ABSTRACT

INTER-RELATIONSHIP OF MECHANICAL AND BIO-CHEMICAL PROCESSES GOVERNING THE SETTLEMENT OF MUNICIPAL SOLID WASTE (MSW) USING THE (C + H)/L RATIO

by

Joseph J. Lifrieri

This research discusses the results of experimentation that determines the rates and magnitudes of consolidation and settlement of solid waste materials dependent upon their actual state of biodegradation decomposition and time in place. The state of decomposition of waste is determined by measuring its cellulose plus hemicellulose to lignin ratio ((C + H)/L). The samples were collected from bioreactors, at consecutive time intervals, to simulate states of decomposition.

Each sample was tested in consolidation to determine the value of the primary compression index C'_c, the secondary compression index “the inorganic creep rate” coefficient, C'_α and the “initial and tertiary rate of biodegradation decomposition of the mass volume” compression indices C_β and $C_{\alpha\beta}$. Gas generated was observed to provide a means to equate observed laboratory time to actual field time. The observed gas volumes generated were compared to calculated theoretical gas volumes determined from a first order decay model based on the USEPA LANDGEM model. The values obtained as part of this research were determined for a loading increment of 2.56 tons per square foot (tsf) for all samples, unless otherwise stated, and indicate that C'_c varies from 0.1831 to 0.2445 for the prepared waste samples. An exponential comparison of C'_c and the (C + H)/L ratio indicates that the value of C'_c decreases with decreasing (C + H)/L ratio. The values for C'_α, ranged from 0.0050 to 0.0095 for the tested samples.

The values for C'_{α} were observed to increase with respect to decreasing (C + H)/L. The value for the coefficient C_{β} is 0.0.1470, for Sample A (LT) and 0.0540 for the Humus. The values of C_{β} for the waste samples ranged from 0.0150 to 0.1470 and, as expected decreased as (C + H)/L decreased. The values of the Secant Modulus of Biodegradation, (Secant_{β}) were observed to be directly proportional to the (C + H)/L ratio, varying from 0.0300 to 0.0109. The value for $C_{\alpha\beta}$ is 0.0340 for Sample A (LT) and 0.0235 for the Humus. Graphical relationships between $C_{\alpha\beta}$ and the (C + H)/L ratio indicate that the value of $C_{\alpha\beta}$ ranged from 0.0055 to 0.0340 decreasing as (C + H)/L decreased.

The results indicate that the inorganic and organic portions of primary settlement may be calculated using Terzaghi's theory of conventional soil mechanics and the C'_{c} and C_{β} coefficients related to strain and also corresponding to the cellulose plus hemicellulose to lignin ratio, (C + H)/L of the waste material, representing its state of biodegradation decomposition. The secondary settlement related to the coefficient C'_{α} and the tertiary coefficient $C_{\alpha\beta}$ were also observed to be dependent upon the existing state of decomposition of the waste material.

By utilizing the C'_{c}, C'_{α}, C_{β}, Secant_{β} and $C_{\alpha\beta}$ rate values, determined for waste at various values of (C + H)/L, predictions of the settlement remaining under structures or fills at any given time in the future can be estimated. The model was validated by comparing observed settlement to predicted settlement for the Kingsland Landfill located in North Arlington, New Jersey. A methodology to predict the settlement of waste of any composition is also presented.

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This dissertation is dedicated to my father and mother
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to my wife of 38 years, Carol, who put up with my constant
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LIST OF SYMBOLS

$A(t)$	Area at time t
A_o	Original area
B_{100}	Total Biodegradation that will Occur
B_r	Remaining Amount of Biodegradation to Occur
B_t	Percent of Biodegradation Remaining
C	Chemical Symbol for Carbon
$(C + H)/L$	Cellulose (C) + Hemicellulose (H) divided by Lignin (L) Ratio
C'_c	Strain Related Compression Index
C'_α	Strain Related Secondary Compression Index
C_{bio}	The Quantity of Carbon Source in the Waste Available for Degradation
C_{lignin}	The Quantity of Carbon Source in the Waste Related to Lignin
CH_4	Chemical Symbol for Methane
CO_2	Chemical Symbol for Carbon Dioxide
COOH	Carboxyl – Carboxylic Acid Functional Group
C_{ult}	Non Degradable Quantity of the Waste
$C_{\alpha\beta}$	Strain Related Tertiary Compression Index
$C_{\alpha\epsilon}$	Secondary Compression Ratio (Sowers 1979)
C_β	Strain Related Biodegradation Compression Index
e_p	Observed Void Ratio
ft^3	Cubic Feet

LIST OF SYMBOLS
(Continued)

G	USEPA Symbol for Annual Methane Generation
H	Height of Refuse
H_o	Thickness of the Layer
h_p	Height of Refuse After Primary Compression,
ID	Inner Diameter
k	Exponential Decay Constant
k_1	Exponential Decay Constant for Readily Biodegradable Waste
k_2	Exponential Decay Constant for Moderately Biodegradable Waste
k_3	Exponential Decay Constant for Slowly Biodegradable Waste
kg	Kilograms
l	Liter
L	Lignin
L_o	Total Amount of Gas that Can be Produced per Unit of Waste
lbs	Pounds
ln	Natural Logarithm
log	Logarithm to Base 10
m	Meters
MSW	Municipal Solid Waste
N	Chemical Symbol for Nitrogen
NA	Not Applicable

LIST OF SYMBOLS
(Continued)

O_2	Chemical Symbol for Oxygen
^{o}F	Degrees Fahrenheit
OH	Hydroxyl – Alcohol Functional Group
^{o}K	Degrees Kelvin
p_o	Existing Overburden Pressure at the Center of the Layer
RPD	Relative Percent Deviation
S	Chemical Symbol for Sulfur
$Secant_{\beta}$	Secant Modulus of Biodegradation
$S_{p\epsilon}$	Strain Based Primary Compression of Waste
S_s	Secondary Compression Settlement
t	Time in Either Years, Minutes or Seconds
t_2	Time at the Start of Biodegradation Settlement.
t_3	Time at Start of Final Tertiary Biodegradation Settlement
t_f	Time for Desired Settlement
t_i	Initial Time
t_{md}	Time in Days at Which Daily Gas Production is Desired Within the Moderately Biodegradable Time Range
t_p	Time for Primary Compression to Occur
t_{rd}	Time in Days at Which Daily Gas Production is Desired Within the Readily Biodegradable Time Range

LIST OF SYMBOLS
(Continued)

t_{sd}	Time in Days at Which Daily Gas Production is Desired Within the Slowly Biodegradable Time Range
$t_{1/2}$	Half Life of Decomposition in Years
tsf	Tons Per Square Foot
USEPA	United States Environmental Protection Agency
V'	Gas Production per Cubic Foot of Waste per Year
V_1	V_o' Measured at the End of the First Phase of Gas Production.
V_{md}	Moderately Biodegradable Original Volume
V_{nd}	Non Degradable Original Volume
V_o'	Initial Gas Production per Cubic Foot of Waste per Year per Year
$V_{phase\ 1}$	Initial Phase of Gas Production => 10 Years
$V_{phase\ 2}$	Final Phase of Gas Production < 10 Years
V_r	Volume Remaining
V_{rd}	Readily Biodegradable Original Volume
V_{sd}	Slowly Biodegradable Original Volume
V_t	Daily Gas Production in ft^3 of Waste per lb per day
w	Water Content in Percent
W	Weight
W_{nd}	Weight of Non Degradable Portion of Waste
W_{org}	Dry Weight of Organic Portion of Waste

LIST OF SYMBOLS
(Continued)

W_w	Weight of Water
Δp	Change in Pressure at the Center of the Layer Caused by the External Load
$\Delta\sigma$	Change in Vertical Stress
ρ_f	Total Final Settlement
$\rho_{primary}$	Primary Settlement
$\rho_{Secant\beta}$	Secant Modulus of Biodegradation Settlement
ρ_α	Secondary Inorganic Settlement
$\rho_{\alpha\beta}$	Tertiary Biodegradation Settlement
ρ_β	Biodegradation Settlement
σ_o	Initial Vertical Stress
%	Symbol for Percent

CHAPTER 1

INTRODUCTION

1.1 Objective

This dissertation presents the general outline of a hypothesis developed by the writer and the results of a laboratory program conducted in support of this hypothesis. All laboratory testing was generally conducted in accordance with the document title "Proposal for Dissertation" submitted in October 2007.

1.2 Hypothesis

The main hypothesis postulated for this work considers that long term magnitudes and rates of settlement within a MSW landfill will be dependent upon mechanical processes and the current and future state of biodegradation related decomposition of the waste mass. The state of biodegradation related decomposition is determined by using the techniques described by Barlaz et.al 2002 and 2003 and Hossain, Gabr and Barlaz (2003) which considers the cellulose plus hemicellulose to lignin ratio (C + H)/L of the waste material.

For discussion and analysis purposes, the total compression of the Municipal Solid Waste (MSW) has been broken down into several components, which is comprised of a relatively large magnitude of primary compression followed by several stages of creep related movements under the sustained loading. The Primary compression would generally occur rapidly due to greater permeability of the MSW and can be modeled using the Terzaghi theory of consolidation utilized in conventional soil mechanics. It is the writer's hypothesis that the strain related coefficient of primary compression, C'_c of MSW is directly related to the state of compaction the landfill has undergone and the cellulose plus hemicellulose to lignin ratio, (C + H)/L of the existing landfill. Although, the C'_c parameter is a slope of strain versus applied loading and therefore a constant for all loading increments, previous full scale testing performed by Paulus, Sokolowski and Sartor in 1999 and 2005 on two existing landfills in Atlantic City, New Jersey and in Rutherford, New Jersey, respectively, has demonstrated that a higher existing state of compaction imparted to the MSW by using dynamic compaction (i.e., reducing the void ratio of the waste and increasing the initial relative density of the waste mass) would result in lower primary compression index C'_c values (Lifrieri et. al. 2007). The lower the (C + H)/L ratio the more soil-like and closer to established C'_c values found within many soil mechanics technical sources, such as Terzaghi, Peck and Mesri, (1996), Ladd (1987) etc. Immediately upon filling, the waste would have a higher (C + H)/L ratio and hence lower C'_c value. Once the biodegradation related decomposition of the waste material is completed, the (C + H)/L ratio would be minimum and therefore the C'_c value of the resultant waste mass should be higher and approach a final constant value of C'_c, similar to that of an organic soil (Hossain, Gabr and Barlaz 2003).

Review of laboratory test data suggests that the creep related secondary settlement, similar to that observed in a soil not subject to biodegradation, would be composed of a conventional soil skeletal phenomenon known as "the inorganic creep rate" (C'_α) related compression index as per the conventional Terzaghi theory followed by the compression resulting from the biodegradation related compression index, which is termed "rate of biodegradation decomposition" of the mass volume, C_β. This compression phase would be dependent upon the existing state of decomposition of the waste material and is estimated using the (C + H)/L ratio. During a complete cycle of time encompassing C'_α and C_β, the "biodegradation secant modulus compression index, $Secant_\beta$ can be used to predict future tertiary settlement depending upon the tertiary compression index, $C_{\alpha\beta}$ and the number of complete log cycles the waste has undergone to reach time final, t_f. Figure 1.1 depicts the construction of the coefficients C'_α, C_β, $Secant_\beta$ and $C_{\alpha\beta}$. The times for the end of primary compression, end of inorganic secondary compression, and the end of biodegradation compression are shown as t_1, t_2 and t_3, respectively. This time factors will be discussed in a later section.

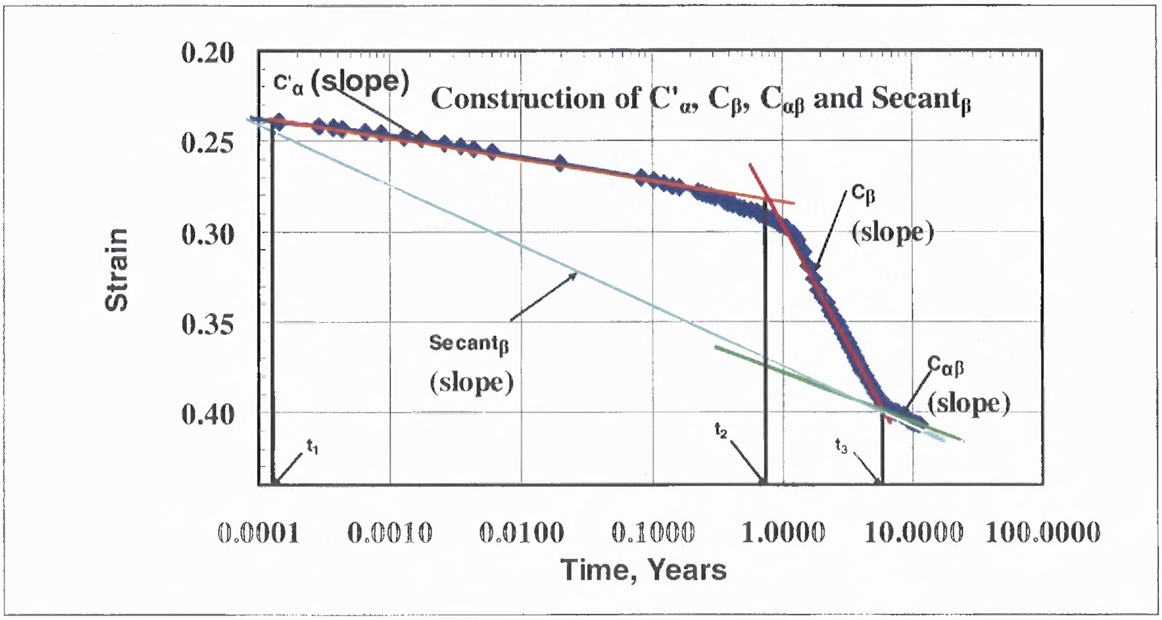

Figure 1.1 Construction of C'_α, C_β, $Secant_\beta$ and $C_{\alpha\beta}$.

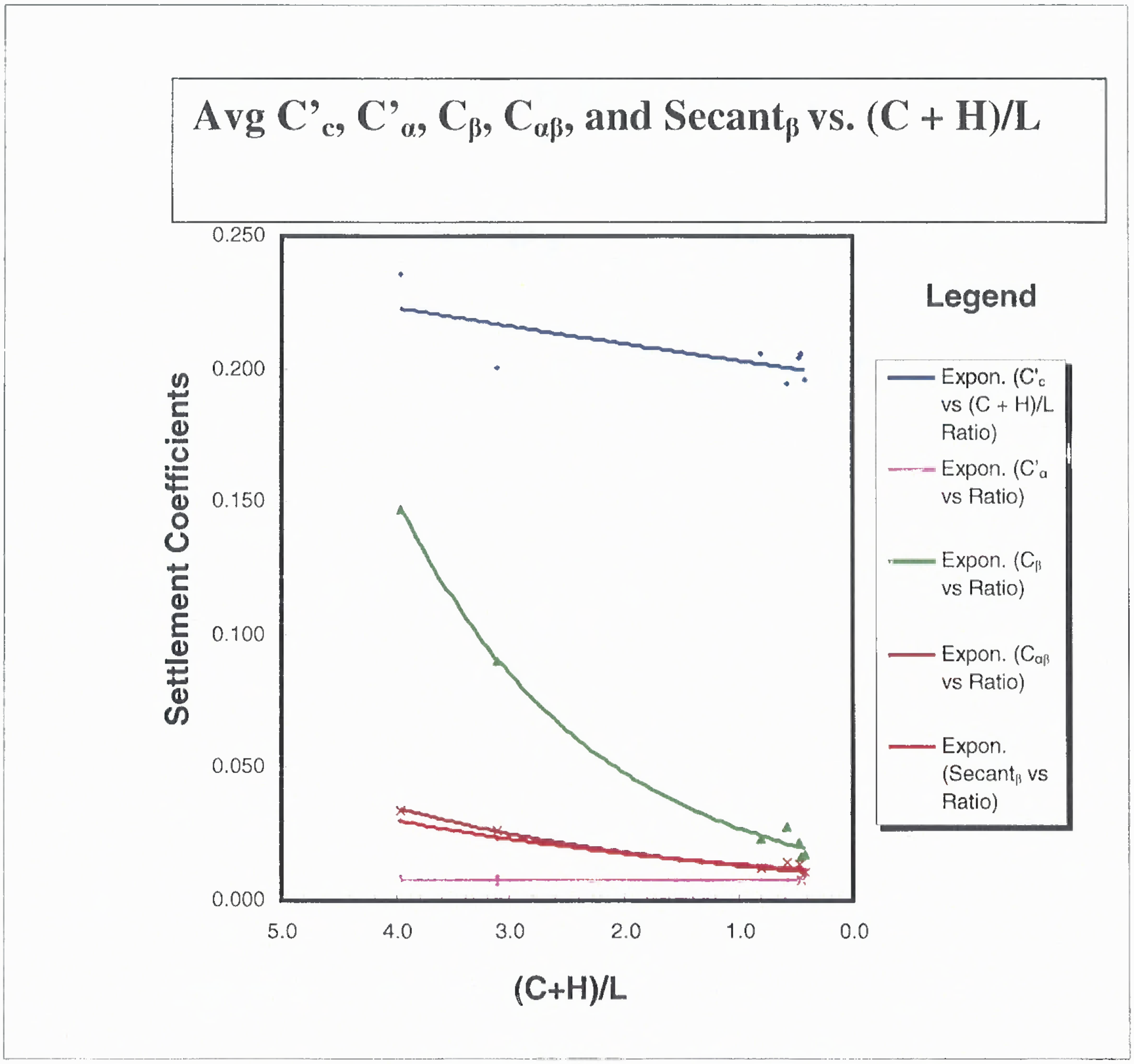

Figure 1.2 Variation of waste properties with the occurrence of biodegradation.

The long term residual tertiary compression following the portion related to C'_α and C_β (the $Secant_\beta$) is termed $C_{\alpha\beta}$ by the author. Figure 1.2 above demonstrates the general trend of these parameters with varying (C + H)/L ratio (i.e. the state of biological decomposition). The lower the ratio the more soil-like and closer to established soil-like C'_α values the waste exhibits. Accordingly, the value of C'_α should follow the C'_α/C'_c relationships (Terzaghi, Peck and Mesri 1996) observed in conventional soil mechanics. Once complete decomposition of the waste material occurs, the value of $C_{\alpha\beta}$ should stabilize at a final tertiary $C_{\alpha\beta}$ value similar to that of C'_{α} representative of an organic soil. It follows that C'_{c} and $C_{\alpha\beta}$ should vary within a relatively narrow range of values and reach final stabilized C'_{c} and $C_{\alpha\beta}$ rate values, as mass volume biodegradation decomposition becomes complete.

The secondary settlement and tertiary portion related to skeletal and mass volume biodegradation decomposition, respectively, resulting from the percent of remaining organic material capable of biodegrading and decomposing would be determined using the (C + H)/L ratio model. The C_{β} rate value will also be dependent on the (C + H)/L ratio. Immediately following placement of the waste, the (C + H)/L ratio will be at a maximum, and once decomposition begins, the C_{β} rate value will be high. At some time after placement of the waste, when most of the biodegradation decomposition is complete, (C + H)/L ratio will be at a minimum and the corresponding C_{β} rate value will be low.

By determining the state of biodegradation decomposition of each selected segment of a landfill, at the time of interest, the author hypothesizes that the percentage of volumetric strain due to biodegradation left to occur can be estimated from the area under the (C + H)/L versus Time curve. It is the opinion of the author that once computed, this percentage can be used to determine C_{β} and $C_{\alpha\beta}$ rate coefficients that may be utilized to make settlement predictions related to remaining mass volume decomposition at any given time of interest. In reality, since the mass volume of material that will decompose is constantly decreasing, it would follow that the value of C_{β} should also decrease with decreasing (C + H)/L ratios. Similarly C_{β} for any given value of (C + H)/L value should be a constant since the compositional nature remains generally unchanged throughout the extent of the testing on that sample. Once mass volume decomposition is complete, it appears reasonable to assume that C_β eventually approaches a $C_{\alpha\beta}$ value and that the biodegradation settlement is no longer significant.

Throughout the biodegradation related decomposition process of the waste material, C'_α will remain constant or vary slightly, dependent upon compositional changes related to decomposition. C'_α is a physical property of the waste, and less dependent upon the biodegradation related decomposition of the waste material since C'_α occurs before decomposition begins. The resultant soil mass should exhibit a final constant tertiary $C_{\alpha\beta}$ rate value similar to the C'_α rate of an organic soil. The C_β rate value will be greatest at the start of biodegradation and will decrease to insignificance at the end of biodegradation, as (C + H)/L decreases and waste compositional character changes. The $C_{\alpha\beta}$ rate value similarly should decrease as the (C + H)/L ratio decreases, the character of the waste composition changes and decomposition becomes complete reaching a constant value similar to that of an organic soil.

By utilizing the C'_c, C'_α, C_β, Secant_β and $C_{\alpha\beta}$ rate values, based upon the waste's (C + H)/L ratio, prediction of the amount of primary settlement, secondary settlement, biodegradation settlement and long term residual tertiary settlement should be possible. By totaling all of the predicted settlement values calculated above it should be theoretically possible to determine predicted settlement under structures or fills at any given time in the future.

1.3 Background and Historical Information

Many authors have attempted to explain MSW landfill settlement using predictive models that consider rheological, empirical and biodegradation methods. Some authors included an accelerated creep factor to account for unexplained observed settlement and recently some authors have attempted to determine anticipated settlements based upon a relationship between secondary settlement and volume loss due to biodegradation of the waste. One author, Oweis (2006) has attempted to assign various compression characteristics to waste exhibiting a specific degree of decomposition based upon the rate of filling and a first order decay constant promulgated by the USEPA.

Mitchell et al (2005) has discussed biological effects on soil behavior, properties and predictability. In accordance with Sowers (1973) mechanical, chemical and biological factors affect the compressibility of waste material. In addition, long term creep also affects the long term settlement characteristics of the waste. According to Sowers (1973) total settlement within landfills is the result of three distinct phases of compression. The first phase is the settlement which occurs as a result the self weight of the waste during placement and/or the result of the application of an external load. This phase usually occurs quickly after the application of the stress or load. The second phase occurs as the result of the dissipation of excess pore pressure and/or gas from the voids within the material. This phase is called "primary compression" and usually occurs within several months of waste placement. According to Sowers (1973), primary compression can be estimated using the principles of conventional soil mechanics. Hossain (2002) recommends a value of ten (10) days be used for t_1, the end of primary compression, or conversely the start of secondary settlement effects. The last stage or phase is called "secondary compression" and can account for the majority of the settlement observed in the landfill over many years. Edil et al. (1990) developed a rheological model to predict landfill settlement. In 1975 Yen and Scanlon developed an empirical relationship using a logarithmic function to determine the rate of settlement. Coduto and Huitric (1990) determined through observation that landfills appeared to settle between 18 and 24% of their original height. None of the above discusses the effects of decomposition on long term settlement of the waste and do not attempt to isolate and quantify the decomposable effects. In an attempt to explain some anomalous observations of settlement in existing landfills, some authors such as Edil et al. (1990) and Ling et. al. (1998) tried to model settlement using power and hyperbolic functions. Although better, these approaches did not prove to be satisfactory indicators or definitive predictive tools for MSW settlement (Park et. al 2002).

The length of time required for the decomposition of the waste has a direct relationship to the length of time that settlement may be of concern for construction projects built over recently closed and orphaned landfills. Recently, many authors have attempted to discern a coefficient of secondary compression that takes into account mechanical and biodegradation continuing settlements with respect to time under constant loading conditions. To date, many of the coefficients postulated by various authors either excluded biodegradation effects, Wall and Zeiss, (1995) or accounted for them by including them in coefficients of secondary settlement that varied with time without accounting for the state of decomposition of the waste, Gabr and Valero, (1995); Coumoulous and Koryalos, (1999). Edgars et al. (1992) and Park and Lee

(1997) added the effect that decomposition of the waste had upon overall settlement values.

In an attempt to further refine settlement predictions some authors, Disbrow (1988); Raghu and Guasconi (2002); Arntz (1993); Durmusoglu, Corapcioglu and Tuncay (2005); Findikakis and Leckie (1979); and, Yesiller, Hanson and Liu (2005) have included the effects of heat flow, landfill gas and liquid flow models to help account for observed settlement. Raghu and Arntz (1993) and the Raghu and Guasconi (2002) NJIT model predicted settlement values that were greater than the predicted values determined by Sowers (1973). Actual values of the level of decomposition from within the landfill were not determined and the actual quantity, in percentage of waste, of decomposed material was not ascertained.

