ as 3.93, the value of CR is determined as

$$CR = 0.43$$

CR is also called as the modified primary compression index, denoted as $C_{ce}$. It should be noted that this value of CR is quite close to the values obtained by other researchers.

5. <u>Secondary Compression Ratio</u> ( $C_{\alpha e}$ )

The rate of secondary compression is found as the slope of the strain versus the log time curve. In Figure 4.2, such a curve is plotted and the slope of the curve for one log cycle is taken. Thus, the slope of the curve is the difference between the two abscissa values for one log cycle, which is

$$C_{\alpha e} = 0.3214 - 0.25 = 0.0714$$

This value is typical as in found by other researchers.

## APPENDIX B

## SETTLEMENT CALCULATIONS USING VARIOUS MODELS

The computations for using various models for predicting landfill settlement are presented in this section.

### B.1 Gibson and Lo Model

The main concern for the use of this model is the wide range of parameters used. As discussed earlier, the parameters vary upto about three orders of magnitude. So, the values of higher end parameters, lower end parameters and the average values of the parameters are used to determine the landfill settlement. Equation 2.3.1.1 is used for the computations.

a.) <u>Using Low End Parameters</u>

$$S_s = H\ \varepsilon(t) = H\ \Delta\sigma(t)\ \{\ a + b(\ 1 - e^{-(\lambda/b)t})\ \}$$

$$S_s = 14 \times \frac{2.54}{100} \times 45\ \{5.11 \times 10^{-7} + 10^{-4}\ (\ 1 - e^{-(9.2 \times 10^{\wedge}-5)\,128})\ \}$$

Thus, $S_s = 2.691 \times 10^{-5}$ m $= 1.0575 \times 10^{-3}$ inch

b.) <u>Using Higher End Parameters</u>

$$S_s = 14 \times \frac{2.54}{100} \times 276.4\ \{3.8 \times 10^{-4} + 5.87 \times 10^{-3}\ (\ 1 - e^{-(4.3 \times 10^{\wedge}-3)\,128})\ \}$$

$S_s = 0.2764$ m $= 11.06$ inch

c.) <u>Using Average values of parameters</u>

$$S_s = 14 \times \frac{2.54}{100} \times 160.7\ \{1.9 \times 10^{-4} + 2.985 \times 10^{-3}\ (\ 1 - e^{-(2.196 \times 10^{\wedge}-3)\,128})\ \}$$

$S_s = 2.089$ inch.

The large differences in all the three values of settlements should be noted.

## B.2 Power Creep Law

The calculations or this model are done according to Equation 2.3.2.1 as under

$$S(t) = H\ \varepsilon(t) = H\ \Delta\sigma(t)\ m\ (t/t_r)^n$$

Here again we have minimum, maximum and the average values of m and n, i.e. the modeling parameters used for this model.

a.) <u>Lower range values</u>

$$S(t) = 14 \times \frac{2.54}{100} \times 10 \times 7.52 \times 10^{-8}(128/1)^{0.297}$$

$$S(t) = 1.12 \times 10^{-6}\ \text{m}$$

$$S(t) = 4.4 \times 10^{-5}\ \text{inch}$$

b.) <u>High range values</u>

$$S(t) = 14 \times \frac{2.54}{100} \times 10 \times 1.38 \times 10^{-4}(128/1)^{1.17}$$

$$S(t) = 0.143\ \text{m}$$

$$S(t) = 5.64\ \text{inch.}$$

c.) <u>Average values of parameters</u>

$$S(t) = 14 \times \frac{2.54}{100} \times 10 \times 6.9 \times 10^{-5}(128/1)^{0.7335}$$

$$S(t) = 8.62 \times 10^{-3}\ \text{m}$$

$$S(t) = 0.34\ \text{inch}$$

Here again a wide range of settlement from $4.4 \times 10^{-5}$ inch to 5.64 inch is observed.