1.4 Statement of Problem

The focus of this work would be to better understand the mechanics and biochemical processes that are responsible for settlement of municipal solid waste (MSW) landfills. To better understand the subject of settlement prediction, it is necessary to consider the state of decomposition of the waste and its associated settlement characteristics with regard to predictability and ease of use. At this time, the existing methods have concentrated more on the magnitude of biodegradation and not the prediction of the rate of biodegradation settlement. Settlement predictions are only based upon empirical and field observation methods. Predictions are not currently made utilizing laboratory testing of waste samples nor are they waste character specific which is the major thrust of this study.

Accurate prediction of settlement of waste materials in landfills has gained increasing importance lately in view of the introduction of the techniques such as leachate recirculation that tend to increase the rate of settlement. It is the author's intention to present a means of determining the settlement characteristics and behavior of a waste landfill by determining its state of biodegradation decomposition, at various times and depths throughout the landfill, by utilizing its cellulose plus hemicellulose to lignin ratio (C + H)/L (Barlaz et al, various) and developing settlement formulae specific to its state of biodegradation decomposition to better predict future settlement.

CHAPTER 2

A REVIEW OF THE PROCESSES OF DECOMPOSITION

2.1 Processes and Phases of Gas Generation

The decomposition of MSW goes through a series of stages or phases: aerobic decomposition, an aerobic acid stage, an accelerated anaerobic methane production stage, and a decelerated methane production stage. During the aerobic stage, the existing oxygen (O_2) within the landfill pore space is depleted and carbon dioxide (CO_2) is generally the major gas produced. Cellulose and hemicellulose do not undergo significant decomposition during this stage. Carboxylic acids consisting of acetic, propionic and butyric acids are produced during the anaerobic acidic stage along with a resultant decrease in the pH. The result is an acidic leachate with small amounts of gas. Cellulose and hemicellulose undergo little to no decomposition during this stage of decomposition. During the anaerobic methane production stage, carboxylic acids are utilized by methane (CH_4) producing organisms to produce CH_4 and CO_2. In this stage, pH increases as acids are utilized as a food source for the bacteria and cellulose and hemicellulose begin to decompose. During the next stage, the decelerated methane production stage, the carboxylic acids have been depleted as a food source, methane production decreases and the rate of cellulose and hemicellulose hydrolysis increases. The rate of increase in cellulose and hemicellulose hydrolysis is inversely proportional to methane production during this stage.

In 1998, the USEPA promulgated the Part WWW of the New Source Performance standards for regulation of gas emissions from landfills.

The gas production for all waste present in the landfill at a given time was calculated using the USEPA LANDGEM model:

$$G = W * L_0 * k * e^{-kt} \tag{2.1}$$

where G is the annual methane generation for year t in m^3 of CH_4/year, W is the weight in tons, t is the time in years after initial waste placement, k is a first order decay rate constant in 1/year (default value = 0.05 $year^{-1}$), and L_o is the total amount of gas that can be produced per unit of waste and in this case is the default value, prescribed by USEPA, of 170 m^3/ton.

Arntz and Raghu (1993) present a gas production model based upon the SIMCON model proposed by C. S. Hollings at the University of British Columbia, discussed by Baron, et al (1981) and modified by Disbrow (1988). In this model the placement of fill and the first phase of gas production are assumed to take place over a period of ten years and are represented by a straight line defined by the equation:

$$V' = V_o' * t \tag{2.2}$$

where V' is the gas production per cubic foot of waste per year, V_o' is the initial gas production per cubic foot of waste per year per year, and t is the time in years after the commencement of the first phase of gas production

The second phase (the post construction gas production phase) is represented by a pseudo-first order equation of the form:

$$V' = V_1'{*}\, e^{-k(t-T)} \qquad (2.3)$$

where k is a constant, T is the duration of the first phase of gas production, and V_1' is V_o' measured at the end of the first phase of gas production.

Utilizing the above defined equations, Arntz and Raghu (1993) assumed that the durations for each phase of gas production was ten years and 30 years, respectively. They further assumed that the rate of gas production remaining after the first and second phases of gas production would be 10% of the total gas produced by the materials. This results in 90% of the total gas production occurring in the first 40 years of the waste disposal. Utilizing values obtained from a landfill in 1985 which had undergone 15 years of decomposition after the commencement of the first phase, the authors measured values of -0.076753, 1.335, and 13.35 respectively for the parameters k, V_o' and V_1'. Utilizing these values in the above equations the authors obtained the following:

$$V' = 1.335 * t \tag{2.4}$$

where t is less than 10 years, and

$$V' = 13.35 * e^{-0.076753(t-10)} \tag{2.5}$$

when t is greater than 10 years.

Figure 2.1 from Raghu and Gausconi, (2002) represents the curve generated using the equations for Phase 1 and Phase 2 over a 40 year period.

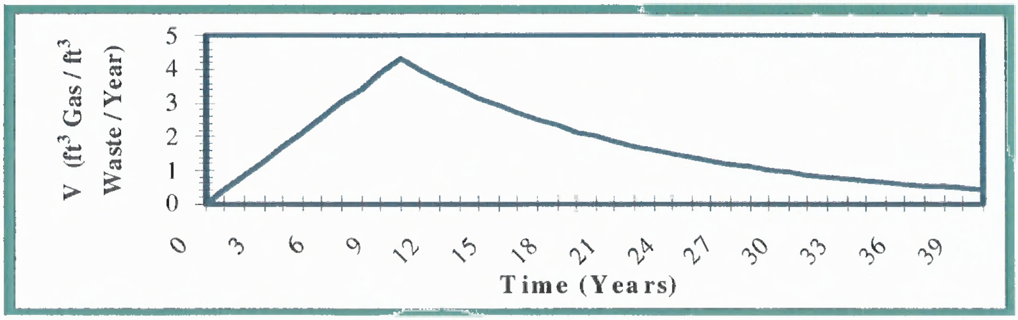

Figure 2.1 Gas production curve for the NJIT model.
Source: Raghu and Gausconi (2002)

To determine the total amount of gas produced, one must integrate Equations 2.4 and 2.5 to get the area under the curve for each phase of gas production, respectively. Integrating gives the following:

$$V = V_o * t_2/2 + (V_1 * T /b) * (1 - e^{-k(t-T)}) \qquad (2.6)$$

where b is a constant of integration. Substituting values measured yields:

$$V_{\text{phase 1}} = 0.667 * t2 \qquad (2.7)$$

where t is between 0 and 10 years,

$$V_{\text{phase 2}} = 173.93 * (e^{-0.076753\,(t-10)} - 1) \qquad (2.8)$$

where t is greater than 10 years.

Utilizing the results of these calculations the authors determined that the total amount of gas produced during the first phase of gas production was 66.7 ft^3 of gas/ ft^3 of waste, and 156.55 ft^3 of gas/ ft^3 of waste for the second phase of gas production, resulting in a total of 223.2 ft^3 of gas/ ft^3 of waste over 40 years.

2.2 Stoichiometry, Chemical Equations and Mass Balance

Tchobanoglous (1993) provided an empirical approach to landfill system behavior by observing landfill gas production. Shelley, Nixon, Bleckmann and et al. (2001) present a systems dynamic model of a landfill reactor. One representation of the sequence of the breakdown of solid waste to methane and carbon dioxide is described below. Although not unique in its path, it describes a general behavioral pattern that is characteristic of many landfills under varying conditions.

The most dominant substrate available for anaerobic biodegradation is carbohydrates. Glucose is selected as a readily available abundant molecule within the landfill system to allow the development of stoichiometrically balanced equations that describe the biodegradation processes that yield methane and carbon dioxide. The rate of hydrolysis is given as the mass of glucose formed per surface area of solid organic waste per day (Shelley, Nixon, Bleckmann and et al. 2001). It is not a biological reaction but this physical and chemical reaction (abiotic) rate that controls the decomposition of organic solid waste within a landfill. Table 2.1 depicts reactions, from Shelley, Nixon, Bleckmann, et al. (2001) and Gottschalk (1986), and represents pathways by which fermentation, acetogenesis and methanogenesis can occur:

Table 2.1 Chemical Equations of Fermentation, Acetogenesis and Methanogenesis

Hydrolysis of solid organics: one mole of glucose cleaved consumes one mole of water

Aerobic degradation of glucose: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

Nitrate anaerobic pathway: $C_6H_{12}O_6 + 3NO_3 + 6\ H \rightarrow 3NH_4 + 6CO_2 + 3H_2O$

Other anaerobic degradation pathways of glucose:
Direct to acetate $C_6H_{12}O_6 \rightarrow 3C_2H_4O_2$
Butyrate forming $C_6H_{12}O_6 \rightarrow C_4H_8O_2 + 2CO_2 + 2H_2$
Propionate and acetate $3C_6H_{12}O_6 \rightarrow 4C_3H_6O_2 + 2C_2H_4O_2 + 2CO_2 + 2H_2O$

Lactate: $C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$

Lactate and ethanol $C_6H_{12}O_6 \rightarrow C_3H_6O_3 + C_2H_6O + CO_2$
Lactate and acetate (bifudim) $2C_6H_{12}O_6 \rightarrow 2C_3H_6O_3 + 3C_2H_4O_2$

Ethanol: $C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$
Clostridial fermentation $C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 12H_2$
Mixed acid $10C_6H_{12}O_6 + 7H_2O \rightarrow 7C_3H_6O_3 + 4C_2H_4O_2 + 8C_2H_6O + CH_2O_2 + 14CO_2 + 13H_2$

Other acetogenic reactions:
From butyrate $C_4H_8O_2 + 2H_2O \rightarrow 2C_2H_4O_2 + 2H^+ + H_2$
From lactate $3C_3H_6O_2 \rightarrow 2C_3H_6O_2 + C_2H_4O_2 + CO_2 + H_2O$
From propionate $C_3H_6O_2 + 3H_2O \rightarrow C_2H_4O_2 + HCO_3^- + 3H_2$
From ethanol $C_2H_6O + H_2O \rightarrow C_2H_4O_2 + 2H_2$

Methanogenic reactions:
From acetate $C_2H_4O_2 \rightarrow CH_4 + CO_2$
From formate $4CH_2O_2 \rightarrow CH_4 + 3CO_2 + 2H_2O$
From CO_2 and H_2 $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Source: Nixon, Bleckmann, et al. (2001) and Gottschalk (1986).

Tchobanoglous (1977) has described simplified formulae to describe the conversion of liquefied organic compounds, representative of the waste content, into simpler acid and related intermediates and to carbon dioxide and methane. The conversions can be represented as follows:

$$C_aH_bO_cN_d \rightarrow nC_wH_xO_yN_z + mCH_4 + (a\text{-}nw\text{-}m)\ CO_2 \qquad (2.9)$$
$$+ (c\text{-}ny\text{-}2a\ \text{-}2nw\text{-}2m)H_2O + (d\text{-}nz)NH_3$$

The terms $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ are molar representations of the composition of the waste content present at the start and end of the process. Assuming complete stabilization, the expression becomes:

$$C_aH_bO_cN_d + [(4a\text{-}b\text{-}2c\text{+}3d)/4]\ H_2O \rightarrow [(4a\text{+}b\text{-}2c\text{-}3d)/8]\ CH_4 + [(4a\text{-}b\text{+}2c\text{+}3d)/8]\ CO_2 + dNH_3 \qquad (2.10)$$

A simplified exercise, from Tchobanoglous (1977) demonstrating the above mass balance equations, is presented in Table 2.2 through 2.6 shown below:

Table 2.2 Mass Balance Equations

Typical Data on Ultimate Analysis of the Combustible Components in MSW								
	Percent by Weight (dry basis)							
Component	Percent Combustible Portion MSW	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash	Percent of Total MSW
Food Waste	18%	48	6.4	37.6	2.6	0.4	5	15%
Paper	48%	43.5	6	44	0.3	0.2	6	40%
Cardboard	5%	44	5.9	44.6	0.3	0.2	5	4%
Plastic	4%	60	7.2	22.8	0	0	10	3%
Textiles	2%	55	6.6	31.2	4.6	0.15	2.5	2%
Rubber	1%	78	10.2	0	2	0	10	1%
Leather	1%	60	8	11.6	10	0.4	10	1%
Garden Trimmings	14%	47.8	6	38	3.4	0.3	4.5	12%
Wood	2%	49.5	6	42.7	0.2	0.1	1.5	2%
Dirt, Ashes, Brick etc.	5%	26.3	3	2	0.5	0.2	68	4%
Total	100%							

Source: Tchobanoglous (1977)

Table 2.3 Typical Data on Ultimate Analysis of the Combustible Components in MSW

Typical Data on Ultimate Analysis of the Combustible Components in MSW Percent by Weight (dry basis excluding Sulfur and Ash)						
	%	Redistributed Content for C, H, O_2, N				% of Total
Component		C	H	O_2	N	
Food Waste	18%	50.73996	6.765328	39.7463	2.74841	94.6
Paper	48%	46.37527	6.396588	46.90832	0.31983	93.8
Cardboard	5%	46.4135	6.223629	47.04641	0.31646	94.8
Plastic	4%	66.66667	8	25.33333	0	90
Textiles	2%	56.46817	6.776181	32.03285	4.72279	97.4
Rubber	1%	86.4745	11.3082	0	2.21729	90.2
Leather	1%	66.96429	8.928571	12.94643	11.1607	89.6
Garden Trimmings	14%	50.21008	6.302521	39.91597	3.57143	95.2
Wood	2%	50.30488	6.097561	43.39431	0.20325	98.4
Dirt, Ashes, Brick etc.	5%	82.7044	9.433962	6.289308	1.57233	31.8

Source: Tchobanoglous (1977)

Table 2.4 Total Component Content Based Upon Percentage in MSW

Total Component Content Based Upon Percentage in MSW					
Component	C	H	O_2	N	
Food Waste	19%	9.65249671	1.287	7.561122	0.522844
Paper	51%	23.5258169	3.24494	23.79623	0.162247
Cardboard	5%	2.35452135	0.31572	2.386628	0.016054
Plastic	4%	2.53646164	0.304375	0.963855	0
Textiles	3%	1.43229353	0.171875	0.812501	0.119792
Rubber	1%	0.54834814	0.071707	0	0.01406
Leather	1%	0.42463085	0.056617	0.082095	0.070772
Garden Trimmings	15%	7.64135711	0.959166	6.074719	0.543527
Wood	3%	1.27596393	0.154662	1.10068	0.005155
Totals		49.3918901	6.566063	42.77783	1.454451

Source: Tchobanoglous (1977)

Table 2.5 Total Component Content in MSW Normalized with Respect to Nitrogen

Element	Percent	Atomic Weight	Moles	Normalized with respect to Nitrogen	
Carbon	49.4	12	4.116667	41.166667	a
Hydrogen	6.4	1	6.4	64	b
Oxygen	42.8	16	2.675	26.75	c
Nitrogen	1.4	14	0.1	1	d
In molar terms the following is derived:					
$C_aH_bO_cN_d + ((4a-b-2c+3d)/4)H_2O \rightarrow ((4a+b-2c-3d)/8)CH_4 + ((4a-b+2c-d)/8)CO_2 + dNH$					
$C_{41.2}H_{64}O_{26.8}N + 12.58H_2O \rightarrow 21.5CH_4 + 19.7CO_2 + NH_3$					
Molecular Weight* Moles	1001.2	226.4	86.0	853.6	17.0
If we assume that the organic portion of waste, is decomposable, and the weight of Total MSW is 100 lbs, at a moisture content of 25%, then the dry weight of the decomposable fraction is equal to:					
(79 lbs – (100lbs* 0.25)) = 54 lbs					

Source: Tchobanoglous (1977)

Table 2.6 Determination of Quantity of Waste After 25 Years

<table>
<tr><td colspan="5">Determine how much of waste decomposes over 25 years:</td></tr>
<tr><td>Component</td><td>% Decomposed Over 25 years</td><td>Percent of Total MSW</td><td>Decomposed Wastes (dry basis)</td><td></td></tr>
<tr><td>Food Waste</td><td>100%</td><td>15%</td><td>8.1</td><td></td></tr>
<tr><td>Paper</td><td>65%</td><td>40%</td><td>14.04</td><td></td></tr>
<tr><td>Cardboard</td><td>75%</td><td>4%</td><td>1.62</td><td></td></tr>
<tr><td>Plastic</td><td>5%</td><td>3%</td><td>0.081</td><td></td></tr>
<tr><td>Textiles</td><td>30%</td><td>2%</td><td>0.324</td><td></td></tr>
<tr><td>Rubber</td><td>10%</td><td>1%</td><td>0.027</td><td></td></tr>
<tr><td>Leather</td><td>10%</td><td>1%</td><td>0.027</td><td></td></tr>
<tr><td>Garden Trimmings</td><td>100%</td><td>12%</td><td>6.48</td><td></td></tr>
<tr><td>Wood</td><td>50%</td><td>2%</td><td>0.54</td><td></td></tr>
<tr><td>Dirt, Ashes, Brick etc.</td><td>0%</td><td>4%</td><td>0</td><td></td></tr>
<tr><td>Total Waste Decomposed</td><td></td><td></td><td>31.239</td><td></td></tr>
<tr><td colspan="5">31.239 lbs decomposed/ 3.597 ft^3 (100 lbs) of waste =8.6775 lbs decomposed per ft^3 of waste over 25 years</td></tr>
<tr><td colspan="5">Determine Weight of Methane and Carbon Dioxide</td></tr>
<tr><td colspan="5">Methane: (86/1001.2)*31.24 = 2.68342 lbs</td></tr>
<tr><td colspan="5">Carbon Dioxide: (853.8/1001.2)*31.24 = 26.64074 lbs</td></tr>
<tr><td colspan="5">Convert Weight of Gases to Volume:</td></tr>
<tr><td colspan="5">100 lbs of waste = 3.597122 ft^3 waste =27.8 lbs/ ft^3 waste</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">Methane: 2.68 lbs/0.0448 lbs/ft^3 = 59.82143 ft^3</td></tr>
<tr><td colspan="5">Carbon Dioxide: 31lbs/0.1235 lbs/ft^3 = 251.0121 ft^3</td></tr>
<tr><td colspan="2"></td><td colspan="3">310.8336 ft^3/3.6 ft^3 of waste</td></tr>
<tr><td colspan="2"></td><td colspan="3">3.108336 ft^3/lb for sample of solid waste used</td></tr>
<tr><td colspan="2"></td><td colspan="3">86.34266 ft^3/ft^3 of waste is equivalent to 31.239% decomposed</td></tr>
<tr><td colspan="5">Comment: By measuring the volume of gas collected or calculated to be produced each year, one theoretically should be able to calculate the % decomposed per year by back calculating the change in mass from the original decomposable fraction of the material</td></tr>
</table>

Source: Tchobanoglous (1977)

Using the above analysis and solving for the amount theoretically decomposed over certain discrete time periods, one is able to solve for the amount of gas that will cumulatively form at each of the selected time intervals. This will be used to equate laboratory time observed to actual field time to determine long term settlement of the waste as discussed in Section 5.3, herein below.

CHAPTER 3

DEGRADATION, COMPRESSIBILITY AND BIOMASS CHARACTERISTICS

3.1 Discussion

In order to allow better predictions of long-term biological degradation settlements, it is imperative that the degree of decomposition that the waste has already undergone be ascertained and established. It is an a priori fact that the chemical nature and rate at which landfill gas is generated is directly related to the waste's age or state of decomposition. Findikakis and Leckie (1979) and Durmusoglu, Corapcioglu and Tuncay (2005) indicate that MSW consists of organic and inorganic waste portions. They suggest that the organic portion of the MSW should be categorized into representative categories, each a function of the biodegradability of the type of constituent. They suggested that three categories be established: readily biodegradable waste; moderately biodegradable waste and slowly biodegradable waste. Readily biodegradable waste consisting of food waste and garden waste made up 30% of the total waste on a dry weight basis and has a field observed half life ($t_{1/2}$) of decomposition of up to five years. Paper products, leather, textiles and wood made up the moderately biodegradable waste portion and represented 45% of the total waste which has a half life of decomposition of up to 30 years. Slowly degradable waste made up approximately 5% of the MSW, has a half life of decomposition of up to 40 years and consisted of plastic products and rubber, Findikakis and Leckie (1979). Inorganic waste consisting of metals, glass, ashes, dirt and fines represented the remainder of the waste and comprise 20% of the MSW waste on a dry weight basis.

Existing age or degree of waste decomposition may be determined by ascertaining gas generation rates and by determining the cellulose plus hemicellulose to lignin ratio (C + H)/L. Wall and Zeiss (1995) evaluated samples for settlement characteristics and concluded that based upon 250 days of testing, decomposition of the waste had little effect upon the settlement characteristics of the material. Other authors attempted to predict the settlement observed using one dimensional analytical approaches and using power creep modeling. None of these authors attempted to ascertain or account for the degree of decomposition of the waste. Disbrow (1988), Raghu and Guasconi (2002) and Arntz and Raghu (1993) held that long-term settlement is a strain related phenomenon directly related to the rate at which gas is produced and removed from the biomass. They believe that by performing an analysis of mass balance between the original amount of the waste and the gas and biomass remaining each year, a relationship can be developed that will better predict the long-term settlement behavior of the mass.

The principal biodegradable constituents of refuse and waste are cellulose and hemicellulose. Hilger and Barlaz (2001) and Hossain, Gabr and Barlaz (2003) indicate that each constituent has a concentration ranging from 29 to 51% and 9 to 12% respectively, in MSW. The other major constituent in MSW waste is lignin which can have concentrations ranging from 15 to 28%. Under methanogenic conditions, Lignin is slowly biodegradable and generally interferes with the breakdown and decomposition of cellulose and hemicellulose. Barlaz et al. (1990) cites that methane production per kg of cellulose is 414.8 liters and 424.2 liters per kg of hemicellulose. The equation, Tchobanoglous (1977), governing the conversion of these constituents to methane and carbon dioxide is:

$$(C_6H_{10}O_5)n + nH_2O \rightarrow 3nCH_4 + 3nCO_2 \qquad (3.1)$$

Hossain, Gabr, and Barlaz (2003) performed oedometer tests on bioreactor and control samples to determine the (C + H)/L ratio and settlement characteristics of the tested waste material and reviewed the work of others. For those samples exhibiting a lower (C + H)/L ratio (more decomposed), an increase in initial settlement (primary compression) under the same applied stress, when compared to less decomposed materials, was observed. The above authors report that the primary Compression Index C'_c increased from a low of 0.16 to a high of 0.37 as the cellulose plus hemicellulose to lignin ratio decreased. They conclude that the use of one unique C'_c value to describe the waste materials is not justified based upon their work and may lead to inaccurate predictions. It is their contention that the C'_c values should be dependent upon the state of decomposition of the waste and the (C + H)/L ratio. They state that it appears that C'_c is inversely related to (C + H)/L and that the state of refuse decomposition controls the magnitudes of the compressibility parameters. The results of the testing performed on waste samples at differing (C + H)/L ratios for this current PhD work do not support the above conclusions of Hossain et al (2003).

Following this initial settlement, a secondary settlement exhibiting two distinct phases was observed, one with an initial shallower slope (C'_{α}) and the other with a slightly steeper slope (C_{β}). When samples tested were in the acid phase, where cellulose and hemicellulose are not decomposed, compressibility with time was observed to occur at a constant rate similar to and indicative of creep mechanics. The above authors described this observed slope of this part of the compression curve as C'_{α}. With time, the slope of the strain time plot was observed to increase slightly indicating to the above authors that increased biological degradation was occurring. They repeated these tests on other samples and observed similar behavior. They concluded that the increase in slope of the settlement-time plots was indicative of the onset of biological degradation and described this biological creep slope as C_{β}. The above authors concluded that "the steeper slope is likely due to the fact that the samples underwent additional decomposition during testing". Values determined for C'_{α} ranged from 0.02 to 0.03 and appeared to be independent of the state of waste decomposition while values for C_{β} ranged from 0.08 to 0.19. They further explain that the range in C_{β} values is dependent upon the state of decomposition of the waste, ranging from 0.05 to 0.10 in the acid phase, up to 0.19 in the active methane producing phase and 0.08 in the decelerated methane producing phase. Other authors, Edgars and Noble (1992) reported values for C'_{α} ranging from 0.01 to 0.04 and C_{β} values ranging from 0.02 to 0.5. These authors reported biological creep indices C_{β} ranging from 0.1 to 0.32. To eliminate the biological creep factor, Hossain, Gabr, and Barlaz (2003) inhibited biological activity and tested for settlement parameters during further compressibility studies. They determined that without the influence of the biological creep factor C_{β}, the creep index, for all the tested samples ranged from 0.015 to 0.03 similar to compressible soils. They found that the lowest value of the measured creep indices were related to the least decomposed of the test samples where the (C + H)/L ratio was 1.29. This also appears to be consistent with observation made by Marchado, Carvalho and Vilar (2002). They concluded that the structure of waste material is more fibrous in nature, and consists of a fibrous portion and a paste portion, which imparts an apparent strength in the lateral and vertical directions as a result of the larger particle sizes and fibers. As the waste decomposes the material skeleton breaks down as particle sizes reduce, migration into existing voids occurs and the structure assumes a less stable shape or collapses, Wall and Zeiss (1995), McDougall and Pyrah (2004).