### B.3 Yen and Scanlon Model

This model is represented by the equation 2.3.3.1a as under

$$m = 0.0268 - 0.0016 \log t_1 \text{ (for fill heights of 12 - 24 m)}$$

where m is the settlement in meters per month and $t_1$ is

$$t_1 = t - (t_c/2)$$

Here, $t_c$, the time for the completion of the landfill is assumed as zero.

$$m = 0.0268 - 0.0016 \log(128/30)$$

$$m = 0.0194 \text{ m per month}$$

$$m = 3.27 \text{ inches for 128 days.}$$

Note that in the equation above, 128 is divided by 30 in order to convert it from days to months.

### B.4 Sowers Model

For the usage of this model, the parameters required are as follows:

Secondary Compression Ratio, $C_{\alpha e} = 0.0714$ ( Experimentally )

Initial Void Ratio, $e_o = 3.93$ ( Experimentally )

Sowers (1973) suggested an alternative method for determining the $C_{\alpha e}$ values, based upon the initial void ratio of the waste (see equation 2.3.4.3)

$$C_{\alpha e} = \frac{(0.03 \text{ to } 0.09)e_o}{(1 + e_o)}$$

Here, 0.03 is used for unfavorable conditions for biodegradation, and 0.09 is used for favorable conditions. In this test cell, the aim is to achieve an accelerated biodegradation, and hence a value of 0.09 is chosen for the computations.

$$C_{\alpha e} = \frac{0.09 \text{ x } 3.93}{(1 + 3.93)}$$

Therefore, $C_{\alpha e}$ = 0.0717

Note the closeness of this $C_{\alpha e}$ value obtained from Sowers method to the one obtained experimentally. Using Sowers Equation 2.3.4.1 for secondary settlement

$S_s = H_p \ C_{\alpha e} \ \log (t/t_p)$

$S_s =$ 11.05 (inch) x 0.0714 x log(128 / 5)

$S_s =$ 1.11 inch of secondary settlement.

Thus the total settlement is

= 2.95 ( primary settlement ) + 1.11 ( Sowers predicted settlement )

= 4.06 inch

It is to be noted that this model is the one which predicts the settlement closest to as observed in the test cell.

## APPENDIX C

## CALCULATION OF GAS PRODUCED

As explained in Chapter 6, the chemical formula of the waste is $C_{68}H_{111}O_{50}N_1$. On decomposition, it gives out methane and carbondioxide. A chemically balanced equation is available for this computation (Tchobanoglous *et al.*, 1993).

$$C_aH_bO_cN_d + \frac{(4a-b-2c+3d)}{4} H_20 \longrightarrow \frac{(4a+b-2c-3d)}{8} CH_4 + \frac{(4a-b+2c+3d)}{8} CO_2 + d\,NH_3$$

Thus, for the formula under study, a = 68, b = 111, c = 50 and d = 1. Therefore,

$$\underset{1741\ \text{g/mole}}{C_{68}H_{111}O_{50}N_1} + 16\,H_20 \longrightarrow \underset{560\ \text{g/mole}}{35\,CH_4} + \underset{1452\ \text{g/mole}}{33\,CO_2} + NH_3$$

The moisture content for this waste is 53.3%, which means that the dry weight is 46.7%. For the test cell, the dry weight will be 4.67 lb. The amount of gases produced can now be calculated.

1. Methane : The specific weight of methane is 0.0448 lb/ft$^3$ at Standard Temperature and pressure (STP). Thus, according to the chemical formula, the amount of methane generated is

$$= \frac{(560\ \text{g})\ (4.67\ \text{lb})}{(1741\ \text{g})\ (0.0448\ \text{lb/ft}^3)}$$

$$= 33.52\ \text{ft}^3 \text{ at STP}$$

$$= 34.64\ \text{ft}^3 \text{ at } 35\ ^\circ\text{C}.$$

2. Carbon dioxide The specific weight of carbon dioxide is 0.1235 lb/ft$^3$ at STP. Hence the amount of $CO_2$ generated is

$$= \frac{(1452 \text{ g})\,(4.67 \text{ lb})}{(1741 \text{ g})\,(0.1235 \text{ lb/ft}^3)}$$