3.2 Settlement and Consolidation

It has been reported in the literature that the compression of waste appears to be the result of self weight, and primary and secondary settlement effects, Sowers, (1973); Wall and Zeiss, (1995); and Durmusoglu et al., (2005). There does not appear to be one definitive model that accounts for observed settlement in landfills under external surcharges as well as self weight loading. The cited authors seem to agree that settlement occurs in three phases. The first phase is compression that occurs as soon as the waste is applied under self weight loading conditions or externally imposed compactive efforts. The second stage, which occurs rapidly, was postulated to represent primary settlement, similar to that observed in Terzaghi theory conventional soil mechanics, where compression is due to the dissipation of pore water and gas from the void spaces, Sowers, (1973); Edil et al., (1990) and has little impact upon long-term predictability of the behavior of the landfill waste. The third stage was postulated to be the result of secondary compression which is controlled by both mechanical, physical and biochemical degradation factors and has the greatest impact upon the settlement behavior of the waste. It was observed within this study that this phase actually consists of two separate and distinct phases, one physical and one related to biodegradation effects. The total settlement is then computed by summing all these factors, or by ignoring initial self weight induced or external compactive efforts, summing primary and secondary settlements only. The research conducted herein this work postulates that the third phase or secondary compression portion, of the above discussed settlement, is made up of three distinct quantifiable phases consisting of mechanical secondary settlement C'_{α}, decomposition settlement C_{β} and a residual tertiary settlement $C_{\alpha\beta}$.

Sowers (1973) developed the following strain based equation for the primary compression of the waste resulting from the instantaneous response to a surcharge loading:

$$S_{p\epsilon} = H * C'_{c} * \log (\sigma_{o} + \Delta\sigma) / \sigma_{o} \qquad (3.2)$$

where, H represents the height of refuse, C'_{c} is the compression ratio, σ_{o} is the initial vertical stress, and $\Delta\sigma$ is the change in vertical stress.

Sowers (1973) developed one of the first models to account for secondary settlements in landfills. Many authors such as Wall and Zeiss (1995) and Raghu and Guasconi (2002) refer to the Sowers model in their discussions and clarify that Sowers attributes secondary settlement of waste to the sum of mechanical, physiochemical and biochemical actions without distinction. The model developed by Sowers for secondary settlement is shown below:

$$S_s = h_p * C_{\alpha\epsilon} * \log (t/t_p) \tag{3.3}$$

where, S_s represents the secondary compression settlement, h_p is the height of refuse after primary compression, $C_{\alpha\epsilon}$, is the secondary compression ratio which is equivalent to $C_{\alpha\beta}$ in this work, t is time in days, and t_p, is the time for primary compression to occur.

To account for the effects of biodegradation, Sowers gives a range of values for $C_{\alpha\epsilon}$ at a specified void ratio for the waste. This range is dependent upon the conditions for biodegradation that exist in the landfill. It does not attempt to break up the secondary compression indices to account for each of the attributes affecting secondary settlement. Sowers also postulated that the secondary compression index was proportional to the observed void ratio. Utilizing the observed void ratio (e_p) Sowers proposed the following equation to calculate the secondary compression ratio based upon strain and suggested that it increases linearly with initial void ratio.

$$C_{\alpha\epsilon} = (0.03 \text{ to } 0.09) * (e_p) / (1 + e_p) \qquad (3.4)$$

The values of the numerical coefficients are similarly dependent upon the conditions for biodegradation that exist in the landfill. Disbrow (1988), Arntz and Raghu (1993) and others believe that a link exists between decomposition of waste and the rate of gas generation, and the volume change of waste in the landfill. They propose that in calculating the settlement of a waste landfill, the volumetric strain that occurs as the result of decomposition and gas production is equal to the vertical strain. They state that this assumption is valid because the thickness of the landfill is much smaller than its length and width. They propose that the volumetric strain that occurs can be calculated by dividing the area under the gas generation curve, discussed above, for a particular year by the total area under the curve. They propose to use an Eulerian system of coordinates wherein the settlement in any particular year is computed as a percentage of the height of the landfill during the prior year and not based upon the original height.

It is apparent from the above discussion that settlement of landfill waste will be dependent upon a number of factors discussed above and others to be defined by this current research. If the landfill is left to settle under its own weight, the settlement will be controlled by the percent of decomposition that occurs over the life of the landfill (Arntz and Raghu, 1993) plus secondary compression, decomposition settlement and residual tertiary settlement after full decomposition has occurred. As decomposition occurs, the material degrades into a biomass that is non decomposable and is not likely to produce gas. In addition, Hossain, Gabr, and Barlaz (2003) determined that the compressibility of the waste is inversely proportional to the cellulose plus hemicellulose to lignin ratio. They concluded that this ratio was an indicator of the amount of existing decomposition of the waste and could be used to determine the relative values of the compressibility parameters C'_c and C'_α. As an example, they cite that when biological activity was inhibited, the Creep Index C'_α for all samples tested ranged from 0.015 to 0.03 and that the coefficient of primary compression was measured to range from 0.16 to 0.25. These values were observed to be inversely proportional to the (C + H)/L ratio in that the lower values of each index was associated with the higher (C + H)/L ratio. They suggest that these values be used in the computation of landfill settlement.

3.3 Biomass Components Cellulose, Hemicellulose, and Lignin and their Determination

Municipal Solid Waste (MSW) refuse is made up of many various types of materials which, for the most part, are composed of plants or derived from plants in various forms or another. Depending upon the material constituents, the amounts of the decomposable portions of the waste vary and contribute to the rate at which the biomass materials decompose and ultimately settle. Cellulose and hemicellulose represent the majority of the biodegradable organic components of MSW. Lignin, the remaining organic component in the MSW, is generally believed to be only very slowly biodegradable under anaerobic conditions (conditions needed for methanogenesis and the production of methane). The presence of inert materials within the waste reduces the concentration of the organic components.

Decomposition settlement of MSW will be governed by the relative amount of this biomass material that is present in the waste. Barlaz (2006) lists various sources citing the organic composition of residential refuse (percent dry weight) and their respective (C + H)/L ratio. For the most part, he found that the (C + H)/L ratio ranged from 1.64 to 5.38 within the various mixed waste types tested. He found that the (C + H)/L ratio ranged from 1.65 to 83.5 for various paper products, wood and residential food waste found in MSW. The values for each constituent are shown in Table 3.1 below:

Table 3.1 Organic Composition of Residential Refuse and their Respective (C + H)/L Ratio

Constituent	(C + H)/L Ratio
Newsprint (Wu et. al. 2001)	3.00
Newsprint (Eleazer et. al. 1997)	2.41
Office Paper (Wu et. al. 2001)	83.5
Office Paper (Eleazer et. al. 1997)	41.6
Corrugated Cardboard (Eleazer et. al. 1997)	3.23
Coated Paper (Eleazer et. al. 1997)	3.45
Branches (Eleazer et. al. 1997)	1.65
Residential Food Waste (Eleazer et. al. 1997)	5.49
Residential Food Waste (Barlaz unpublished)	6.35
Residential Food Waste (Barlaz unpublished)	2.88

Source: As shown above

The high (C + H)/L values of the "office paper" reflect the removal of lignin from the product to produce a whiter material suitable for office use. The lower (C + H)/L values of the wood branches reflect the higher lignin content of the bark and outer wall of the plant.

The relative concentrations of the biomass constituents (cellulose, hemicellulose and lignin) are important factors to the prediction of decomposition, and by extrapolation, also settlement, of any individual or mixed waste material. It has been shown that the more lignin present in the waste material the less bioavailability of the cellulose and hemicellulose for decomposition, Barlaz (2006) and Stinson J. A., Ham R. K. et al (1995). Available data indicates that wood products decay slowly in landfills, Barlaz (2006). This is postulated to be the result of the higher lignin concentration of the wood materials and the encapsulation of the cellulose and hemicellulose fractions by lignin.

The following discusses the biomass lignocelluloses; cellulose, hemicellulose and lignin. The structure of a plant is made up of three main parts; cellulose, hemicellulose and lignin. Together these form the lignocelluloses which are the main food source for decomposition (Figure 3.1).

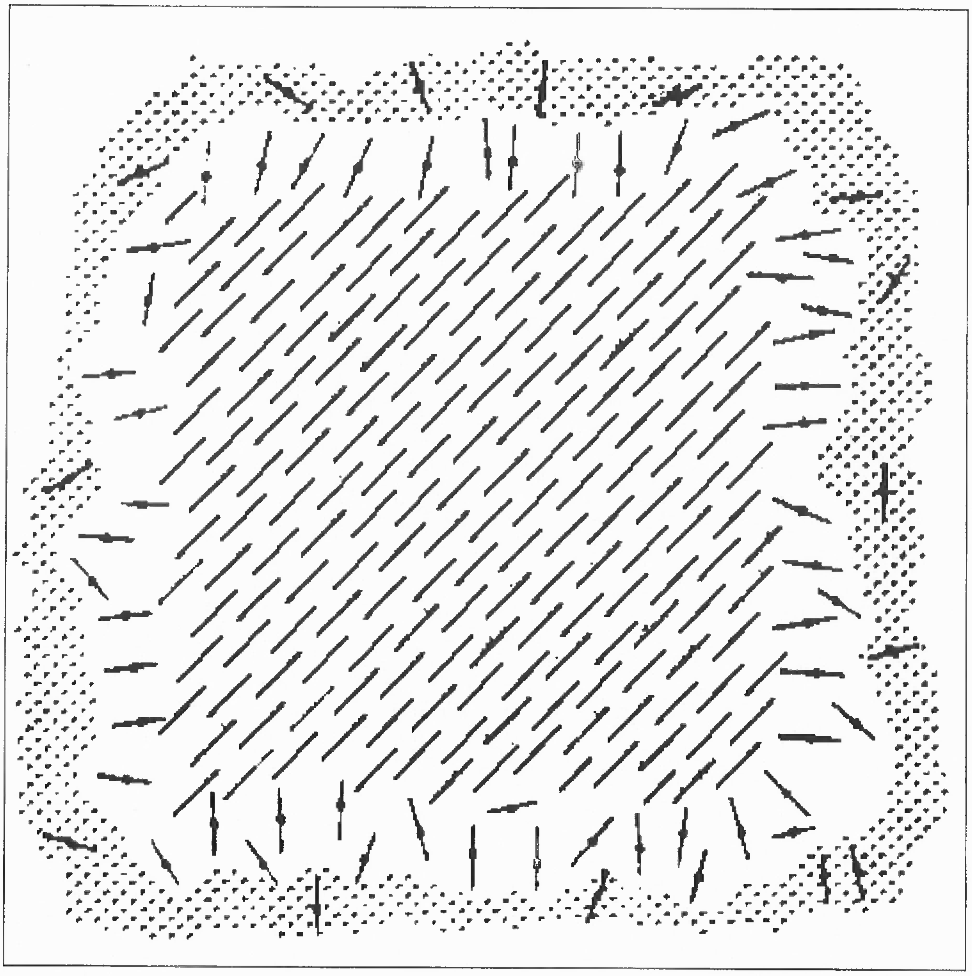

Figure 3.1 Typical plant cell structure depicting cellulose (–), hemicellulose (-·· -) and lignin (:::::::) complex in a cell wall.
Source: (Jeffries, T.W. 1987)

Cellulose and hemicellulose are a major component of plant derived organic wastes. Cellulose is a long chain of sugar molecules that are linked together and it is what gives wood its strength. It is the main component of plant cell walls, and the basic building block for many textiles and for paper (source: General Chemistry online). Cellulose is sometimes produced by animal matter but for the most part is a byproduct of plants. Cellulose is the load-bearing element of the pulp fiber, and chemical degradation of the cellulose results in a fiber with inferior strength properties (Gurnagul et al 1992). Generally, plants are hollow in the center (see Figure 3.2). This part is called the "lumen" which is formed by spiral layers of cellulose which impart strength and flexibility to the plant structure.

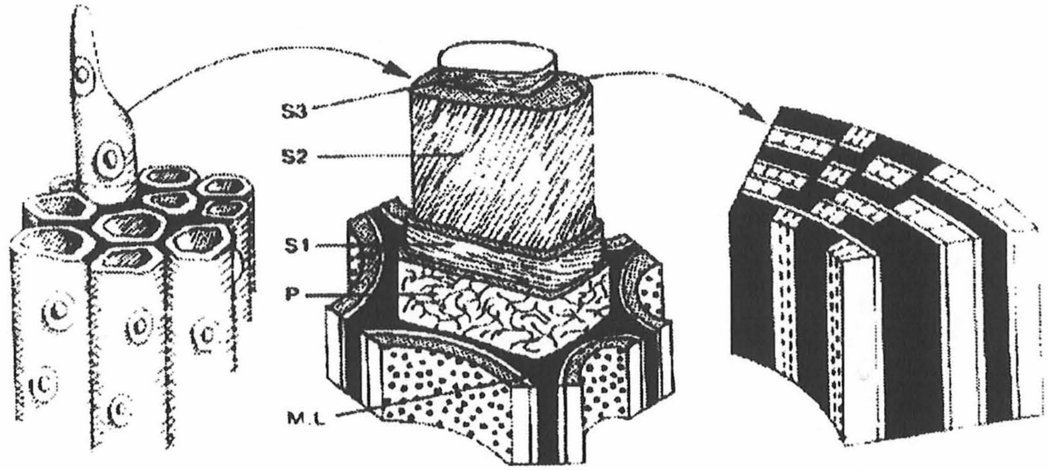

Figure 3.2 Artistic rendering of cellulose, hemicellulose and lignin in the cell wall.
Source: (Boda, B 2002 and Pekka Maijala et. al. 2000)

Cellulose consists of sugar molecules that are covalently linked in a long chain (see Figure 3.3 and 3.4).

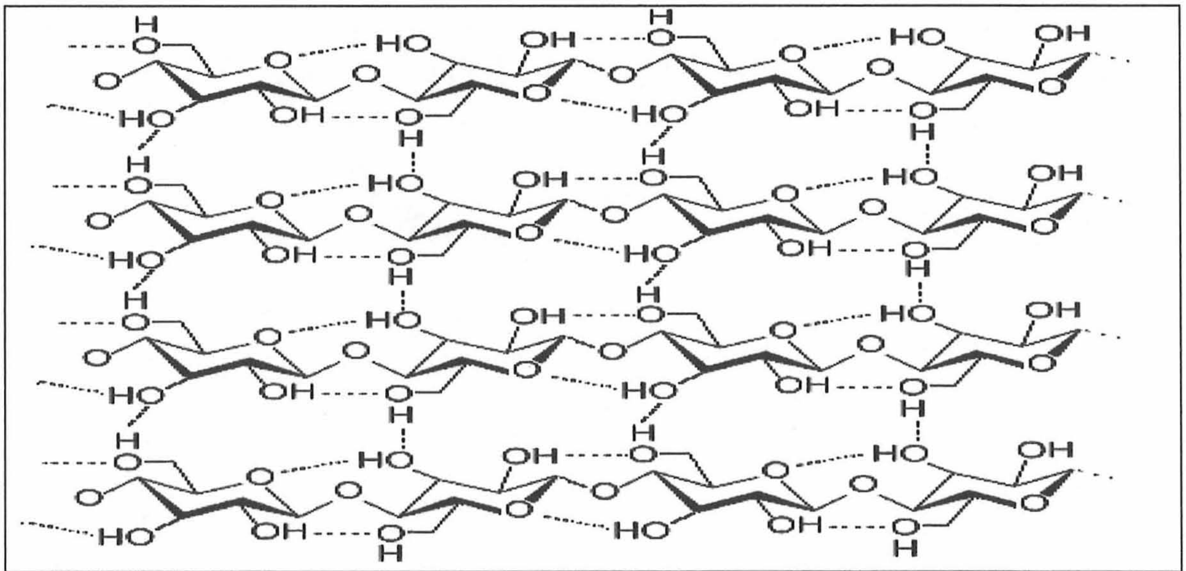

Figure 3.3 Molecular chained structure of cellulose.
Source: http://en.wikipedia.org/wiki/Lignin 2009

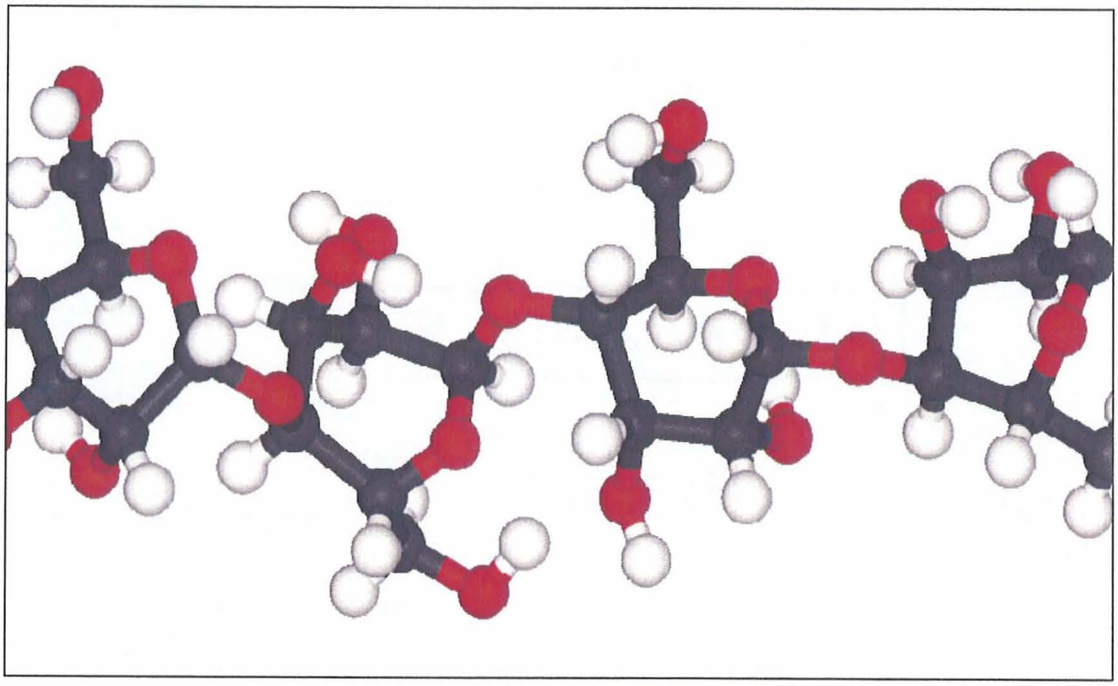

Figure 3.4 3-D image of molecular chained structure of cellulose.
Source: http://en.wikipedia.org/wiki/Lignin - Author Ben Mills April 2009

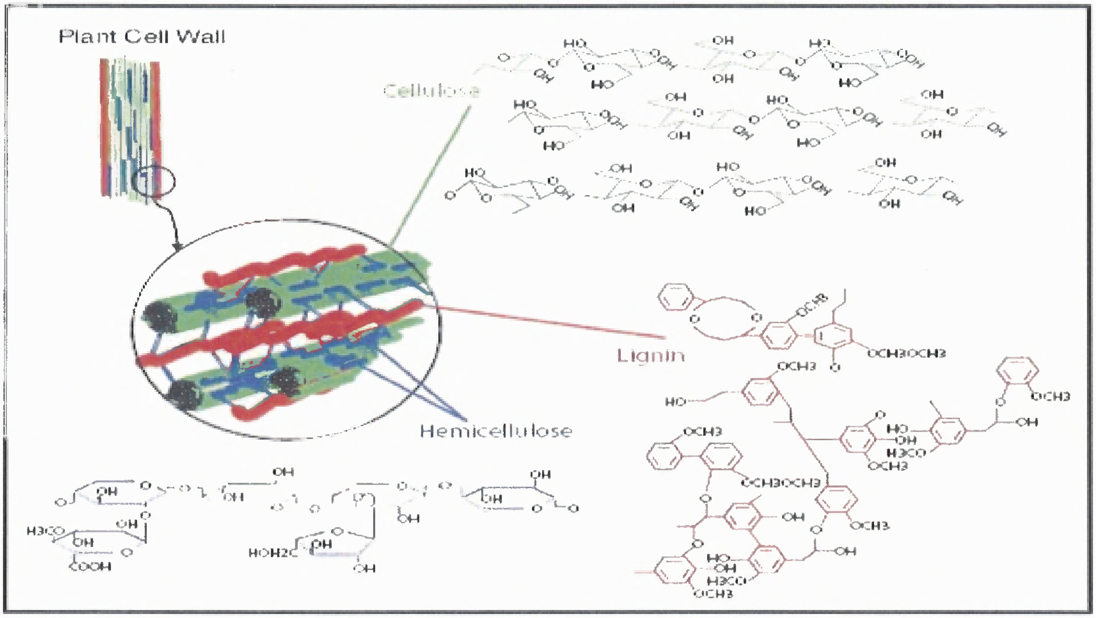

Figure 3.5 Lignocellulose constituents.
Source : (Sierra, Smith, Granda et al. 2008), Producing Fuels and Chemicals from Lignocellulosic Biomass, Chemical Engineering Progress, Friday, August 1 2008

The cellulose portion of the plant is surrounded by the hemicellulose portion which provides a transition link, in the form of chemical bonding, between the inner cellulose and the exterior lignin. The lignin portion of the structure accounts for the resistance of the plant to decay. Together these lignocelluloses constitute 97 to 99% of the total mass of dry woody material Boda, B., (2002), Szengyel, Zs et al (2000) and Fengel, Wegener, et al (1989). During decomposition of lignocelluloses, microorganisms produce cellulase and hemicellulase (enzymes) to hydrolyze the polysaccharide molecules into soluble sugars, which are then used as a food source by the microorganisms Godley, Lewin, Graham et al (2004).

The combination of molecules is chemically stable, insoluble, and responsible for the strength of the plant cell. It is the main component of plant cell walls, and is found within many textiles and paper products. The sugar units that make up the cellulose structure are linked in a chain by combining the -OH group and H ions. Cellulose is a polysaccharide produced by linking additional sugars to one another. Cellulosic materials tend to form a crystalline structure that contains less ordered areas that are "amorphous" and act as a separation within these crystalline areas. These amorphous areas are less resistant than the crystalline portions and represent the potential points for chemical and biochemical attack, Dorée et al. (1947), The Merck index (1968), and Bola, B. (2002).

Hemicellulose is another polysaccharide that serves as a bonding or linking material between the cellulose and the lignin. Hemicellulose is composed of carbohydrates based on pentose sugars, mainly xylose, as well as hexose sugars, such as glucose and mannose. Hemicellulose comprises 25 to 35 percent of the dry weight of wood materials (see Figure 3.5). Hemicellulose is second only to cellulose in abundance among carbohydrates. The hemicellulose serves in this manner due to its loose structure and high content of -OH and –COOH groups. Hemicelluloses are heterogeneous polymers of pentose (xylose, arabinose), hexose (mannose, glucose, galactose), and sugar acids. The hemicelluloses are very hydrophilic because of their chemical structure.

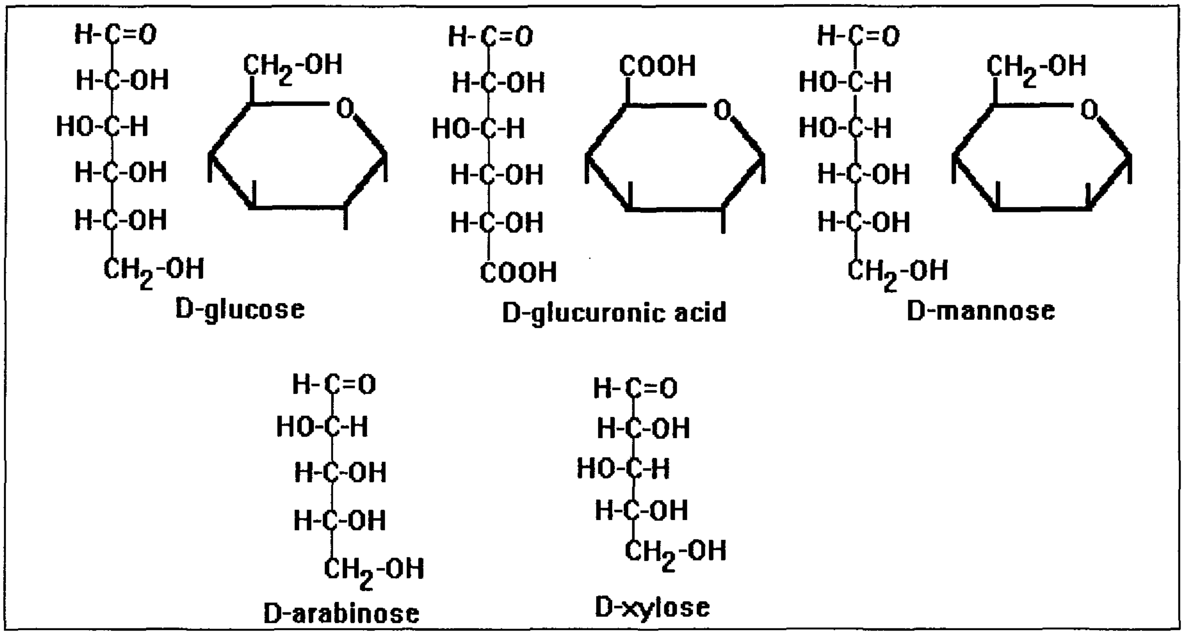

Figure 3.6 Structure of D-sugars forming hemicellulose molecules.
Source: www.cfs.purdue.edu/class/f&n630/pdfs/hemicellulose.pdf 2009

Lignin is a complex three-dimensional molecule that gives the wood fiber rigidity and enhances the plant's resistance towards microorganism attack while acting as a chemical adhesive joining the fibers together in the stem, Berggren R (2003). It is a macromolecule with covalent bonds and a very high molecular weight that makes up the secondary wall of a plant cell (see Figure 3.6).

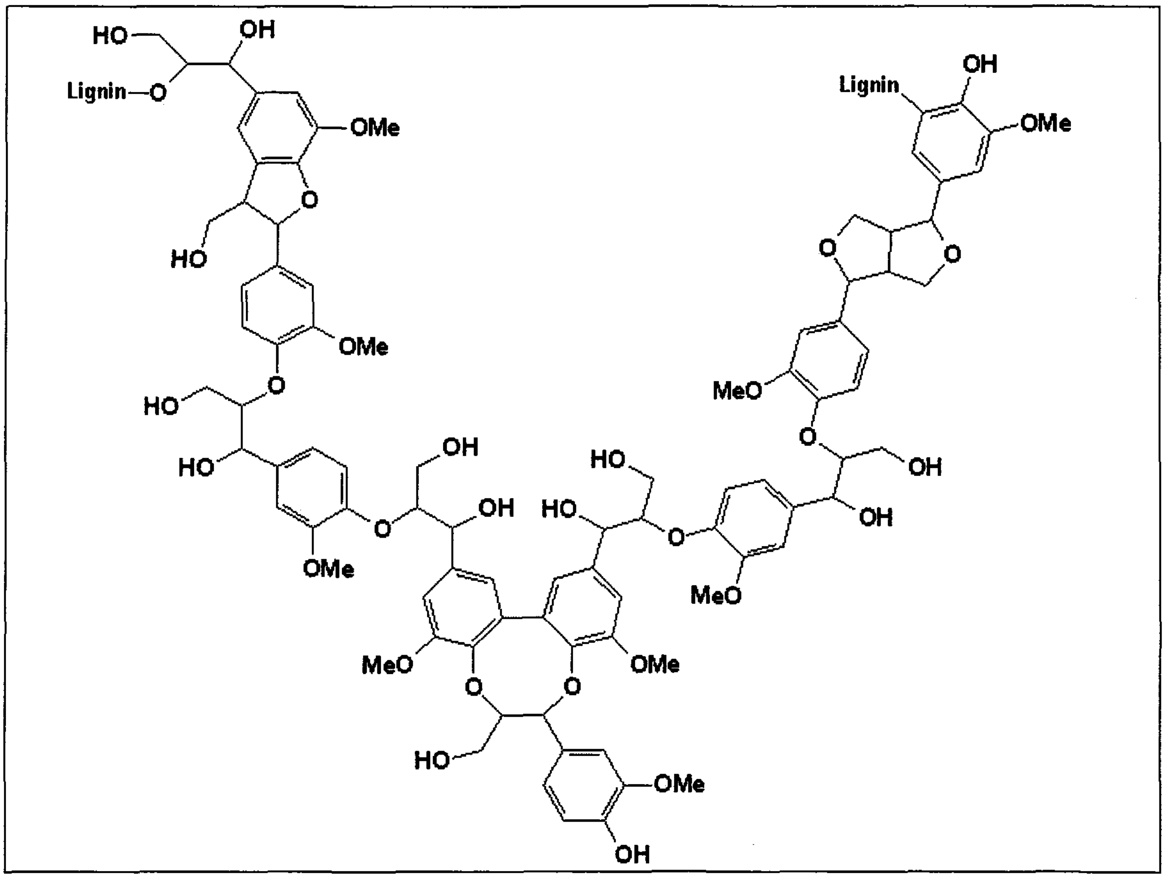

Figure 3.7 Typical structure of a small piece of a lignin molecule (Me is methanol).
Source: http://en.wikipedia.org/wiki/Lignin 2009

Lignin, is hydrophobic and serves as a water-proofing cover surrounding the cellulose material (Boda, B 2002). Lignin is very resistant to chemical and biological attack and constitutes 20 to 35% of typical woody materials. Lignin will only breakdown and decompose during the aerobic phase of decomposition and is very resistant to decomposition during subsequent anaerobic phases Ahmed et al (2001). The bioavailability of cellulose to decomposition is limited by the presence of lignin and is inversely proportional in that the larger the fraction of lignin present in the material the less cellulose will be available to decompose and form methane. Stinson J.

A., Ham R. K. et al (1995) state that the physical presence of the lignin, alone, inhibits the decomposition of the cellulose.

By utilizing the relative percentages of the cellulose, hemicellulose and lignin present in a refuse waste material, the (C + H)/L ratio of the material can be determined. This ratio will be shown to be a predictor of the settlement properties of the subject waste materials.

CHAPTER 4

TESTING PROGRAM AND RESULTS OBTAINED

4.1 Sample Preparation

Twenty four refuse samples were constituted and prepared in the laboratory. Each sample weighed two pounds and was composed of constituent percentages of a combination of municipal solid waste, construction and demolition debris, and cover material typical of northeastern NJ landfills. (Characterization Studies of Various Counties in Northern NJ, performed by PS&S Consulting Engineers 11/92, 2/93, 5/93, 7/93) shown in Figure 4.1.

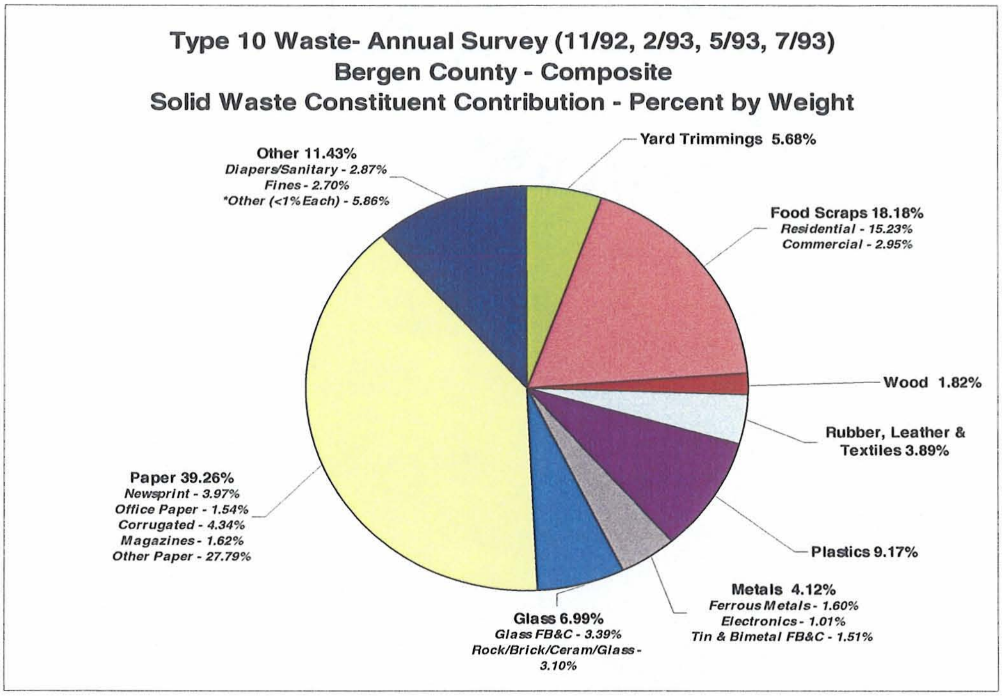

Figure 4.1 Composition of typical municipal solid waste in northeastern New Jersey.
Source: PS&S, LLC Report to Bergen and Union County Utilities Authority (1993)

Samples were prepared in accordance with the following generalized characterization constituents and percentages by weight shown in Table 4.1 and graphically in Figure 4.2 and photographically in Figure 4.3 below:

Table 4.1 Constituents in a Typical Northeastern New Jersey Municipal Solid Waste

Constituent	Weight in lbs	Percentage
Paper	18.38	38.30
Yard Waste	3.00	6.30
Wood	1.00	2.10
Metal	0.20	0.40
Plastic	6.00	12.50
Textiles	1.30	2.70
Glass	5.12	10.60
Food	9.00	18.80
Soil	4.00	8.30
Totals	48.00	100.00

Source: PS&S, LLC Report to Bergen and Union County Utilities Authority (1993)

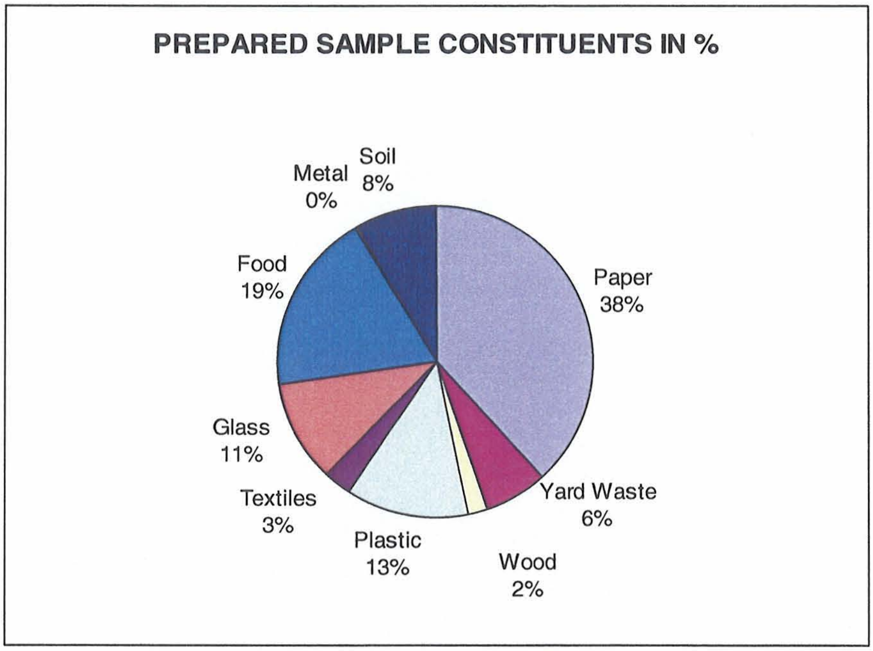

Figure 4.2 Constituents in a typical northeastern New Jersey municipal solid waste.
Source: PS&S, LLC Report to Bergen and Union County Utilities Authority (1993)

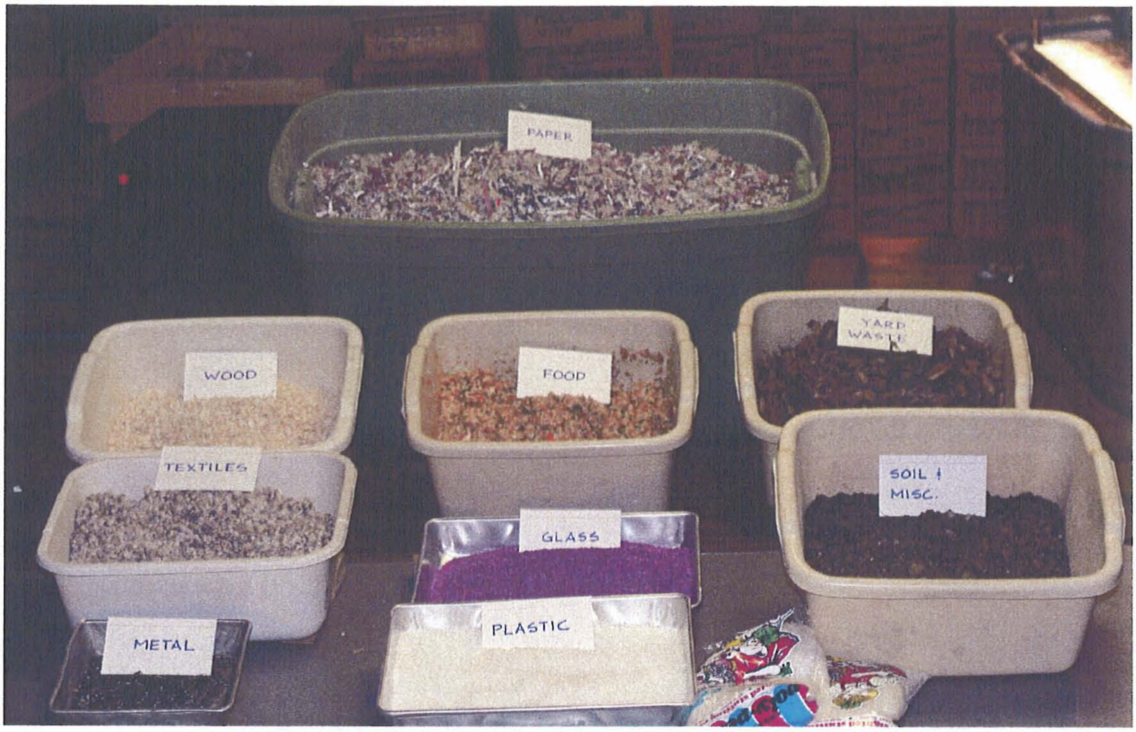

Figure 4.3 Components of municipal solid waste samples used for testing.

In order to ensure sample homogeneity, each of the eight constituents was divided into 24 parts by weight. One part from each of the eight constituent was then combined to make 24 separate representative MSW samples, each weighing two pounds. Eighteen of the 24 samples were subsequently placed into 18 bioreactors (Figure 4.4), submerged in a water bath (Figure 4.5) and kept at a constant temperature of 110 °F (43.3 °C, 316.3 °K), for enhanced biodegradation by mesophilic organisms, Tchobanoglous 1977, Barlaz, Ham and Schaefer (1989) and El-Fadil et al (1996), and subsequent testing. See Appendix A and Tables A.1 through A.4 for a record of temperature readings during testing. Prior to placement into the bioreactors the samples were moisture conditioned to achieve a targetedmoisture content of approximately 170 percent by weight, as shown in Table 4.2, to ensure that leachate is generated by exceeding the waste's field capacity and discussed by Barlaz, Ham and Schaefer (1989).

Figure 4.4 Assembled bioreactors used for composition of waste.

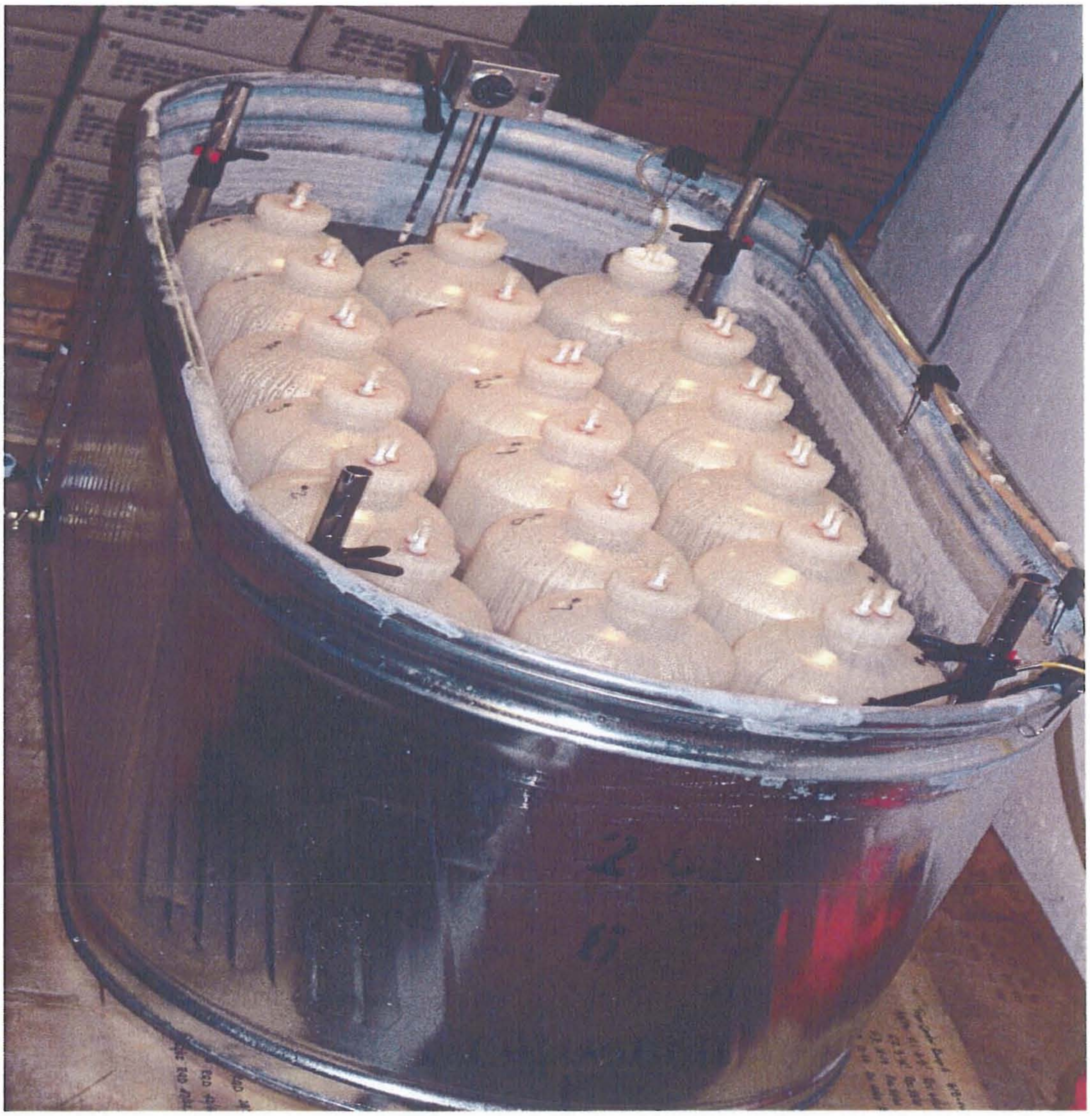

Figure 4.5 Bioreactors undergoing biodegradation in water bath.

Table 4.2 Moisture Content Determination in Solid Waste used for this Study

Solid Waste Study								
Moisture Content: Homogenized Solid Waste Samples								
Targeted Moisture Content of 170.0%								
Sample/Bag #	W. of Sample w/ Bag (lbs.)	W. of Bag (lbs.)	W. of Sample (lbs.)	** Initial Moisture Content	Dry W. (lbs.)	Dry W. x +/- 2.70 (lbs.)	W. Bag (lbs.)	W. of Sample @ 170% Moisture (Sample+Bag) (lbs.)
1	1.992	0.045	1.947	30.5%	1.492	3.879	0.045	3.925
2	2.018	0.045	1.973	27.2%	1.551	4.033	0.045	4.080
3	1.986	0.045	1.941	23.9%	1.567	4.073	0.045	4.120
4	2.015	0.045	1.970	27.0%	1.551	4.033	0.045	4.080
5	1.999	0.045	1.954	29.6%	1.508	3.92	0.045	3.965
6	1.998	0.045	1.953	22.8%	1.59	4.135	0.045	4.180
7	1.991	0.045	1.946	27.1%	1.531	3.981	0.045	4.025
8	2.003	0.045	1.958	32.6%	1.477	3.84	0.045	3.885
9	1.983	0.045	1.938	33.8%	1.448	3.766	0.045	3.810
10	2.004	0.045	1.959	32.0%	1.484	3.859	0.045	3.905
11	1.992	0.045	1.947	31.7%	1.478	3.844	0.045	3.890
12	1.998	0.045	1.953	22.1%	1.6	4.159	0.045	4.205
13	1.998	0.045	1.953	32.0%	1.479	3.847	0.045	3.895
14	1.989	0.045	1.944	28.4%	1.514	3.936	0.045	3.980
15	1.980	0.045	1.935	26.2%	1.533	3.987	0.045	4.030
16	1.989	0.045	1.944	38.5%	1.404	3.649	0.045	3.694
17	2.009	0.045	1.964	27.2%	1.544	4.015	0.045	4.060
18	1.986	0.045	1.941	30.7%	1.485	3.861	0.045	3.905
A*	1.330	0.045	1.285	31.7%	0.976	2.537	0.045	2.580
B*	1.325	0.045	1.280	28.4%	0.997	2.591	0.045	2.640
C	1.962	0.045	1.917	29.6%	1.479	3.846	0.045	3.900
D	2.004	0.045	1.959	35.6%	1.445	3.756	0.045	3.805
E	2.021	0.045	1.976	27.5%	1.549	4.029	0.045	4.075
F	1.995	0.045	1.950	20.6%	1.617	4.204	0.045	4.250
							**Avg. M.C. = 29.0%	

Eighteen separate samples were placed into 18; 8-L (2- Gallon) polypropylene mason jar reactors with sealed screw caps and allowed to decompose. The reactor jars were modified for installation of the following: a leachate collection port, a water inlet, and a gas collection port. Each port was fabricated to accept ¼" ID tubing. Gas was collected in Tedlar-like SKC sample gas bags fitted with a polymer shut-off valve. Leachate was collected in 10-L SKC sample bags. Assembled reactors were tested for leaks using a vacuum pump. A general overall description of the bioreactor bottle apparatus is shown in Table 4.3 and was obtained courtesy of Professor Barlaz of the University of North Carolina.

Table 4.3 Parts List for the Refuse Decomposition Bioreactors (Barlaz 2007)

Function	**Part Name**	**Part Number**	**Vendor**
Reactor Ports for Air and Liquid Flow	Nalgene barbed bulkhead fitting kits, 1/4" tubing ID	EW-06259-10	Cole-Parmer
Gas Bag	Tedlar, 2 mil, 24"x 24" (44L) with foil (LAM) cover, and with two fittings at opposite corners of a diagonal—one JACO polypropylene tube fitting (JACOP) and one JACO polypropylene fitting with septum installed. Also: one Luer Valve (LUER) installed in LAM cover only, but on the opposite surface (NCOR)		Pollution Measurement Corporation
Reactor	2-gallon polypropylene mason jar	71169	United States Plastic Corp.
Gas Bag valve	1/4-28 polymer shut-off valve	P-721A	Upchurch Scientific
Tubing	Tygon Lab Tubing 1/4" ID x 3/8" OD, 50 ft/pack	EW-06408-50	Cole-Parmer
Leachate Bag	Empty all-in-one EVA container with connector (2000 ml)	68000-580 (Baxter 2B8122)	VWR Scientific
Tubing Clamps	Herbie clamps	AA, B, and BB	Speedy Products
Fitting from Tubing to Gas Bag	Chrome-plated brass male quick-turn x barb, for 1/4" To 5/16" tube ID	51465K11 7	McMaster-Carr
Gas Bag valve	Female Luer to male threaded adapter	P-624	Upchurch Scientific
Leachate Bag	Nylon single barbed tube fitting reducing coupling for 1/4" X 3/16" tube ID	5463K152	McMaster-Carr
Tubing	Tygon Lab Tubing 3/16" ID x 5/16" OD, 50 ft/pack	EW-06408-03	Cole-Parmer
Tubing connector	Nylon single barbed tube fitting tee for 1/4" tube ID	5463K606	McMaster-Carr
Leachate Sampling Port	Nalgene single barbed tube fitting tee barb x male x barb for 1/4" tube ID, 1/8" NPT	5463K532	McMaster-Carr

Source: Personal Correspondence and Permission from Dr. Morton Barlaz University of North Carolina(2007)

The bioreactors were arranged in groups of three to minimize use of equipment and cost. The proposed arrangement is shown in Figure 4.6 below:

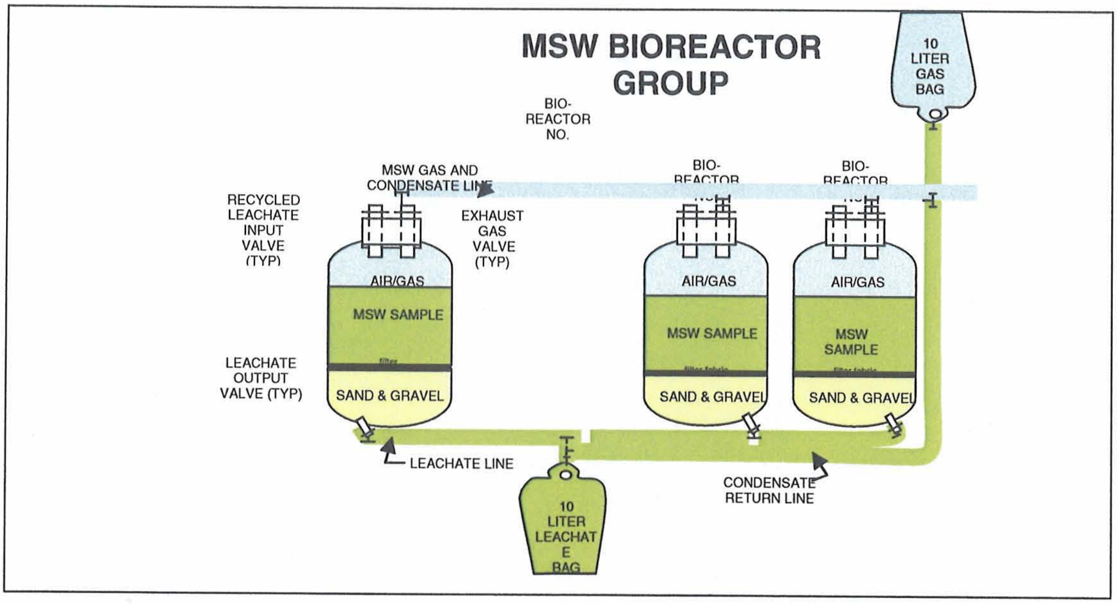

Figure 4.6 Line diagram of bioreactors subjected to biodegradation with gas collection unit.