$$= 31.53 \text{ ft}^3 \text{ at STP}$$

$$= 32.59 \text{ ft}^3 \text{ at } 35\,^\circ\text{C}.$$

Therefore the theoretical amount of gas generated is found out as follows:

$$\text{Volume per lb.} = \frac{34.64 + 32.59}{4.67}$$

$$= 14.4 \text{ ft}^3/\text{lb}.$$

# APPENDIX D

## THE ROOT TIME METHOD ADOPTED FOR THE STUDY

The Root Time method is used in this study to determine the time required for the primary settlement to take place. It requires compression readings covering a much shorter length of time as compared to the Log time method, which requires a well defined curve in the secondary portion of the settlement curve. Also at times, it is very difficult to get a linear pattern for this behavior. Hence, in such cases and in particularly in this study, it is appropriate to go for this method.

In this method, the settlement readings are plotted against the square root of time and the degree of consolidation against the factor of square root of time. Ideally, this curve should be linear up to 60% consolidation and at 90% consolidation, the abscissa (PQ) is 1.15 the abscissa (PR) of the production of the linear part of the curve. This is used to determine the point on the experimental curve corresponding to U = 90%. Here, the linear portion of the curve starting from point P is extended till it intercepts the x axis at Q. Measure OQ and find OR as 1.15 times of OQ. On joining P and R, it cuts the curve at its abscissa value as 2.7. This corresponds to 0.9 ( for 90% consolidation), and thus the point for 100% consolidation is determined as 3.0. Where ever the line y = 3 intercepts the curve gives the square root T value as 2.266. Thus the time required for primary consolidation is the square of 2.266 which is 5.134. Figure D.1 gives the graphical explanation for this.

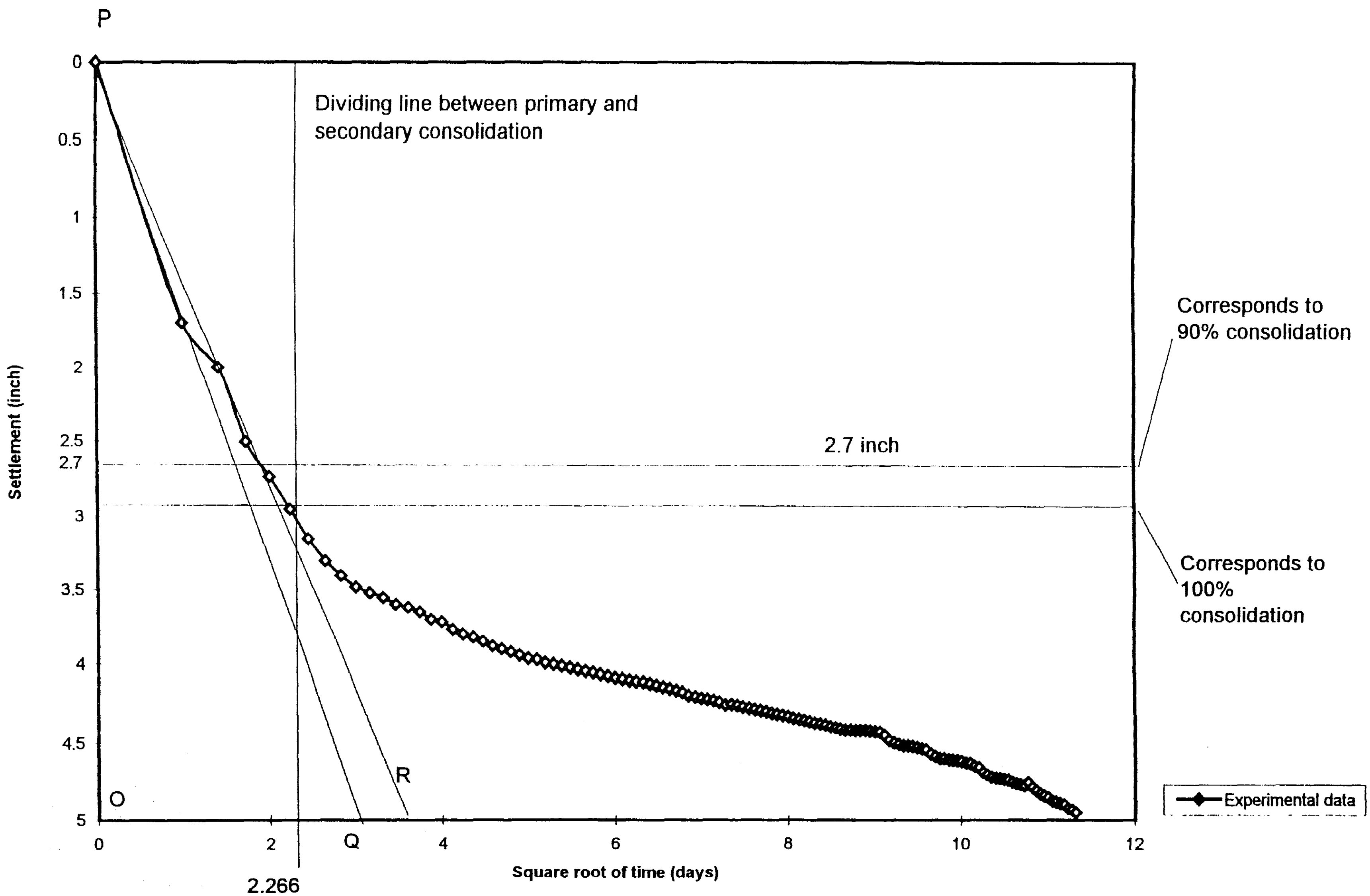


**Figure D.1** Using the Root Time method for determining time for primary consolidation.

## APPENDIX E

## COMPARISON OF SETTLEMENT USING VARIOUS MODELS

Calculation were performed for all the different models studied earlier and were compared with the data obtained from the test cell. This is shown as below in Table E.1.

**Table E.1** Settlement Data for Various Models

| T in days | Gibson and Lo model (inch) | Yen Scanlon (inch) | Sowers Model (inch) | Power creep Law (inch) | Expt data (inch) |
|---|---|---|---|---|---|
| 1 | 0.442198754 | 0.057656964 | | 0.01932 | 1.7 |
| 2 | 0.456903169 | 0.10614871 | | 0.04347226 | 2 |
| 3 | 0.471575318 | 0.151181102 | | 0.069861674 | 2.5 |
| 4 | 0.48621527 | 0.193966985 | | 0.09781767 | 2.73 |
| 5 | 0.500823096 | 0.235082379 | | 0.126999505 | 2.95 |
| 6 | 0.515398867 | 0.274866552 | 3.012471628 | 0.157196939 | 3.15 |
| 7 | 0.529942653 | 0.313543681 | 3.065290636 | 0.188265971 | 3.3 |
| 8 | 0.544454524 | 0.351273099 | 3.111044543 | 0.220101198 | 3.4 |
| 9 | 0.558934551 | 0.388173938 | 3.151402348 | 0.252621819 | 3.48 |
| 10 | 0.573382803 | 0.424338669 | 3.187503636 | 0.285763741 | 3.52 |
| 11 | 0.587799349 | 0.459841162 | 3.220161222 | 0.319474768 | 3.55 |
| 12 | 0.602184261 | 0.494741797 | 3.249975263 | 0.3537115 | 3.6 |
| 13 | 0.616537606 | 0.52909085 | 3.277401522 | 0.388437226 | 3.62 |