The samples were initially charged with leachate from an existing landfill and were allowed to biodegrade/decompose over a period of 20 months. To enhance biodegradation decomposition, generated leachate was reintroduced into each sample bioreactor. Two jars were sampled consecutively on a bimonthly basis to obtain material for testing at different states of decomposition (see Table 4.4) and to provide repeatability of laboratory testing results in accordance with the following table:

Table 4.4 Sample Removal for Testing Schedule

Reactor	Date Scheduled to be Removed	Date Removed and Tested
Humus	12/18/2007	08/1/2009
A (LT)	12/12/2007	08/30/2009
A, B	12/12/2007	02/11/2008
1, 2	02/15/2008	04/17/2008
3, 4	04/20/2008	06/14/2008
5, 6	06/16/2008	12/05/2008
7, 8	08/15/2008	01/16/2009
9, 10	12/08/2008	05/17/2009
11, 12	01/21/2009	06/26/2009

During biodegradation of the MSW samples, gas was generated and collected from three bioreactors within one 30-liter SKC Sample Bag 232 Series. The volume collected over time was determined by visual methods using the recommended proper inflation diagram provided by the manufacturer of the bags and shown below in Figure 4.7:

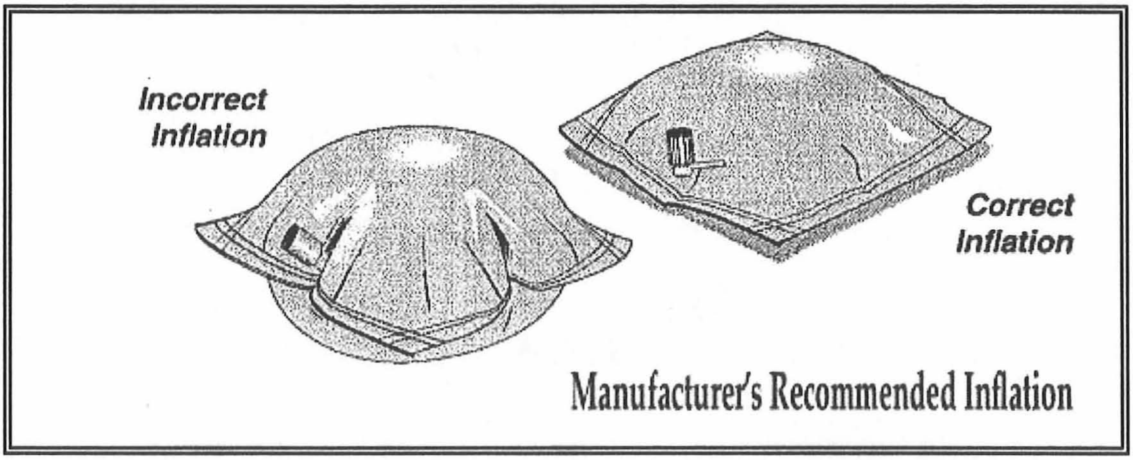

Figure 4.7 Manufacturer's recommended inflation for gas collection bags.
Source: SKC Sample Bag 232 Series Data Sheet

Once filled to proper volume, the date is recorded and the volume per bioreactor is determined, assuming each of the three bioreactors produced the same quantity of gas. The bags were then emptied and reattached for future volume measurements.

Immediately following the preparation of the samples for testing, Samples A, B, A (LT) and the humus sample were prepared and placed within an ELE / Soiltest Medium Capacity Consolidation Apparatus Frame (C-285) utilizing an ELE / Soiltest Fixed Ring Consolidometer (C-252) and allowed to consolidate at various pressures for a period of two months or as long as determined during testing to yield desired results. A sample of the refuse, Sample A (LT) and the typical humus compost sample were held for up to 22 months until the research testing was completed. As samples were removed from the bioreactors, they were placed inside one gallon zip-locked bags. Each sealed bag was rotated and shaken to ensure proper mixing and to maintain uniform moisture content. The sample was removed from each zip-locked bag and placed in loose 1/4 inch thick lifts inside the Consolidometer ring (approximately one tablespoon per lift). A hard rubber stopper with a diameter of slightly less than 2.5 inches (sample diameter) was then placed on top of each lift and tamped seven times with a 3.5 lb cylindrical weight dropped from a height of approximately one inch. The rubber stopper served to create a uniform / flat sample surface. This procedure was repeated until a compacted height of one inch was obtained after final trimming and cosmetic patching. (Typically six to seven loose lifts were required to attain a final compacted height of one inch). The Consolidometer ring, containing the compacted sample, was then weighed prior to assembly in the Consolidometer. Moisture content samples were obtained from the trimmings. The samples were then placed in the consolidometer and allowed to consolidate. Each sample was placed into the consolidometer and removed in accordance with the schedule shown in Table 4.4 above.

Consolidation parameters, C'_c, total secondary C'_α, C_β, $Secant_\beta$ and long-term residual tertiary $C_{\alpha\beta}$ values, for each waste sample collected were determined at its specific state of decomposition where possible. The initial settlement of the sample occurred very rapidly usually within two minutes of initial load placement. Creep rate values of secondary compression C'_α, rates of biodegradation decomposition, C_β, the Secant Modulus of Biodegradation $Secant_\beta$ and residual tertiary settlement, $C_{\alpha\beta}$, which are dependent upon the (C + H)/L ratio (state of decomposition of waste), were determined by holding the load for two to four months. In order to determine the (C + H)/L ratios, the samples were sent to the University of North Carolina laboratory (run by Dr. Barlaz and Laboratory Manager Mr. David Black) for analysis. The procedure for this test is presented elsewhere in this work.

4.2 Laboratory Data Results

Utilizing the manufacturer's diagram for proper bag inflation, shown on Figure 4.7, the quantity of gas from each set of three bioreactors was determined. A value of produced gas for an individual bioreactor was determined by dividing by three, the number of bioreactors attached to each SKC sample bag. As bioreactors were removed for (C + H)/L and consolidation testing the measured quantity of gas was then divided by the appropriate number of remaining bioreactors to obtain the value of gas produced for each of the remaining or individual bioreactors.

The manufacturer of the SKC sample bag 232 Series recommends that the proper bag inflation configuration, shown on Figure 4.7, represents 80 % of the maximum bag volume. According to the manufacturer, the rated capacity of the bag is the maximum bag volume. During this experiment a ten liter and a 30 liter bag were used. This means that at the proper inflation recommended by the manufacturer, each bag would retain a volume of eight and 24 liters, respectively.

The following Table 4.5 is a log of the observed gas volumes produced by the set of bioreactors cells composed of Jars 16, 17 and 18. These were chosen for display since they would be the last to be removed and most representative of undisturbed longer term decomposition for the waste tested. The table shows the date the gas was released, the cumulative numbers of days from initial waste placement, the bag designation, jar set numbers, volume of gas within each bag, volume of gas produced by each bioreactor cell jar, cumulative gas produced by each bioreactor cell jar and any notes that may be pertinent.

Table 4.5 Observed Gas Volumes Bioreactor in Cell Jars 16, 17, and 18

Date	Cum. No. of Days	Bag No.16, 17,18 (Vol)	Jar No.	# of Jars	Vol. of Bag	Act. Vol. of Gas/bag	Vol. of Gas/Jar	Vol. of Gas/Jar /lb	Cum. Vol of Gas/Jar	CumVol. of Gas/lb of MSW	Gas Remaining	Daily Vol. of Gas/Jar	Daily Vol. of Gas/lb of MSW
						liter	liter	ft³/lb	liter	ft³/lb		liter	ft³/lb
12/20/2007	7	(10 L)	16 17, 18	3	10	8	2.67	0.047	1.33	0.047	6.143		
12/24/2007	11			3	10	8	2.67	0.047	1.33	0.094	6.096	0.67	0.012
12/26/2007	13			3	10	8	2.67	0.047	1.33	0.141	6.049	1.33	0.024
12/28/2007	15			3	10	8	2.67	0.047	1.33	0.188	6.002	1.33	0.024
12/31/2007	18			3	10	8	2.67	0.047	1.33	0.235	5.955	0.89	0.016
1/2/2008	20			3	10	8	2.67	0.047	1.33	0.282	5.908	1.33	0.024
1/7/2008	25	(30 L)	16 17, 18	3	30	24	8.00	0.141	4.00	0.424	5.766	1.60	0.028
1/11/2008	29			3	30	24	8.00	0.141	4.00	0.565	5.625	2.00	0.035
1/18/2008	36			3	30	24	8.00	0.141	4.00	0.706	5.484	1.14	0.020
1/22/2008	40			3	30	24	8.00	0.141	4.00	0.847	5.343	2.00	0.035
1/28/2008	46			3	30	24	8.00	0.141	4.00	0.989	5.201	1.33	0.024
2/4/2008	53			3	30	24	8.00	0.141	4.00	1.130	5.060	1.14	0.020
2/11/2008	60			3	30	24	8.00	0.141	4.00	1.271	4.919	1.14	0.020
2/17/2008	66			3	30	24	8.00	0.141	4.00	1.412	4.778	1.33	0.024
2/23/2008	72			3	30	24	8.00	0.141	4.00	1.554	4.636	1.33	0.024
3/1/2008	79			3	30	24	8.00	0.141	4.00	1.695	4.495	1.14	0.020
3/7/2008	85			3	30	24	8.00	0.141	4.00	1.836	4.354	1.33	0.024
3/14/2008	92			3	30	24	8.00	0.141	4.00	1.977	4.213	1.14	0.020
3/21/2008	99			3	30	24	8.00	0.141	4.00	2.119	4.071	1.14	0.020
3/28/2008	106			3	30	24	8.00	0.141	4.00	2.260	3.930	1.14	0.020
4/4/2008	113			3	30	24	8.00	0.141	4.00	2.401	3.789	1.14	0.020
4/11/2008	120			3	30	24	8.00	0.141	4.00	2.542	3.648	1.14	0.020
4/19/2008	128			3	30	24	8.00	0.141	4.00	2.684	3.506	1.00	0.018
4/26/2008	135			3	30	24	8.00	0.141	4.00	2.825	3.365	1.14	0.020
5/5/2008	144			3	30	24	8.00	0.141	4.00	2.966	3.224	0.89	0.016
5/14/2008	153			3	30	24	8.00	0.141	4.00	3.107	3.083	0.89	0.016
5/22/2008	161			3	30	24	8.00	0.141	4.00	3.249	2.941	1.00	0.018
5/30/2008	169			3	30	24	8.00	0.141	4.00	3.390	2.800	1.00	0.018
6/9/2008	179			3	30	24	8.00	0.141	4.00	3.531	2.659	0.80	0.014
6/23/2008	193			3	30	24	8.00	0.141	4.00	3.672	2.518	0.57	0.010
7/11/2008	211			3	30	24	8.00	0.141	4.00	3.813	2.377	0.44	0.008
8/5/2008	236			3	30	24	8.00	0.141	4.00	3.955	2.235	0.32	0.006
9/8/2008	270			3	30	24	8.00	0.141	4.00	4.096	2.094	0.24	0.004
2/15/2009	430			3	30	24	8.00	0.141	4.00	4.237	1.953	0.05	0.001

Figure 4.8 is a graph comparing time, in number of days of decomposition, to the gas produced per pound of MSW, for bioreactor cell jars 16, 17 and 18, on a cumulative basis.

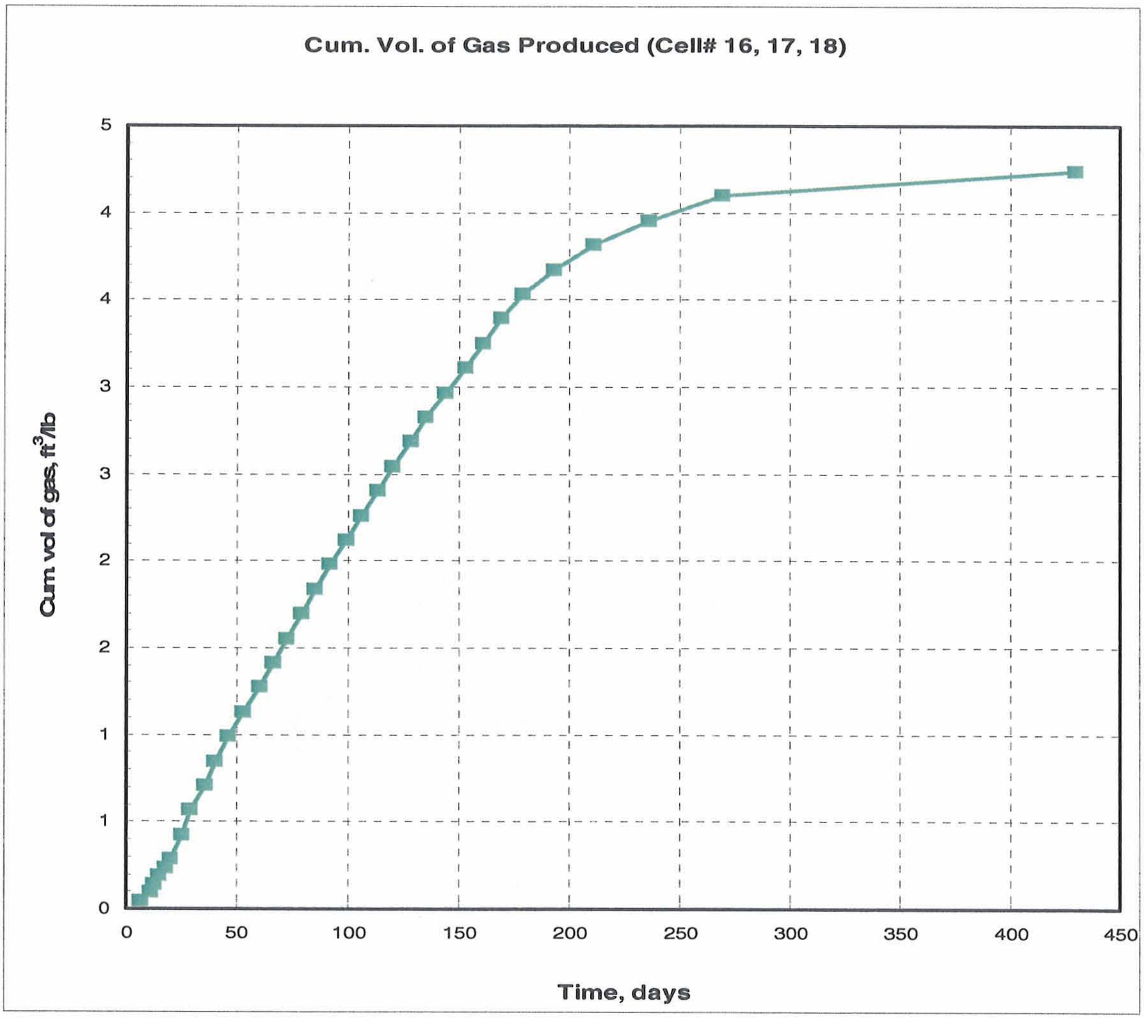

Figure 4.8 Cumulative volume of gas in cubic feet / lb of MSW.

Figure 4.9 and 4.10 represent a series of best-fit graphs depicting the daily volume of gas produced in ft^3 per pound of MSW versus the time in days from bioreactor cells 16, 17 and 18. Leachate was recycled on an approximate monthly basis. The schedule of leachate recycling is shown in Appendix A. The spikes in the gas production roughly correspond to leachate recycle recharging of the bioreactors. The area under the curves represent the total volume of gas produced which can be determined graphically or by integration of the respective formulae between corresponding time limits in ten (10) day intervals.

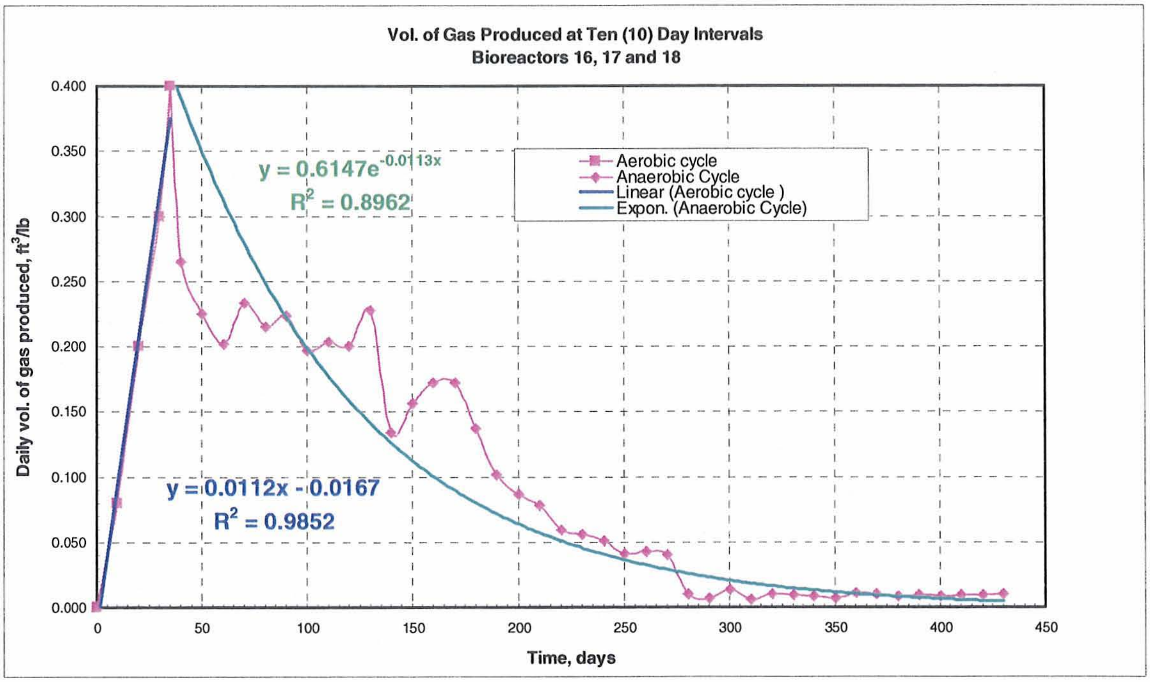

Figure 4.9 Daily volume of gas produced in Cells 16, 17 and 18.

In Figures 4.9 and 4.10, duration limits, in days, for each phase of degradation were selected by visually inspecting the graphs and directly reading the corresponding time where distinct gas graph ranges begin and end. The values of k_1, k_2, and k_3 are then determined by a best fit exponential matching of the distinct regions of the gas production curve. In Figures 5.2 and 5.3 three regions require best fit matching.

These time durations are the durations in which the occurrence of degradation of a particular type of waste dominates. For instance, during the period from 35 days (t_1) to 60 days (t_2), most of the waste that decomposes belongs to the category of readily decomposable type. For the waste tested, the values for the "k_n" modifiers were determined to be 0.0823 for k_1 (readily biodegradable), 0.0084 for k_2 (moderately biodegradable) and 0.0049 for k_3 (slowly biodegradable). These descriptive modifiers are similar to those developed by Findikakis et al (1979) and are utilized here to bracket the ranges unique to each specific range. These values, although specific to the waste tested, were not used in lieu of the values presented by Findikakis (1979) because the values were obtained from visual estimates of gas produced and not from a program of rigorous measurement methods.

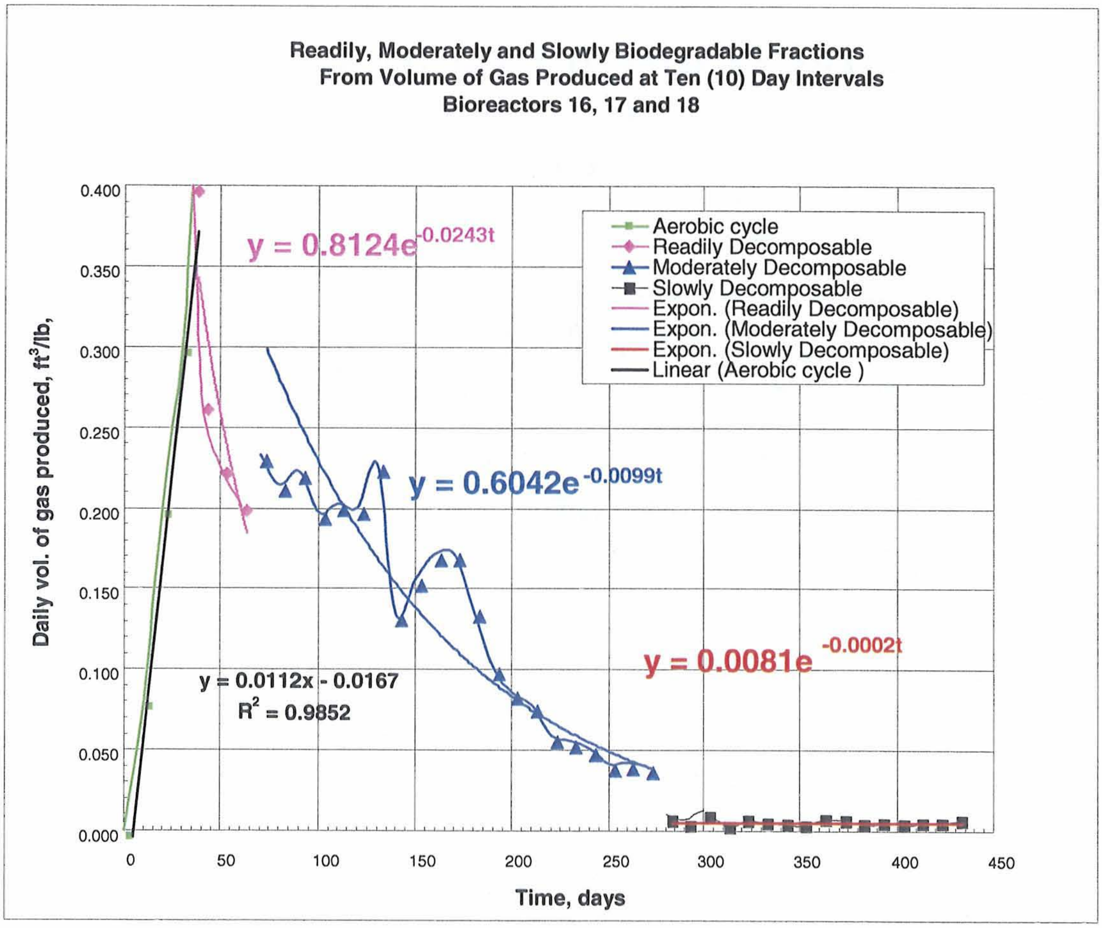

Figure 4.10 Determinations of Coefficients for the Descriptive Modifiers k_n.

Figure 4.10 shows a straight line followed by three exponentially decreasing curves, similar to the patterns shown by Raghu and Gausconi (2002).

The equations for the straight line and the exponential curves were obtained by curve fitting and are presented below.

For the straight line portion of the graph which represents day zero to day of maximum daily volume production, (35 days) equation 4.1 is obtained.

$$V_t = (0.0112*t) - 0.0167 \qquad (4.1)$$

where V_t is the daily gas production in ft^3 of waste per lb per day. The value for t is the time in days that has elapsed after the beginning of gas production.