| 14 | 0.630859454 | 0.562930838 | 3.302794272 | 0.423620456 | 3.65 |
| 15 | 0.645149875 | 0.596298188 | 3.326434356 | 0.459233853 | 3.7 |
| 16 | 0.659408937 | 0.629224457 | 3.348548178 | 0.495253441 | 3.72 |
| 17 | 0.673636709 | 0.66173725 | 3.369320921 | 0.531658008 | 3.77 |
| 18 | 0.687833259 | 0.693860917 | 3.388905984 | 0.568428642 | 3.8 |
| 19 | 0.701998657 | 0.725617101 | 3.407431864 | 0.605548364 | 3.82 |
| 20 | 0.716132971 | 0.75702516 | 3.425007271 | 0.643001842 | 3.85 |
| 21 | 0.730236268 | 0.788102516 | 3.441724993 | 0.680775154 | 3.88 |
| 22 | 0.744308618 | 0.818864929 | 3.457664858 | 0.718855597 | 3.9 |
| 23 | 0.758350087 | 0.849326725 | 3.472896046 | 0.757231532 | 3.92 |
| 24 | 0.772360743 | 0.879500981 | 3.487478899 | 0.795892248 | 3.94 |
| 25 | 0.786340655 | 0.909399687 | 3.501466364 | 0.834827857 | 3.96 |
| 26 | 0.80028989 | 0.93903387 | 3.514905158 | 0.874029194 | 3.97 |
| 27 | 0.814208514 | 0.968413709 | 3.527836705 | 0.913487747 | 3.99 |
| 28 | 0.828096595 | 0.997548629 | 3.540297908 | 0.953195578 | 4 |
| 29 | 0.841954201 | 1.02644738 | 3.552321784 | 0.993145272 | 4.01 |
| 30 | 0.855781398 | 1.05511811 | 3.563937992 | 1.033329886 | 4.02 |
| 31 | 0.869578252 | 1.083568423 | 3.575173271 | 1.073742897 | 4.03 |
| 32 | 0.883344831 | 1.11180543 | 3.586051814 | 1.114378172 | 4.04 |
| 33 | 0.897081201 | 1.139835801 | 3.596595579 | 1.155229929 | 4.05 |
| 34 | 0.910787427 | 1.167665798 | 3.606824557 | 1.196292707 | 4.06 |

| T in days | Gibson and Lo model (inch) | Yen Scanlon (inch) | Sowers Model (inch) | Power creep Law (inch) | Expt data (inch) |
|---|---|---|---|---|---|
| 35 | 0.924463577 | 1.195301317 | 3.616757001 | 1.23756134 | 4.07 |
| 36 | 0.938109716 | 1.222747916 | 3.62640962 | 1.279030933 | 4.08 |
| 37 | 0.95172591 | 1.250010843 | 3.63579775 | 1.320696842 | 4.09 |
| 38 | 0.965312225 | 1.277095065 | 3.6449355 | 1.36255465 | 4.1 |
| 39 | 0.978868726 | 1.304005285 | 3.653835879 | 1.404600156 | 4.105 |
| 40 | 0.992395479 | 1.330745966 | 3.662510907 | 1.446829356 | 4.11 |
| 41 | 1.005892549 | 1.357321347 | 3.670971715 | 1.489238429 | 4.12 |
| 42 | 1.019360001 | 1.383735461 | 3.679228628 | 1.531823726 | 4.13 |
| 43 | 1.032797901 | 1.409992147 | 3.687291243 | 1.574581756 | 4.14 |
| 44 | 1.046206312 | 1.436095069 | 3.695168494 | 1.617509178 | 4.15 |
| 45 | 1.0595853 | 1.46204772 | 3.702868713 | 1.66060279 | 4.16 |
| 46 | 1.07293493 | 1.487853442 | 3.710399682 | 1.70385952 | 4.17 |
| 47 | 1.086255265 | 1.513515428 | 3.717768683 | 1.747276419 | 4.19 |
| 48 | 1.09954637 | 1.539036737 | 3.724982535 | 1.790850654 | 4.199 |
| 49 | 1.11280831 | 1.564420301 | 3.732047637 | 1.834579498 | 4.2076 |
| 50 | 1.126041147 | 1.589668931 | 3.73897 | 1.878460327 | 4.2157 |
| 51 | 1.139244946 | 1.614785326 | 3.745755278 | 1.922490614 | 4.223 |
| 52 | 1.152419772 | 1.639772079 | 3.752408794 | 1.966667922 | 4.2307 |
| 53 | 1.165565686 | 1.664631683 | 3.758935569 | 2.010989901 | 4.2484 |
| 54 | 1.178682753 | 1.689366539 | 3.76534034 | 2.05545428 | 4.2461 |
| 55 | 1.191771037 | 1.713978956 | 3.771627587 | 2.100058868 | 4.2538 |
| 56 | 1.204830599 | 1.738471161 | 3.777801543 | 2.144801544 | 4.2615 |
| 57 | 1.217861504 | 1.762845301 | 3.783866221 | 2.18968026 | 4.2692 |
| 58 | 1.230863814 | 1.787103446 | 3.78982542 | 2.234693031 | 4.2769 |
| 59 | 1.243837592 | 1.811247598 | 3.795682747 | 2.279837935 | 4.2845 |
| 60 | 1.2567829 | 1.835279689 | 3.801441628 | 2.325113111 | 4.2922 |
| 61 | 1.269699801 | 1.859201586 | 3.807105316 | 2.370516754 | 4.2999 |
| 62 | 1.282588358 | 1.883015096 | 3.812676907 | 2.416047113 | 4.3076 |
| 63 | 1.295448632 | 1.906721968 | 3.818159349 | 2.46170249 | 4.3153 |
| 64 | 1.308280685 | 1.930323893 | 3.82355545 | 2.507481235 | 4.323 |
| 65 | 1.321084581 | 1.953822513 | 3.828867887 | 2.553381746 | 4.3307 |
| 66 | 1.333860379 | 1.977219417 | 3.834099215 | 2.599402466 | 4.3384 |
| 67 | 1.346608142 | 2.000516145 | 3.839251873 | 2.645541882 | 4.3461 |
| 68 | 1.359327932 | 2.023714193 | 3.844328193 | 2.69179852 | 4.3538 |
| 69 | 1.372019809 | 2.046815013 | 3.849330403 | 2.738170948 | 4.3615 |
| 70 | 1.384683836 | 2.069820014 | 3.854260636 | 2.784657771 | 4.3692 |
| 71 | 1.397320073 | 2.092730563 | 3.859120935 | 2.831257632 | 4.3769 |
| 72 | 1.409928581 | 2.115547993 | 3.863913255 | 2.877969207 | 4.3849 |
| 73 | 1.422509421 | 2.138273597 | 3.868639473 | 2.924791207 | 4.3922 |
| 74 | 1.435062654 | 2.160908631 | 3.873301386 | 2.971722375 | 4.3999 |
| 75 | 1.44758834 | 2.183454321 | 3.877900721 | 3.018761484 | 4.4076 |
| 76 | 1.46008654 | 2.205911857 | 3.882439136 | 3.065907339 | 4.408 |
| 77 | 1.472557314 | 2.2282824 | 3.886918223 | 3.113158773 | 4.4096 |
| 78 | 1.485000722 | 2.25056708 | 3.891339514 | 3.160514646 | 4.41 |
| 79 | 1.497416825 | 2.272766997 | 3.895704482 | 3.207973846 | 4.412 |
| 80 | 1.509805682 | 2.294883224 | 3.900014543 | 3.255535286 | 4.415 |
| 81 | 1.522167353 | 2.316916807 | 3.904271061 | 3.303197903 | 4.419 |