The post peak production throughout the range within which k_1 governs (i.e., within the readily decomposable waste range, t_{rd}, 35 days through 60 days), the daily gas volume production can be given as,

$$\text{Readily Biodegradable daily volume} = 0.8124*e^{-q} \qquad (4.2)$$

where, q is equal to k_1t_{rd}, t_{rd} is the time in days at which daily gas production is desired, and k_1, k_2... k_n are best fit exponential matches for each distinct region of the biodegradation gas production curve (from Figure 4.10 $k_1 = 0.0243$, $k_2 = 0.0099$, and $k_3 = 0.0002$) and is obtained by solving for ln(y) and plotting this value vs. time arithmetically. The values of k_n are the same as those shown as the exponent of the log function depicted on Figure 4.10.

Similarly within the moderately, t_{md}, and slowly decomposable, t_{sd}, time ranges (i.e., throughout the range within which k_2 governs, 60 to 270 days or throughout the range within which k_3 governs, 270 days to end of testing), the daily gas volume production can be given as:

$$\text{Moderately Biodegradable daily volume} = 0.6042 * e^{-r} \tag{4.3}$$

where, r is equal to k_2t_{md}, t_{md} is the time in days at which daily gas production is desired within the moderately biodegradable time range. For slowly decomposable:

$$\text{Slowly Biodegradable daily volume} = 0.0081 * e^{-s} \tag{4.4}$$

where, s is equal to k_3t_{sd}, t_{sd} is the time in days at which daily gas production is desired within the slowly biodegradable time range. The values for k_2 and k_3 are the best fit exponential matches obtained from the testing.

To determine the total volume of gas produced per lb of waste, the above formulae may be integrated from time zero to the time at the end of gas production.

4.3 Laboratory Analytical Procedure for Determination of (C + H)/L

The following laboratory procedures and analysis for the determination of the cellulose, hemicellulose and lignin content of the refuse waste material was provided by Professor M.A. Barlaz of the Department of Civil, Construction, and Environmental Engineering, North Carolina State University and is presented verbatim in Table 4.6, as received from Professor Barlaz. Professor Barlaz and his assistant Mr. David Black performed the biological laboratory analysis of the (C + H)/L ratios and the Biological Methane Production (BMP) on the samples of refuse waste from this research experiment which is being used to determine the settlement properties of the tested waste material at various values of the (C + H)/L ratio of the waste and to determine when the samples have reached the point at which further decomposition is no longer practical.

Table 4.6 Laboratory Procedures and Analysis for the Determination of the Cellulose, Hemicellulose and Lignin Content of Refuse

"Cellulose Hydrolysis Methodology"

The complete analysis of cellulose and hemicellulose involves three distinct steps; hydrolysis, sample cleanup and High Pressure Liquid Chromatography (HPLC) analysis, published in 1991 by Petterson and Schwandt (Petterson, R.C., Schwandt, V., 1991 "Wood sugar analysis by anion Chromatography" J. Wood Chem. Technol. 11, 495–501) and subsequently updated by Davis in 1998 (Davis, M.W., 1998. "A rapid modified method for compositional carbohydrate analysis of lignocellulosics by high pH anion-exchange chromatography with pulsed amperometric detection" (HPAEC/PAD). J. Wood Chem. Technol. 18 (2), 235–252.). Conceptually, samples of refuse that have been ground to pass a 1 mm screen are subjected to an acid hydrolysis. During hydrolysis, cellulose and hemicellulose are converted to their monomeric sugars glucose, xylose, mannose, arabinose and galactose, which are quantified by HPLC. The glucose originates from cellulose and the other sugars from hemicellulose. The refuse that remains includes lignin, other organics that do not dissolve in 72% sulfuric acid, and inorganics. The lignin content is calculated as the weight loss after combustion, at 550°C, of the solids that remain after refuse hydrolysis. The acid hydrolysate, which contains the monomeric sugars, is cleaned prior to injection into an HPLC equipped with a pulsed amperometric detector. This method assumes that all non-cellulosic organic material is lignin, which is not perfectly accurate. Plastics and rubber are likely to be counted as lignin in this technique.

The values obtained by HPLC analysis must be corrected to account for the fact that sugars were originally in polysaccharide chains, and therefore each resulting sugar molecule is, on average, 18 mass units heavier (one H_2O molecule added for every sugar molecule in the polymer)."

"Refuse Hydrolysis Procedure:

The methodology for cellulose/hemicellulose hydrolysis given below is a modification of a procedure developed by Petterson R.C. and Schwandt V (USDA's Forest Products Laboratory, Madison, WI) 1991. "Wood sugar analysis by anion chromatography" J. Wood Chem. Technol. 11, 495–501.

1. The procedure begins with samples that have been ground in a Wiley mill to pass a 1mm screen. If the dryness of a ground refuse sample is suspect, then re-dry it for one day in a 65°C oven. To re-dry ground refuse samples in Mason jars, do the following: Remove the jar lid and cover the mouth of the jar with aluminum foil. Replace the threaded outer ring. Using a disposable 18-gauge needle, punch lots of holes in the aluminum foil. Put the jar into a 65°C oven for at least one day. When the refuse is dry, remove the jar from the oven. Work quickly, as the dried refuse will immediately begin to absorb moisture from the air. Unscrew the threaded outer ring and replace the aluminum foil with the metal lid. Replace the threaded outer ring, screwing it down tightly.

2. Prepare Gooch crucibles and filters by inserting a glass fiber filter (Whatman 934AH) into a crucible. Rinse the crucible with de-ionized water and place the crucible and filter in the furnace at 550°C for one hour. Allow crucibles to cool in a desiccator. After cooling, store the crucibles in a place where they will be protected from dust and dirt. A clean box with a secure lid, or a tray lined with paper towels and covered with aluminum foil, is ideal for this purpose. NOTE: Once crucibles have been cleaned in this way; do NOT handle them with your fingers; use tongs or a clean gloved hand only.

3. Place approximately 1 gram of sample in a Gooch crucible with the fiber filter and wash with 150 ml of a 2:1 mixture of toluene and 95% ethanol. Use a filter flask, with a vacuum aspirator to provide suction. This step must be performed in a fume hood and the toluene/ethanol collected and disposed of as hazardous waste.

4. Dry the refuse in the crucible at 75°C for at least 12 hours and then allow to cool 2 hours in a desiccator. Carefully stir the refuse approximately 6 hours into the drying time.

5. Remove about 0.3 gram of washed refuse from the crucible and place it in a screw-cap test tube. Record the weight of refuse removed to 4 decimal places. When weighing, work quickly and with one crucible at a time because the dried solids will immediately begin to absorb moisture from the air upon removal from the desiccator.

Add 3 ml of 72% (w/w) sulfuric acid to the sample. Using a long glass stirring rod, carefully mix the refuse and acid, trying to avoid splashing the slurry onto the walls of the tube (the objective is to have the solids in the acid and not clinging to the sides of the test tube). After mixing, leave the stirring rod in the test tube. Then place it in a shaking water bath at 30°C for 1 hour, agitating gently.

Use a graduated cylinder to measure 63ml of high purity water and pour into each test tube.

Prepare a fucose solution to serve as an internal standard. Weigh 1g of fucose and dilute to volume with de-ionized water in a 25ml volumetric flask. Record the weight to 4 decimal places. Using a calibrated automatic pipettor add 1.0 ml of the fucose solution into the tube. NOTE: Immediately proceed to the next step. Do not allow the fucose to remain in contact with the strong acid longer than necessary; otherwise the fucose recovery may be abnormally low. Analyze the fucose stock solution diluted 1/20 as a check. Note that a fresh fucose solution should be prepared daily.

Use a graduated cylinder to measure 20 ml of high purity water. Attach a 20 gauge disposable needle to a 20 ml syringe and draw up the 20 ml of water. Use the glass rod to thoroughly stir the mixture. Lift up the stirring rod and use about half of the water in the syringe to rinse the solids off the rod and back into the test tube. Touch the glass rod to a clean part of the test tube's inner wall to allow the excess water to drain off. While rotating the test tube, use the syringe's remaining water to rinse down the walls of the test tube. Seal the test tube with a #6 silicone stopper (Thomas Scientific P/N 8747-E65). Secure the stopper with an appropriate screw cap— tighten it firmly but avoid over tightening.

Place the test tube in an autoclavable tray and autoclave for 60 minutes at 121°C and 15 psi. After the autoclave cycle is complete, do not leave the samples in the autoclave; remove samples as soon as the autoclave indicates that it is okay to remove them (but no sooner). The autoclave remains hot even when not in use, and leaving the samples in it longer than necessary causes some wood sugar destruction. Place the rack in an undisturbed place and allow the tubes to cool.

Filter the sample through a glass fiber filter in a Gooch crucible (as prepared in step 2). Use a filter flask, with a vacuum aspirator to provide suction. Transfer the filtrate to a plastic bottle and store it in the refrigerator. Wash the rest of the solids out of the test tube and into the crucible with a squirt bottle of de-ionized water while the tube is inverted over the crucible. Continue rinsing until at least 200 ml of wash water has been collected in the filter flask. Note that the water rinse serves two purposes— it facilitates transfer of the solids from the test tube to the crucible, and it washes the solids (getting rid of the sulfuric acid that would interfere with the lignin analysis).

Dry the remaining solids in the crucible at 75°C for at least 24 hours, then allow 2 hours to cool in a desiccator. Then, weigh the crucible and dried solids to 4 decimal places. When weighing, work quickly and with one crucible at a time because the dried solids will immediately begin to absorb moisture from the air upon removal from the desiccator.

Place the Gooch crucible containing the solids in a 105°C furnace. Increase the furnace temperature to 550°C. Allow the furnace to remain at 550°C for 2 hours, and then reduce the temperature to 105°C. After the oven cools to 105°C, remove the Gooch crucible and allow 2 hours to cool in a desiccator.

Weigh the crucible again. When weighing, work quickly and with one crucible at a time because the dried solids will immediately begin to absorb moisture from the air upon removal from the desiccator. The weight loss on ignition represents lignin."

"Hydrolysate Clean-Up Procedure:

1. Remove the hydrolysis sample from the refrigerator and allow it to equilibrate to room temperature. Shake the bottle gently to help ensure a homogeneous mixture. Avoid vigorous shaking, as this will tend to produce foam. NOTE: If the sample was frozen it is absolutely essential that it be shaken very well after thawing. Failure to do so will result in the sugars being concentrated at the bottom of the bottle, resulting in an abnormally low fucose recovery.

Weigh out 1.98 g of barium hydroxide octahydrate (Ba(OH)2*8H2O) into a 50 ml plastic centrifuge tube. Using a graduated cylinder for measuring, pour 16 ml of hydrolysate into the centrifuge tube. Cap the tube tightly and vortex at high speed (setting ~6) until the crystals of barium hydroxide dissolve. The solution will become milky white due to the formation of insoluble barium sulfate, which can make the undissolved crystals harder to see. When you can no longer see barium hydroxide crystals on the bottom of the tube, this step is complete.

Centrifuge for 10 minutes at 3,500 rpm. When centrifugation is complete, handle the tube(s) carefully to avoid disturbing the white precipitate of barium sulfate.

Step 4 is only required for an HPLC system without a guard column

Condition a Maxi-Clean C18 cartridge (Alltech P/N 20934) by forcing 10 ml of methanol through it with a syringe (preferably glass). Then force 10 ml of ultrapure de-ionized water through the cartridge with a syringe.

NOTE #1: DO NOT squirt the liquids through the cartridge or the preperation procedure will be ineffective; the liquid should exit the bottom of the cartridge as discrete drops.

NOTE #2: After the last of the water has entered the cartridge do NOT force air into the cartridge and don’t let it dry out. One way to ensure this is to fill the syringe with water to about 0.5 cm above the 10 ml mark and depress the plunger only to the 1 ml mark; then remove the cartridge and continue with the rest of the procedure.

5. Remove the plunger from a 20 ml plastic disposable syringe. Attach a 0.2 micron syringe filter (Acrodisc PF, Fisher P/N 09-730-242) to the outlet of the cartridge.

6. Carefully, so as to avoid disturbing the precipitate, pour the sample into the syringe barrel. Insert the plunger and force the sample through the filter into a 20ml plastic scintillation vial. Samples should be kept frozen until ready for analysis.

7. Prepare a 1/20 dilution of the purified hydrolysate by pipetting1 ml into a 10 ml volumetric and diluting to volume with de-ionized water. Note: Different dilutions may be necessary based upon the concentrations of your samples and the range of your standard curve. The samples may first be analyzed full strength, and the appropriate dilutions determined empirically.

8. Fill 5 ml "Poly Vial" auto sampler vials (Dionex P/N 20933*) with pure hydrolysate and the diluted hydrolysate with one vial per solution.

9. Cap the vials with "Poly Vial" filter caps (Dionex P/N 20934*) by inserting them until the top of the slotted cap rim is flush with the mouth of the vial (i.e., room is left for expansion). Insert filled vials into an auto sampler cassette and store in the freezer until use.

10. Store leftover, undiluted hydrolysate in the freezer. Dump unused, diluted

hydrolysate into the waste bottle.

* Can be ordered together as Dionex P/N 38141"

Source: Personal Correspondence and Permission from Dr. Morton Barlaz University of North Carolina (2007):

4.4 Evaluation of Laboratory Testing Results

4.4.1 Determination of End of Primary Compression

Figure 4.11, shown below, shows a plot of the strain deformation versus the square root of time so that a construction, in accordance with Taylor's method, can be made to determine the value corresponding to completion of primary compression (t_{90}) for Sample A (LT) at a selected loading increment of 2.56 tsf. Although Taylor's method is not appropriate for material exhibiting significant secondary effects, it approximates the end of primary settlement where the initial straight line portion of the deformation curve ends. Therefore t_{90} using Taylor's method is assumed to be the end of primary settlement for the purposes of this study. The log fitting method to determine t_{100} was not utilized because the primary compression occurs very rapidly within the laboratory and this portion of the strain-time curve cannot be constructed which would yield meaningful results. In addition, the author reviewed plots of settlement versus time for five extensometers placed at a landfill site in northern New Jersey that had undergone dynamic compaction treatment and soil land filling to raise grade. The results are shown in Appendix C and indicate that no clear primary compression phase could be observed following filling. Graphical construction within the inorganic secondary settlement range of the curves indicates that the observed C'_α parameter ranged from 0.0018 to 0.0039 averaging 0.0030.

The author opines that the proper procedure to establish the actual end of primary in the field is to install piezometers within the waste and determine the time at which the excess pore pressures dissipate. The graph shown below is for Sample A (LT) at a loading increment of 2.56 tsf. The value for t_{90} in this and all cases for this sample is less than four minutes. This indicates that for this sample and for all the others tested the "primary compression" occurs in less than four minutes so that the initial slope observed on the % strain versus time plots, shown in Figures 4.13, 4.14, and 4.15 represents "secondary compression or C'_α. Evaluation of the field time for end of primary compression will be discussed in section 5.3.

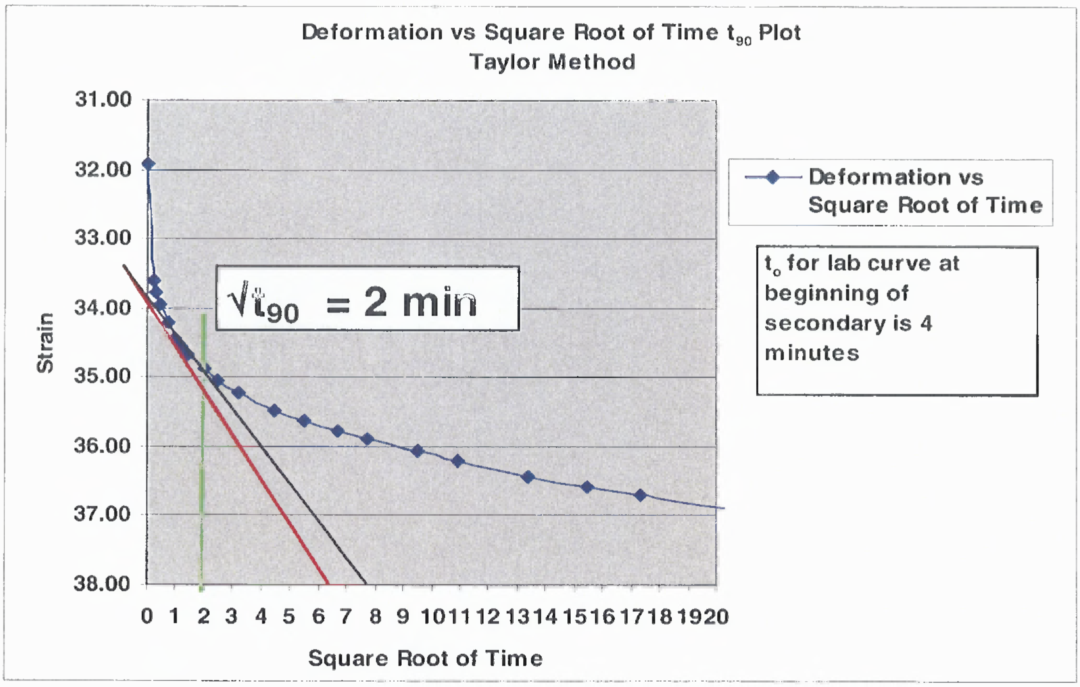

Figure 4.11 Square root of time method for t_{90}.

4.4.2 (C + H)/L and Its Relationship with the Phases of Compression

Table 4.7 shown below, depicts the values of (C + H) / L for samples tested to date. Most of the column headings are self explanatory except for the one labeled "RPD" which stands for the Relative Percent Deviation and is defined as "the Standard Deviation divided by the Average times 100".

In this section, the relationship between (C+H)/L and various phases of compression will be discussed. Based on this discussion, a methodology for determining the time of the start and the end of biodegradation (C_β) phase will be presented.

Table 4.7 Laboratory Testing for Cellulose + Hemicellulose over Lignin

							% Cellulose		% Hemi - cellulose	
Sample ID	NCSU Lab #	Sample Date	W before grinding	Ungrindables	% Ungrindables	% H_2O	Avg.	RPD	Avg.	RPD
Solid Waste Sample A	07-188	12/4/07	-	0.0	0.00	**	54.11	1.5%	10.94	4.3%
Solid Waste Sample B	07-189	12/4/07	-	0.0	0.00	**	48.13	2.5%	9.46	3.4%
Cell #1	08-183	2/15/08	105.8	0.0	0.00	61.5	35.24	10.1%	6.83	7.6%
Cell #2	08-184	2/15/08	114.9	0.0	0.00	57.3	37.78	6.3%	7.22	4.9%
Sample #3	08-807	12/14-07 - 4/17/08		0.0	0.00	**	16.44	5.2%	3.90	4.5%
Sample #4	08-808	12/14-07 - 4/17/08		0.0	0.00	**	25.27	1.9%	5.58	1.8%
Sample Cell #5	08-1109	6/9/08		0.0	0.00	**	15.96	1.0%	4.54	1.4%
Sample Cell #6	08-1110	6/9/08		0.0	0.00	**	15.17	11.3%	4.05	10.7%
Cell #7	08-1777	12/14/08-8/12/08	105.8	0.8	0.8%	**	9.65	5.5%	3.39	1.5%
Cell #8	08-1778	12/14/08-08/12/08	114.9	0.8	0.7%	**	12.86	14.9%	4.35	11.1%
Cell #9	08-2297	12/14/07-12/4/08		0.0	0.00	**	6.53	0.5%	2.25	1.9%
Cell #10	08-2298	12/14/07-12/4/08		0.0	0.00	**	8.28	7.5%	2.92	4.1%
Sample #11	09-72	12/14/07-01/13/09		0.0	0.0%	**	7.88	21.9%	2.88	21.4%
Sample #12	09-73	12/14/07-01/13/09		0.0	0.0%	**	7.27	6.0%	2.57	11.0%

Source: N.C. State University Department of Civil, Construction, and Environmental Engineering

Table 4.7 Continued Laboratory Testing for Cellulose + Hemicellulose over Lignin

	% Lignin		% Organic Solids		% Lipophilic Extractives		(C + H)/L/VS	(C + H)/L	Time	(C + H)/L
Sample ID	Avg.	RPD	Avg.	RPD	Avg.	RPD	%	From avgs	Days	Avg
Solid Waste Sample A	14.45	0.6%	79.70	0.4%	-0.65	-87.0%	99.7%	4.50	0.00	
Solid Waste Sample B	16.83	3.7%	76.65	1.8%	-1.16	-1.2%	97.1%	3.42	0.00	3.96
Cell #1	13.45	0.4%	49.70	9.1%	-0.11	-25.7%	111.7%	3.13	73.00	
Cell #2	14.52	13.8%	38.80	5.1%	-0.86	-7.4%	153.4%	3.10	73.00	3.11
Sample #3	27.85	0.5%	41.50	5.1%	0.70	4.6%	116.1%	0.73	135.00	
Sample #4	28.53	5.2%	45.75	2.3%	0.73	34.9%	129.8%	1.08	135.00	0.91
Sample Cell #5	32.10	0.5%	44.55	2.4%	0.17	16.6%	118.1%	0.64	188.00	
Sample Cell #6	37.84	1.0%	52.80	1.3%	0.12	55.3%	108.0%	0.51	188.00	0.57
Cell #7	38.46	23.3%	37.50	8.7%	2.91	19.2%	137.3%	0.34	252.00	
Cell #8	33.53	16.9%	40.88	14.2%	6.08	1.4%	124.1%	0.51	252.00	0.43
Cell #9	18.84	2.0%	32.45	8.9%	0.56	3.8%	85.1%	0.47	366.00	
Cell #10	23.31	9.5%	42.25	10.2%	0.59	0.0%	81.7%	0.48	366.00	0.47
Sample #11	21.23	18.7%	41.85	7.9%	0.27	36.7%	76.4%	0.51	406.00	
Sample #12	24.13	13.5%	42.65	6.5%	0.27	8.0%	79.6%	0.41	406.00	0.46

* Samples 08-184 and 08-185 were dried in oven for about 30 minutes without weighing as initial request for information did not indicate moisture analysis was needed

Samples were removed from oven, cooled, and prepared for moisture analysis by Yuki
**Not requested.

Source: N.C. State University Department of Civil, Construction, and Environmental Engineering

Figure 4.12 depicts the relationship between the (C + H)/L ratio and time. It also depicts the relationship between observed gas produced and time which was presented earlier in Figure 4.8. Figure 4.12 shows a decrease in the (C + H)/L ratio and increase in cumulative gas produced with increasing time. This decrease of (C + H)/L and increase in gas production are the result of biodegradation decomposition, is expected and is the premise of this research. By inspection, one is able to see that the (C + H)/L relationship is decaying exponentially and is approaching the horizontal asymptotically approaching a time when decomposition occurs very slowly. At this point the biodegradation decomposition is essentially complete and biodegradation settlements are at a minimum. It is observed from Figure 4.12 that the start of biodegradation compression (end of inorganic secondary compression phase) t_2 corresponds to a (C + H)/L ratio value of 3.00 and the end of biodegradation (start of tertiary compression) t_3, corresponds to a (C + H)/L ratio value of 0.50. These values will vary depending upon the character of the waste material.

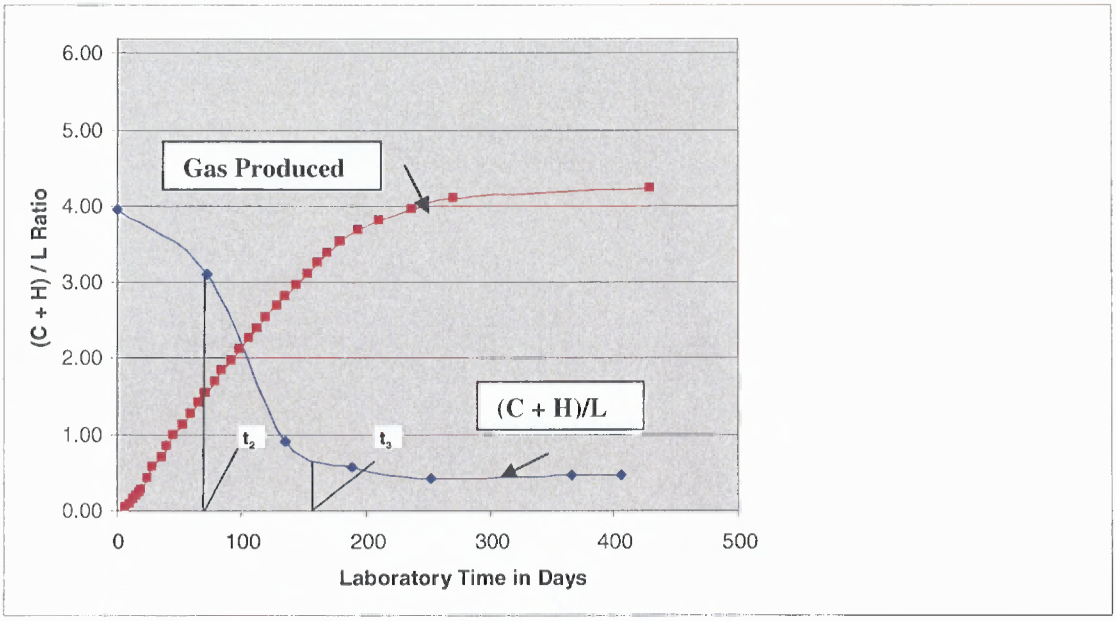

Figure 4.12 (C + H)/L and gas produced vs. laboratory time.