| T in days | Gibson and Lo model (inch) | Yen Scanlon (inch) | Sowers Model (inch) | Power creep Law (inch) | Expt data (inch) |
|---|---|---|---|---|---|
| 82 | 1.534501897 | 2.338868768 | 3.908475351 | 3.350960661 | 4.421 |
| 83 | 1.546809375 | 2.360740101 | 3.912628678 | 3.398822544 | 4.443 |
| 84 | 1.559089845 | 2.382531777 | 3.916732264 | 3.446782559 | 4.471 |
| 85 | 1.571343368 | 2.404244746 | 3.920787285 | 3.494839738 | 4.489 |
| 86 | 1.583570001 | 2.425879933 | 3.924794879 | 3.542993128 | 4.5 |
| 87 | 1.595769804 | 2.447438242 | 3.92875614 | 3.591241802 | 4.511 |
| 88 | 1.607942836 | 2.468920558 | 3.93267213 | 3.639584849 | 4.511 |
| 89 | 1.620089156 | 2.490327743 | 3.936543869 | 3.688021378 | 4.515 |
| 90 | 1.632208822 | 2.511660643 | 3.940372348 | 3.736550517 | 4.521 |
| 91 | 1.644301893 | 2.532920082 | 3.944158523 | 3.78517141 | 4.528 |
| 92 | 1.656368427 | 2.554106868 | 3.947903318 | 3.833883219 | 4.533 |
| 93 | 1.668408482 | 2.575221791 | 3.951607628 | 3.882685125 | 4.561 |
| 94 | 1.680422117 | 2.596265623 | 3.955272318 | 3.931576321 | 4.578 |
| 95 | 1.692409389 | 2.61723912 | 3.958898229 | 3.98055602 | 4.591 |
| 96 | 1.704370356 | 2.638143024 | 3.96248617 | 4.029623446 | 4.593 |
| 97 | 1.716305077 | 2.658978058 | 3.966036931 | 4.078777841 | 4.6 |
| 98 | 1.728213608 | 2.679744934 | 3.969551273 | 4.128018459 | 4.603 |
| 99 | 1.740096006 | 2.700444346 | 3.973029935 | 4.177344571 | 4.606 |
| 100 | 1.751952331 | 2.721076976 | 3.976473636 | 4.226755457 | 4.61 |
| 101 | 1.763782638 | 2.741643491 | 3.97988307 | 4.276250416 | 4.619 |
| 102 | 1.775586985 | 2.762144548 | 3.983258913 | 4.325828754 | 4.623 |
| 103 | 1.787365428 | 2.782580786 | 3.986601821 | 4.375489792 | 4.64 |
| 104 | 1.799118025 | 2.802952836 | 3.989912429 | 4.425232864 | 4.651 |
| 105 | 1.810844832 | 2.823261315 | 3.993191357 | 4.475057315 | 4.683 |
| 106 | 1.822545906 | 2.843506828 | 3.996439204 | 4.5249625 | 4.697 |
| 107 | 1.834221303 | 2.863689969 | 3.999656555 | 4.574947788 | 4.713 |
| 108 | 1.84587108 | 2.883811322 | 4.002843976 | 4.625012555 | 4.719 |
| 109 | 1.857495293 | 2.903871457 | 4.00600202 | 4.675156191 | 4.722 |
| 110 | 1.869093997 | 2.923870938 | 4.009131222 | 4.725378095 | 4.725 |
| 111 | 1.88066725 | 2.943810315 | 4.012232106 | 4.775677675 | 4.732 |
| 112 | 1.892215106 | 2.96369013 | 4.015305179 | 4.826054351 | 4.745 |
| 113 | 1.903737622 | 2.983510915 | 4.018350935 | 4.87650755 | 4.755 |
| 114 | 1.915234853 | 3.003273191 | 4.021369856 | 4.927036711 | 4.763 |
| 115 | 1.926706855 | 3.022977473 | 4.024362411 | 4.977641279 | 4.769 |
| 116 | 1.938153683 | 3.042624265 | 4.027329055 | 5.028320709 | 4.75 |
| 117 | 1.949575391 | 3.062214062 | 4.030270235 | 5.079074467 | 4.779 |
| 118 | 1.960972037 | 3.081747352 | 4.033186383 | 5.129902024 | 4.8 |
| 119 | 1.972343673 | 3.101224612 | 4.036077922 | 5.180802861 | 4.823 |
| 120 | 1.983690356 | 3.120646315 | 4.038945263 | 5.231776466 | 4.837 |
| 121 | 1.995012139 | 3.140012923 | 4.041788809 | 5.282822336 | 4.85 |
| 122 | 2.006309079 | 3.159324891 | 4.044608951 | 5.333939974 | 4.869 |
| 123 | 2.017581228 | 3.178582668 | 4.047406071 | 5.385128891 | 4.875 |
| 124 | 2.028828642 | 3.197786694 | 4.050180543 | 5.436388608 | 4.887 |
| 125 | 2.040051375 | 3.216937402 | 4.052932729 | 5.487718649 | 4.895 |
| 126 | 2.05124948 | 3.236035219 | 4.055662985 | 5.539118546 | 4.918 |
| 127 | 2.062423013 | 3.255080565 | 4.058371657 | 5.590587841 | 4.929 |
| 128 | 2.073572027 | 3.274073853 | 4.061059085 | 5.642126078 | 4.945 |

# APPENDIX F

## DATA FOR DETERMINING 'k' VALUES

Following is the data used to determine the 'k' values as explained in Chapter 6:

**Table F.1** Data to find 'k' values

| Time (days) | Settlement (inch) | Fraction of settlement | Fraction of mass lost for k=0.0512 | Mass lost kg for k= 0.0512 | Fraction of mass lost for k=0.1515 |
|---|---|---|---|---|---|
| 10 | 0.2375036 | 0.02149354 | 0.0014018 | 0.00096581 | 0.004142083 |
| 20 | 0.4750073 | 0.04298708 | 0.0028015 | 0.00193027 | 0.008267009 |
| 30 | 0.613938 | 0.05556 | 0.0041994 | 0.00289337 | 0.012374849 |
| 40 | 0.7125109 | 0.06448063 | 0.0055952 | 0.00385513 | 0.016465674 |
| 50 | 0.78897 | 0.0714 | 0.0069892 | 0.00481553 | 0.020539554 |
| 60 | 0.8514416 | 0.07705354 | 0.0083811 | 0.00577459 | 0.024596561 |
| 70 | 0.9042606 | 0.08183354 | 0.0097711 | 0.00673231 | 0.028636762 |
| 80 | 0.9500145 | 0.08597417 | 0.0111592 | 0.00768868 | 0.032660229 |
| 90 | 0.9903723 | 0.08962646 | 0.0125453 | 0.00864371 | 0.036667031 |
| 100 | 1.0264736 | 0.09289354 | 0.0139295 | 0.00959741 | 0.040657236 |
| 110 | 1.0591312 | 0.09584898 | 0.0153117 | 0.01054976 | 0.044630913 |
| 120 | 1.0889453 | 0.09854708 | 0.016692 | 0.01150078 | 0.04858813 |
| 130 | 1.1163715 | 0.1010291 | 0.0180704 | 0.01245047 | 0.052528957 |
| 200 | 1.2639773 | 0.11438708 | 0.0276649 | 0.01906113 | 0.07966146 |
| 300 | 1.402908 | 0.12696 | 0.041209 | 0.02839302 | 0.117079881 |
| 400 | 1.5014809 | 0.13588063 | 0.0545645 | 0.03759493 | 0.152976972 |
| 500 | 1.57794 | 0.1428 | 0.0677339 | 0.04666865 | 0.187414587 |
| 600 | 1.6404116 | 0.14845354 | 0.0807199 | 0.05561599 | 0.220452063 |
| 700 | 1.6932306 | 0.15323354 | 0.093525 | 0.0644387 | 0.252146328 |
| 800 | 1.7389845 | 0.15737417 | 0.1061517 | 0.0731385 | 0.28255199 |
| 900 | 1.7793423 | 0.16102646 | 0.1186025 | 0.08171713 | 0.311721443 |
| 1000 | 1.8154436 | 0.16429354 | 0.1308799 | 0.09017626 | 0.339704947 |
| 1100 | 1.8481012 | 0.16724898 | 0.1429863 | 0.09851756 | 0.366550718 |
| 1200 | 1.8779153 | 0.16994708 | 0.154924 | 0.10674267 | 0.392305015 |
| 1300 | 1.9053415 | 0.1724291 | 0.1666955 | 0.1148532 | 0.417012213 |
| 1400 | 1.9307343 | 0.17472708 | 0.178303 | 0.12285077 | 0.440714885 |
| 1500 | 1.9543744 | 0.17686646 | 0.1897488 | 0.13073692 | 0.463453871 |
| 1600 | 1.9764882 | 0.17886771 | 0.2010352 | 0.13851323 | 0.485268354 |
| 1700 | 1.9972609 | 0.18074759 | 0.2121643 | 0.14618122 | 0.506195919 |
| 1800 | 2.016846 | 0.18252 | 0.2231385 | 0.1537424 | 0.526272628 |

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