4.4.3 Settlement Parameters and Relationships

In this section, the results obtained from this study for the individual settlement parameters and their relationships to one another, C'_α, C_β, $C_{\alpha\beta}$, $Secant_\beta$, C_β / C_α, $C_{\alpha\beta}$ / C_α, $C_{\alpha\beta}$ / C_β and (C + H)/L ratio will be discussed. The determination of the individual parameters is depicted in Figure 1.1. Table 4.8 shown below, depicts the values obtained for C'_α, C_β, $C_{\alpha\beta}$, $Secant_\beta$, C_β / C'_α, $C_{\alpha\beta}$ / C'_α, $C_{\alpha\beta}$ / C_β and (C + H)/L ratio for each of the samples tested at specific load increments. Values for C'_α and C_β were obtained from Figure 4.13. Average $Secant_\beta$ values for Samples 1, 2 and 3, and the average $C_{\alpha\beta}$ values for Samples 2 and 4 were obtained from Figures 4.33 and 4.36, respectively.

Table 4.8 Summary of Laboratory Testing

Sample No. @ 2.56 tsf	(C + H)/L	(C + H)/L (avg)*	C'_c	C'_α	C_β	$C_{\alpha\beta}$	$C_{\alpha\beta}/C'_\alpha$
A (LT)	N/A	3.96	0.2356	0.0090	0.1470	0.0340	3.78
A	4.50	3.96	0.2445	0.0050			
B	3.42	3.96	0.2277	0.0065			
1	3.13	3.11	0.2148	0.0070			
2	3.10	3.11	0.1863	0.0050			
3	0.52	0.80	0.219	0.0085			
4	1.08	0.80	0.1925	0.0090	0.0235		
5	0.64	0.58	0.1950	0.0075	0.0210		
6	0.51	0.58	0.1933	0.0075	0.0350	0.0140	1.87
7	0.34	0.43	0.2094	0.0080	0.0150	0.0100	1.25
8	0.51	0.43	0.1831	0.0065	0.0200	0.0110	1.69
9	0.47	0.48	0.2083	0.0090	0.0200	0.0145	1.61
10	0.48	0.48	0.1999	0.0085	0.0235	0.0120	1.41
11	0.51	0.46	0.1965	0.0095	0.0158	0.0093	0.98
12	0.41	0.46	0.2148	0.0075	0.0175	0.0055	0.73
H-10			0.2145	0.0056	0.0540	0.0235	4.20

* Value obtained by averaging pairs of tested values for duplicate samples

Table 4.8 Continued Summary of Laboratory Testing

Sample No. @ 2.56 tsf	$C_{\alpha\beta}/C_\beta$	Avg. C'_c	Avg. C'_α	Avg. C_β	Avg. $C_{\alpha\beta}$	Biodegradation Secant Modulus	Avg. Biodegradation Secant Modulus
A (LT)		0.2356	0.0090	0.1470	0.0340	0.0300	0.0300
A							
B		0.2358	0.0058				
1							
2		0.2006	0.0060	0.0900	0.0260*	0.0236*	0.0236*
3							
4		0.2058	0.0088	0.0235	0.0122*	0.0127	0.0127
5						0.0117	
6	0.4000	0.1942	0.0075	0.028	0.0140	0.0118	0.0118
7	0.6667					0.0110	
8	0.5500	0.1963	0.0073	0.0175	0.0105	0.0109	0.0110
9	0.725					0.0126	
10	0.5106	0.2041	0.0088	0.0218	0.0133	0.0117	0.0122
11	0.5886					0.0119	
12	0.3143	0.2057	0.0085	0.0167	0.0074	0.01210	0.0120
H-10	0.4352	0.1852	0.0056	0.0540	0.0235	0.0198	0.0198

* Values obtained by utilizing the relationship shown on Figures 4.33 through 4.36

Figure 4.13 depicts the percent strain versus time plots for all tested MSW samples and for the Humus H-10 sample at a load increment of 2.56 tsf. An inspection of this figure yields values of C'_α for all samples. For Samples A (LT) and Humus H-10, C_β and $C_{\alpha\beta}$ can be constructed. Appendix B, Table B.1 through B.9, lists the consolidation strain readings versus time obtained for Sample A (LT) The values of C'_α obtained for the 2.56 tsf loading increment ranges from 0.0050 to 0.0095 for the waste samples and 0.0056 for the Humus. The value for C_β at 2.56 tsf is 0.0.1470, for Sample A (LT) and 0.0540 for Sample H-10. The value for $C_{\alpha\beta}$ is 0.0340 for Sample A (LT) and 0.0235 for Sample H-10. Values of the Secant Modulus of Biodegradation, Secant_β ranges from 0.0105 to 0.0240 with increasing (C + H)/L ratio. Inspection of the figure for these early tested samples leads one to quickly conclude that the samples need to be held under test loading for a longer period of time to achieve C_β and $C_{\alpha\beta}$ ranges and values.

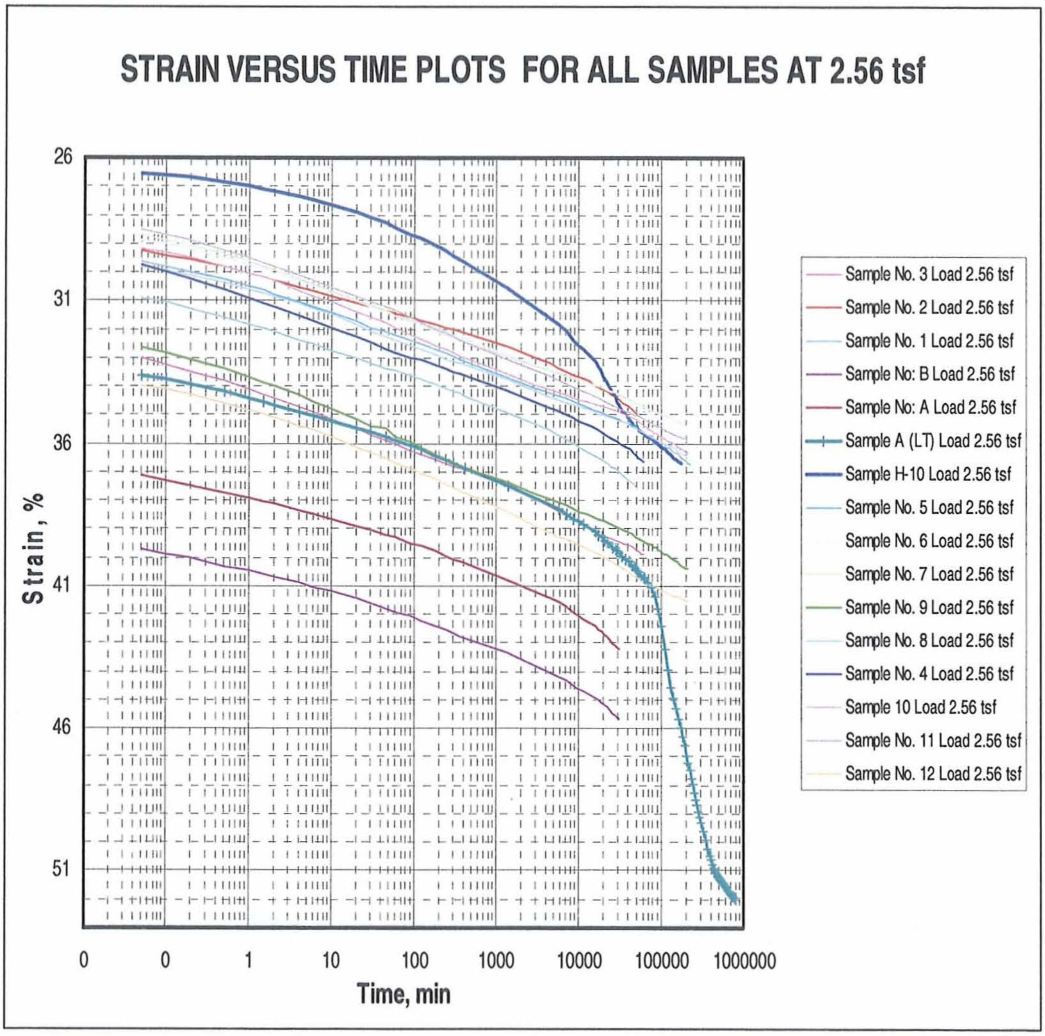

Figure 4.13 Strain vs. Time plots for all samples at 2.56 tsf.

Figure 4.14 enlarges the plot shown in Figure 4.12 to facilitate visualization and construction of the C_β and $C_{\alpha\beta}$ values from the curves for Samples A (LT) and Humus H-10.

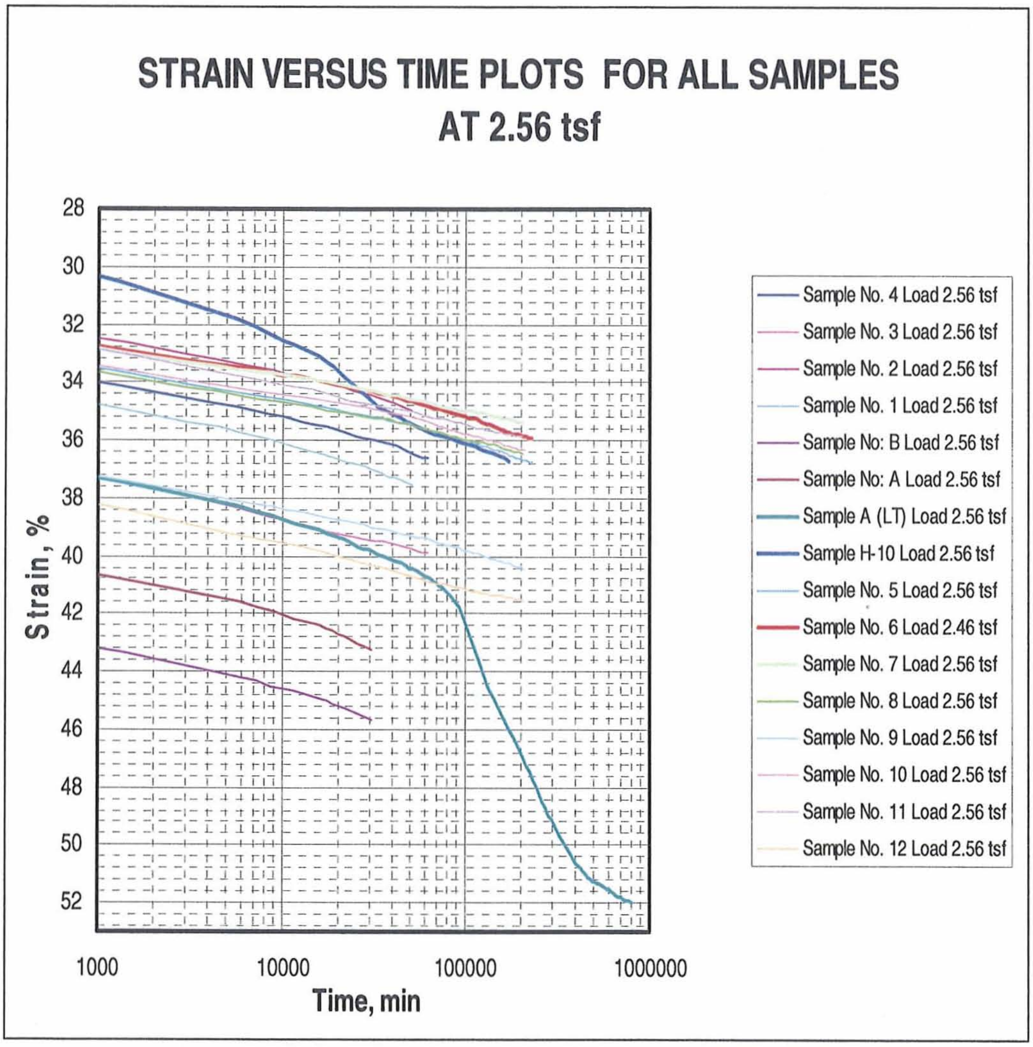

Figure 4.14 Strain vs. Time plots for all samples at 2.56 tsf.

Figure 4.15 depicts the percent strain versus time plots for all MSW samples and for the Humus H-10 sample at a load increment of 1.27 tsf. An inspection of the figure also yields construct values of C'_α for all samples. The values of C'_α obtained for this load increment range from 0.0080 to 0.0140 for the waste samples and 0.0080 for the Humus Sample H-10. The values for C_β for the Humus Sample H-10 and for Sample A(LT) are 0.0605 and 0.0315, respectively. The loading cycle for the 1.27 tsf load was not held long enough to determine C_β and $C_{\alpha\beta}$ for any of the other waste samples.

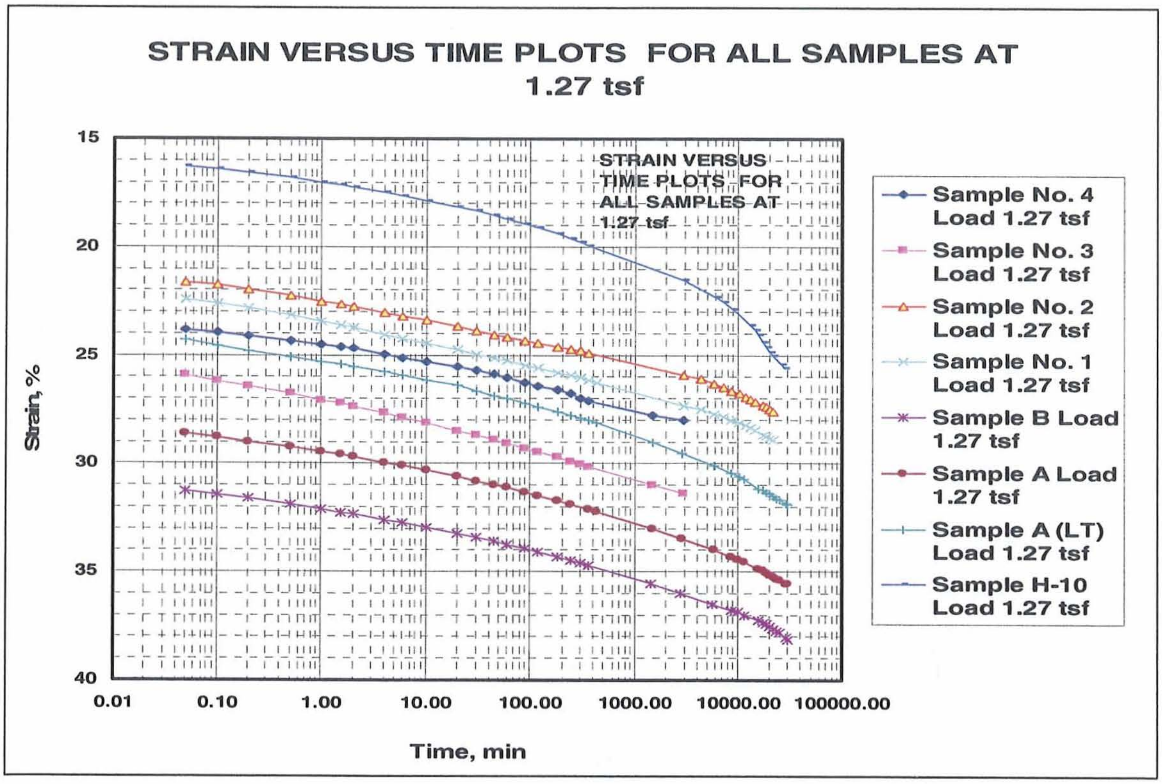

Figure 4.15 Strain vs. Time plots for all samples at 1.27 tsf.

Although the primary compression occurs quickly it does contribute to settlement of the sample and the larger overall layer of the waste. As a result, Figure 4.16 depicts the relationship between (C + H)/L and C'_c, Appendix D contains graphical representations of the comparison between the (C + H)/L ratio and the values for C'_c, C'_α, C_β, Secant_β, and $C_{\alpha\beta}$. These graphs were utilized to fill in some gaps in the data which developed because Samples 1, 2, 3 and 4 did not consolidate long enough within the oedometers to enable values to be constructed for some of these coefficients for the cited samples only. All the graphs were constructed utilizing an exponential relationship between the (C + H)/L ratio and the various coefficients. An exponential curve fitting approach was selected for the development of the missing data based upon the results of comparisons between the curve fitting methods shown below.

The following coefficients for Samples 1, 2, 3, and 4 were determined using the figures shown in Appendix D as Figures D.1, D.2, D.3, D.4, and D.5.

Table 4.9 Settlement Parameters Determined Using Charts to Fill Data Gaps

Sample #	Figure #	Coefficient	Value
1 and 2	D3	Avg C_β	0.0900
1 and 2	D4	Avg Secant_β	0.0236
1 and 2	D5	Avg $C_{\alpha\beta}$	0.0260
3 and 4	D4	Avg Secant_β	0.0127
3 and 4	D5	Avg $C_{\alpha\beta}$	0.0122

The values developed using the figures referenced in Appendix D agree favorably with those expected and were used in some of the validation examples with good results.

Table 4.10 shows a comparison of calculated values for the Secant Modulus vs. (C + H)/L using exponential, linear and logarithmic curve fitting methods of determination.

An inspection of the curves, shown on Figure D.6, indicates that the exponential curve fitting method to be the best approximation and closer to that which would be expected, given the decay processes at work in waste decomposition. A comparison between the different methods indicates good agreement between the exponential and linear curve fitting methods, approximately less that 11%, and less favorable percentages between the linear and logarithmic comparison and the exponential and logarithmic comparison with variations of up to 19% to 159%, and 23% to 180%, respectively.

Table 4.10 Comparison of Secant Modulus versus (C + H)/L Ratio

Linear Secant Modulus	Exponential Secant Modulus	Logarithmic Secant Modulus	(C + H)/L	Linear/Exp	Linear/Log	Exp/Log
Secant Modulus						
0.0302	0.0303	0.0290	4.00	100%	104%	104%
0.0297	0.0295	0.0288	3.90	101%	103%	102%
0.0291	0.0287	0.0286	3.80	102%	102%	100%
0.0286	0.0279	0.0284	3.70	102%	101%	98%
0.0281	0.0272	0.0282	3.60	103%	100%	97%
0.0276	0.0265	0.0279	3.50	104%	99%	95%
0.0270	0.0258	0.0277	3.40	105%	98%	93%
0.0265	0.0251	0.0274	3.30	106%	97%	91%
0.0260	0.0244	0.0272	3.20	106%	96%	90%
0.0254	0.0238	0.0269	3.10	107%	95%	88%
0.0249	0.0231	0.0266	3.00	108%	94%	87%
0.0244	0.0225	0.0263	2.90	108%	93%	85%
0.0238	0.0219	0.0260	2.80	109%	92%	84%
0.0233	0.0213	0.0257	2.70	109%	91%	83%
0.0228	0.0208	0.0254	2.60	110%	90%	82%
0.0223	0.0202	0.0251	2.50	110%	89%	81%
0.0217	0.0197	0.0248	2.40	110%	88%	79%
0.0212	0.0191	0.0244	2.30	111%	87%	78%
0.0207	0.0186	0.0240	2.20	111%	86%	78%
0.0201	0.0181	0.0236	2.10	111%	85%	77%
0.0196	0.0177	0.0232	2.00	111%	84%	76%
0.0191	0.0172	0.0228	1.90	111%	84%	75%
0.0185	0.0167	0.0223	1.80	111%	83%	75%
0.0180	0.0163	0.0219	1.70	111%	82%	75%
0.0175	0.0159	0.0213	1.60	110%	82%	74%
0.0170	0.0154	0.0208	1.50	110%	81%	74%
0.0164	0.0150	0.0202	1.40	109%	81%	74%
0.0159	0.0146	0.0196	1.30	109%	81%	75%
0.0154	0.0142	0.0189	1.20	108%	81%	75%
0.0148	0.0139	0.0182	1.10	107%	81%	76%
0.0143	0.0135	0.0174	1.00	106%	82%	78%
0.0138	0.0131	0.0165	0.90	105%	83%	79%
0.0132	0.0128	0.0155	0.80	104%	85%	82%
0.0127	0.0124	0.0144	0.70	102%	88%	86%
0.0122	0.0121	0.0131	0.60	101%	93%	92%
0.0117	0.0118	0.0116	0.50	99%	101%	102%
0.0111	0.0115	0.0097	0.40	97%	115%	118%
0.0106	0.0112	0.0073	0.30	95%	145%	153%
0.0101	0.0109	0.0039	0.20	93%	259%	280%

The rest of the tested samples and coefficients were determined from the laboratory testing program and were used to construct the following graphical figures.

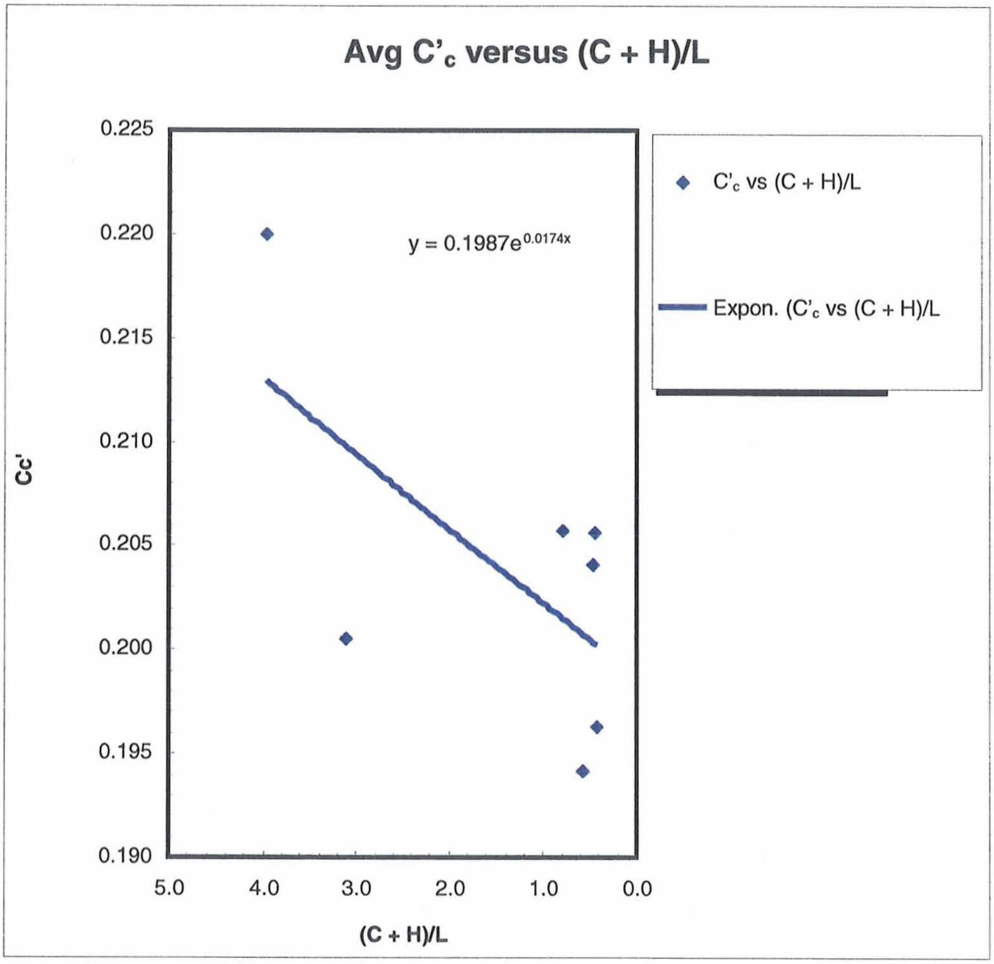

Figure 4.16 C'$_c$ versus (C + H)/L.

Figures 4.17 through 4.32 depict a comparison of percent strain to load in tsf and the resultant construction of the C'$_c$ (Compression Index) slope for each of the samples tested. The results indicate that C'$_c$ varies from 0.1831 to 0.2445 for the MSW samples and 0.2145 for the Humus H-10 sample. The results of the research experiment, shown in Figure 4.16, of the MSW samples indicate that the parameter C'$_c$

decreases as the value of (C + H)/L decreases. The earlier work by Hossain, Barlaz and Gabr (2003) indicated that C'$_c$ increased with decreasing (C + H)/L. In their work they only tested samples with a (C + H)/L value of less than 1.29.

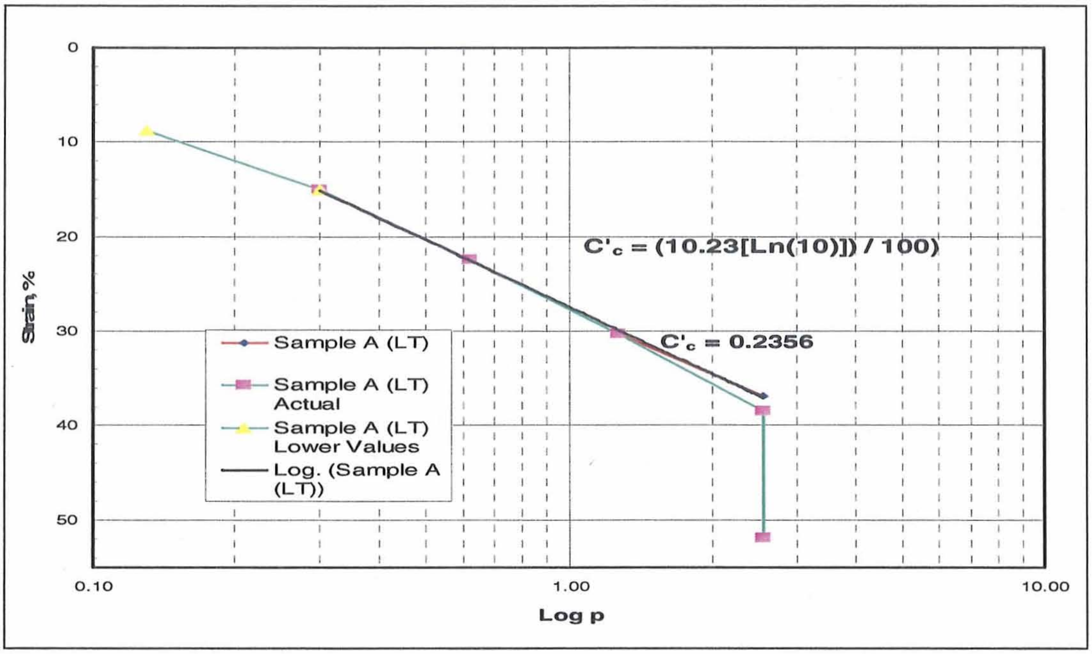

Figure 4.17 C'$_c$ Value for strain vs. load plots for Sample A (LT).

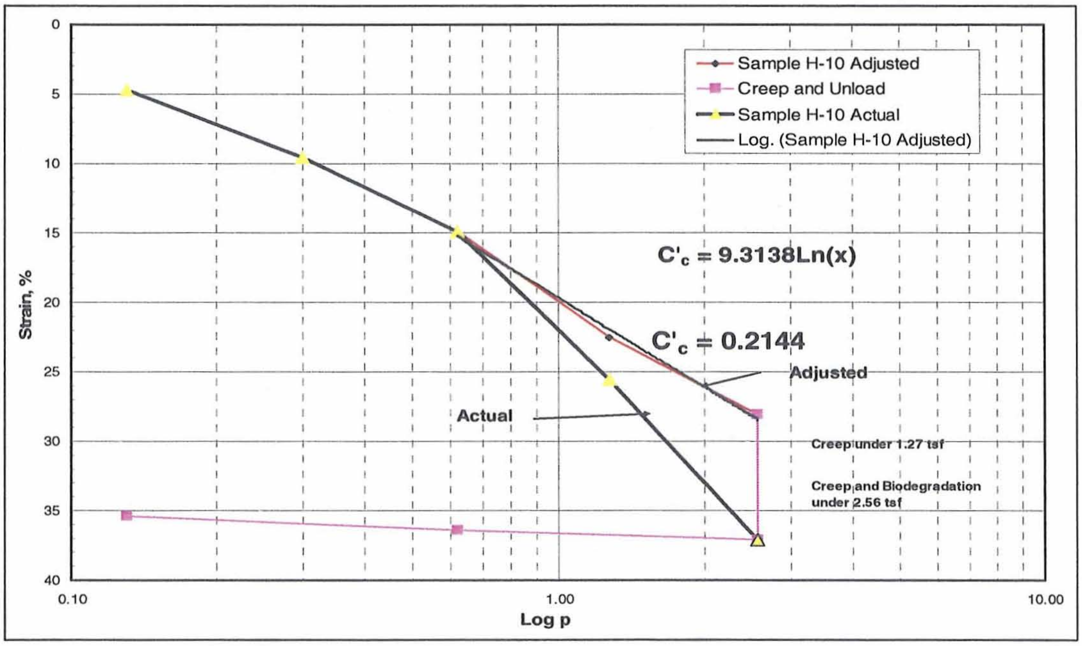

Figure 4.18 C'$_c$ Value for strain vs. load plots for Sample H-10.

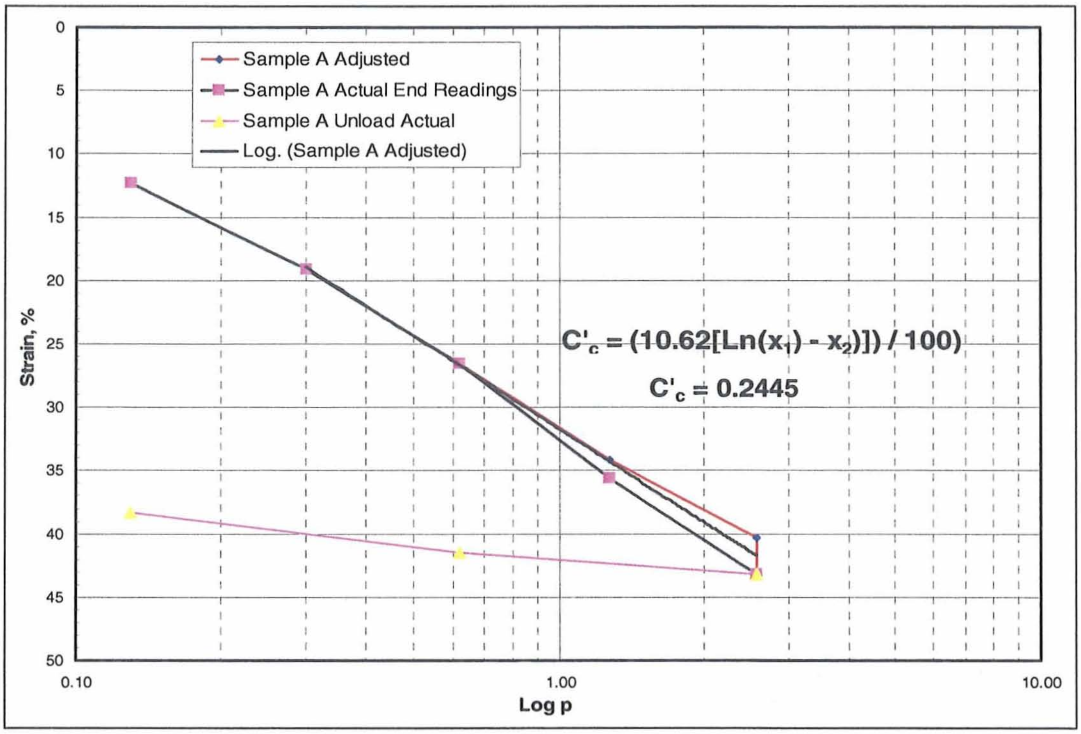

Figure 4.19 C'$_c$ Value for strain vs. load plots for Sample A.

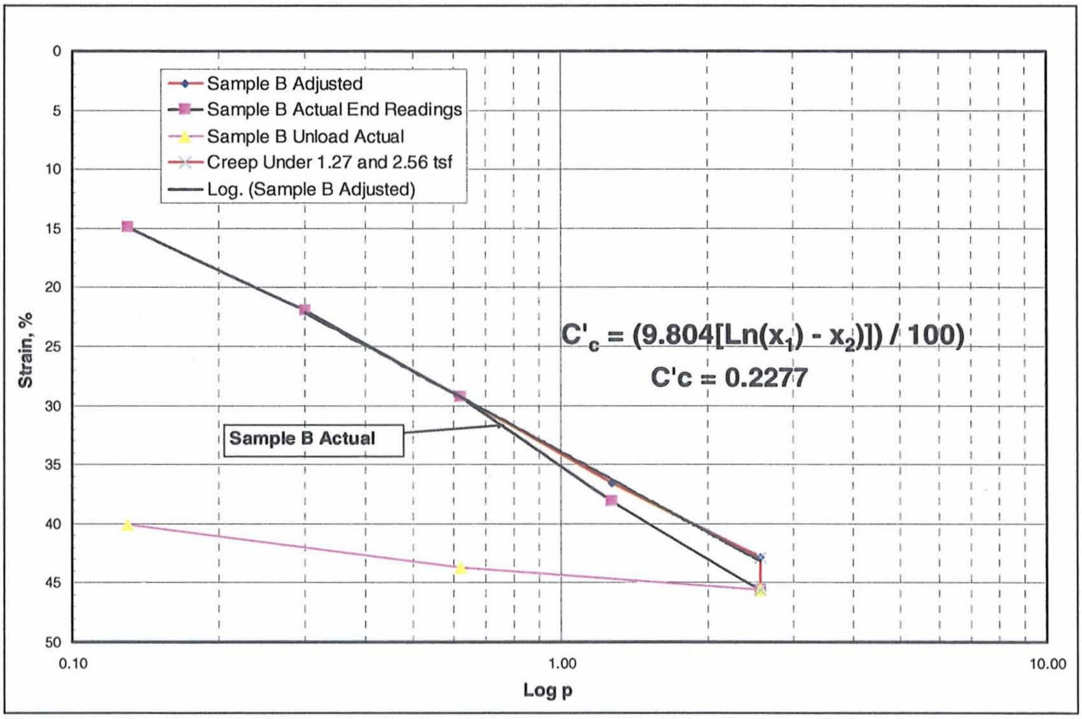

Figure 4.20 C'$_c$ Value for strain vs. load plots for Sample B.

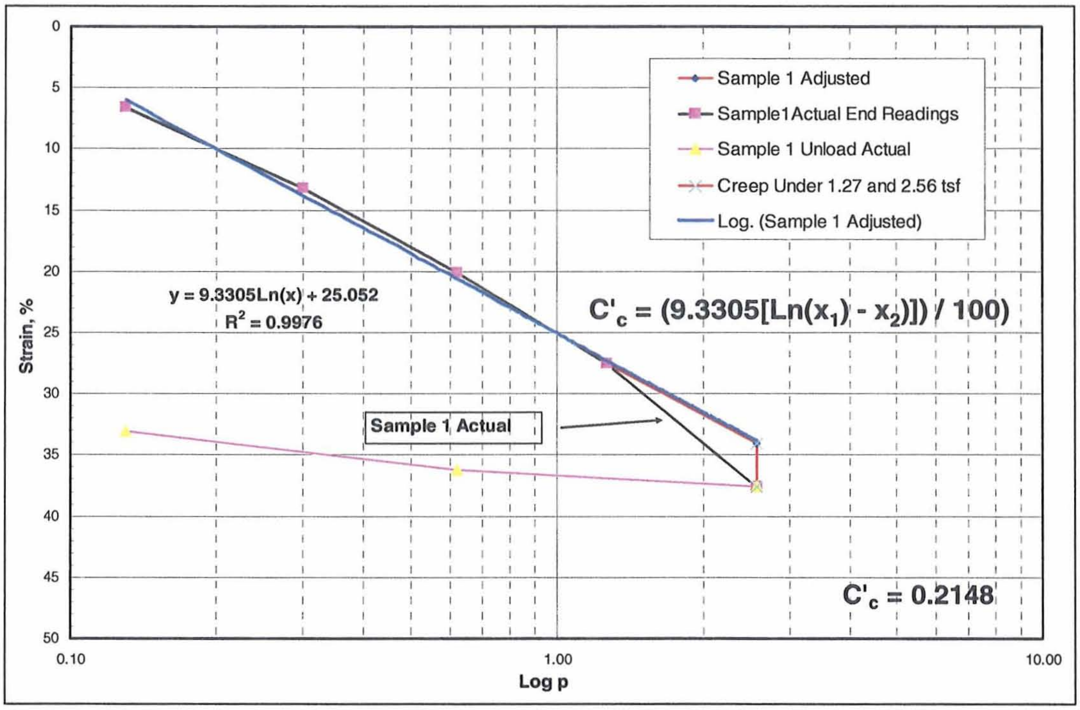

Figure 4.21 C'$_c$ Value for strain vs. load plots for Sample 1.

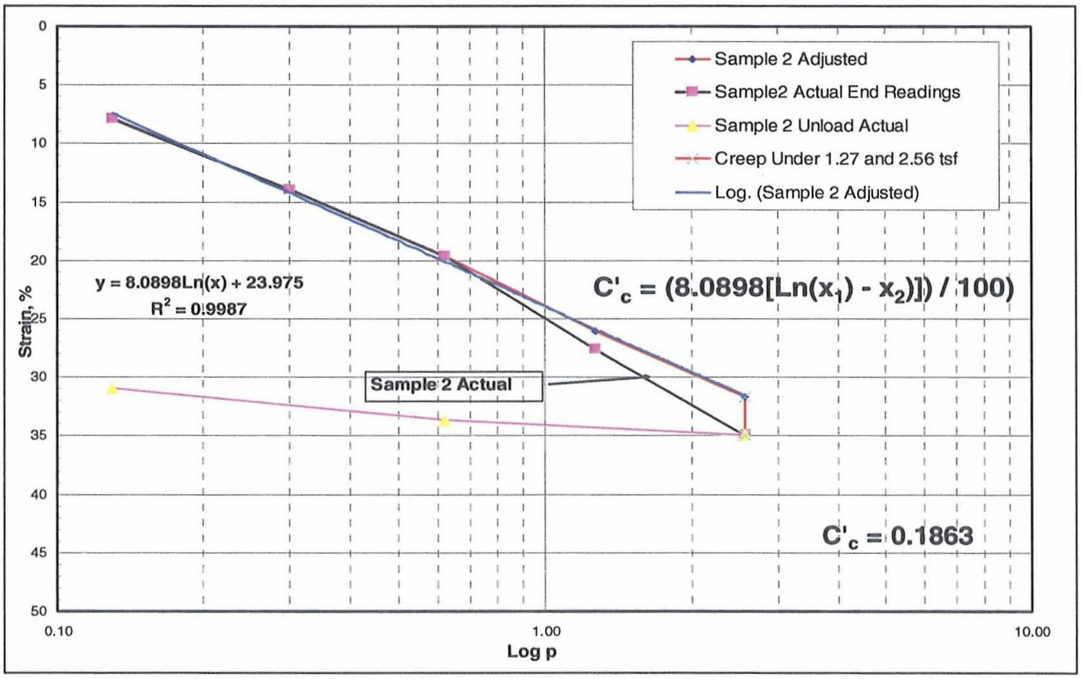

Figure 4.22 C'$_c$ Value for strain vs. load plots for Sample 2.

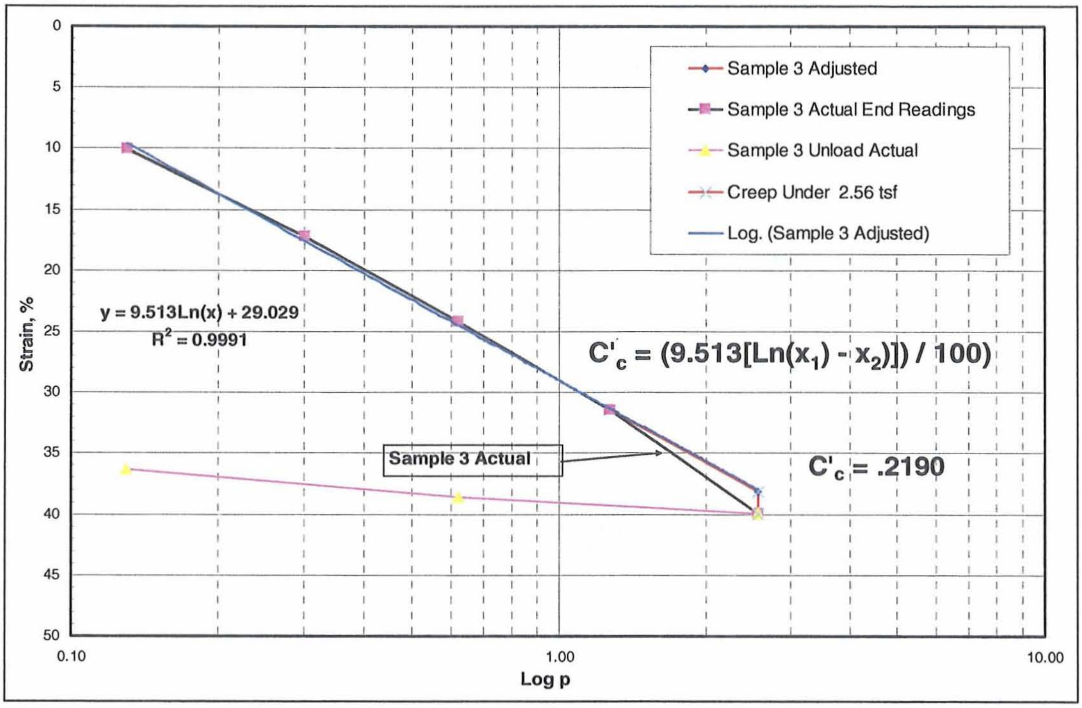

Figure 4.23 C'$_c$ Value for strain vs. load plots for Sample 3.

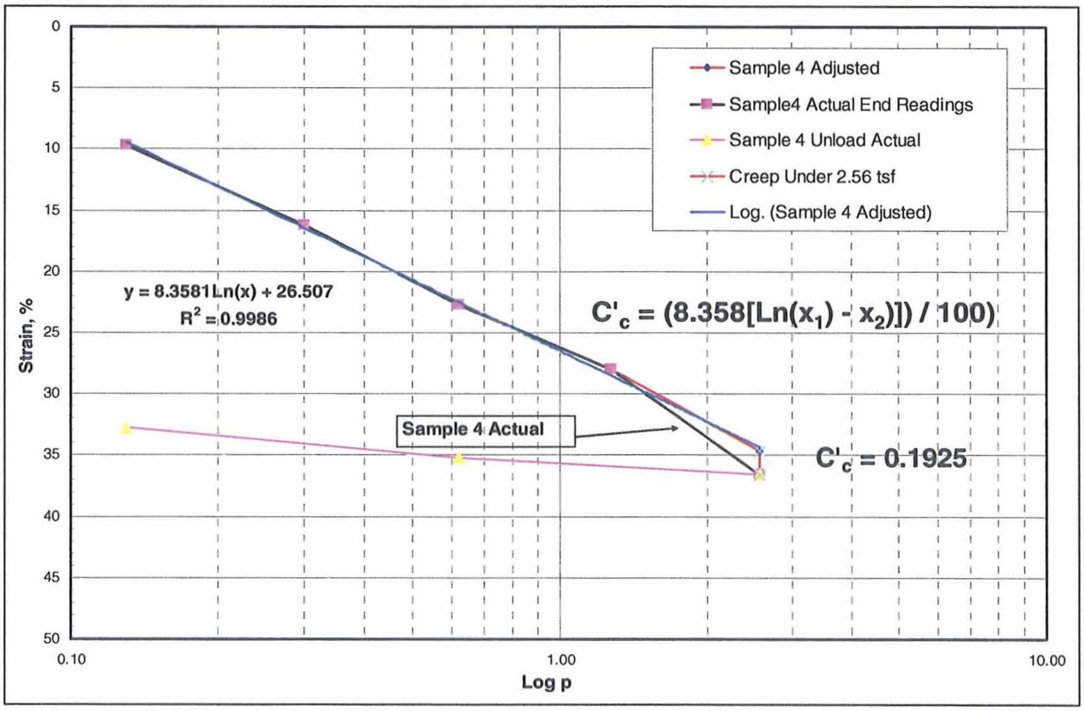

Figure 4.24 C'$_c$ Value for strain vs. load plots for Sample 4.

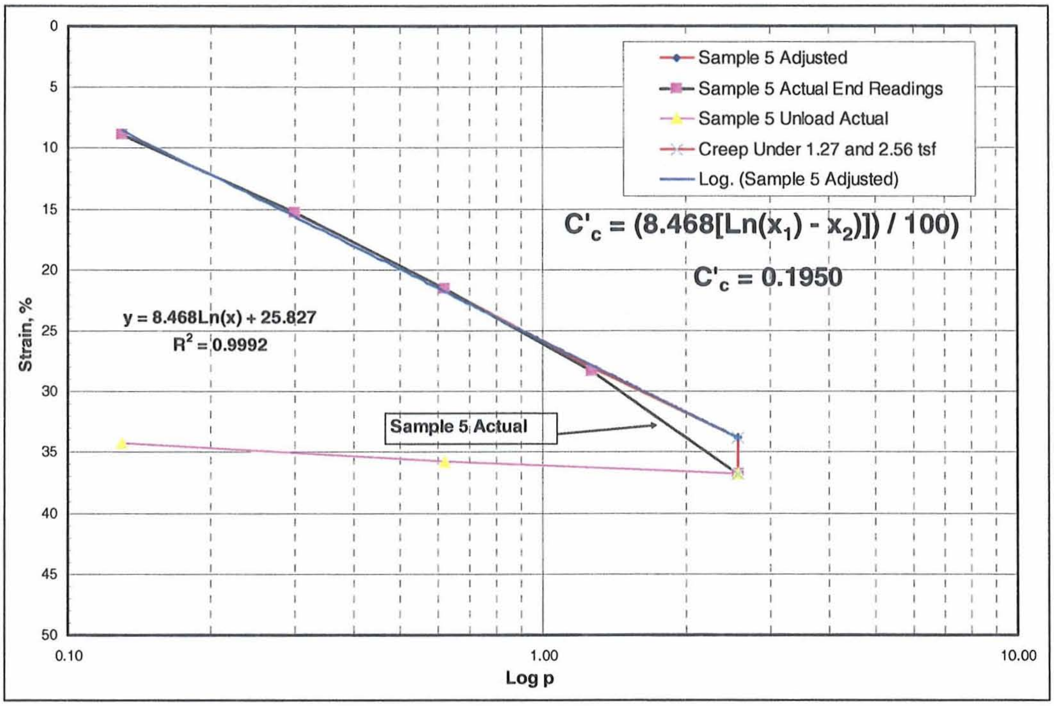

Figure 4.25 C'c Value for strain vs. load plots for Sample 5.

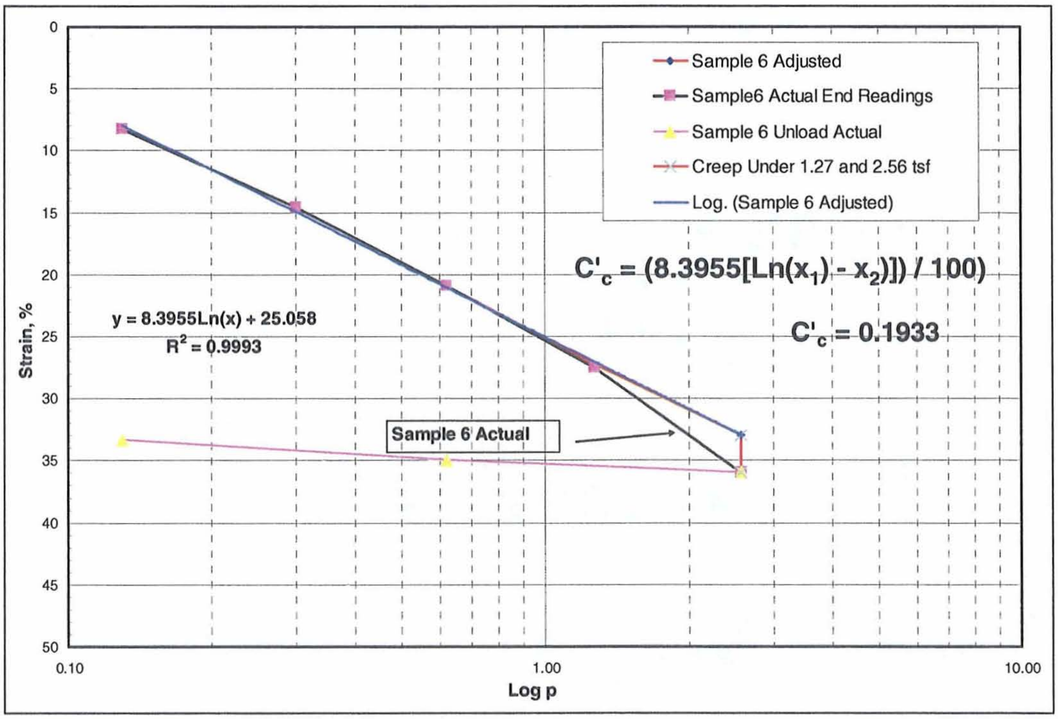

Figure 4.26 C'_c Value for strain vs. load plots for Sample 6.

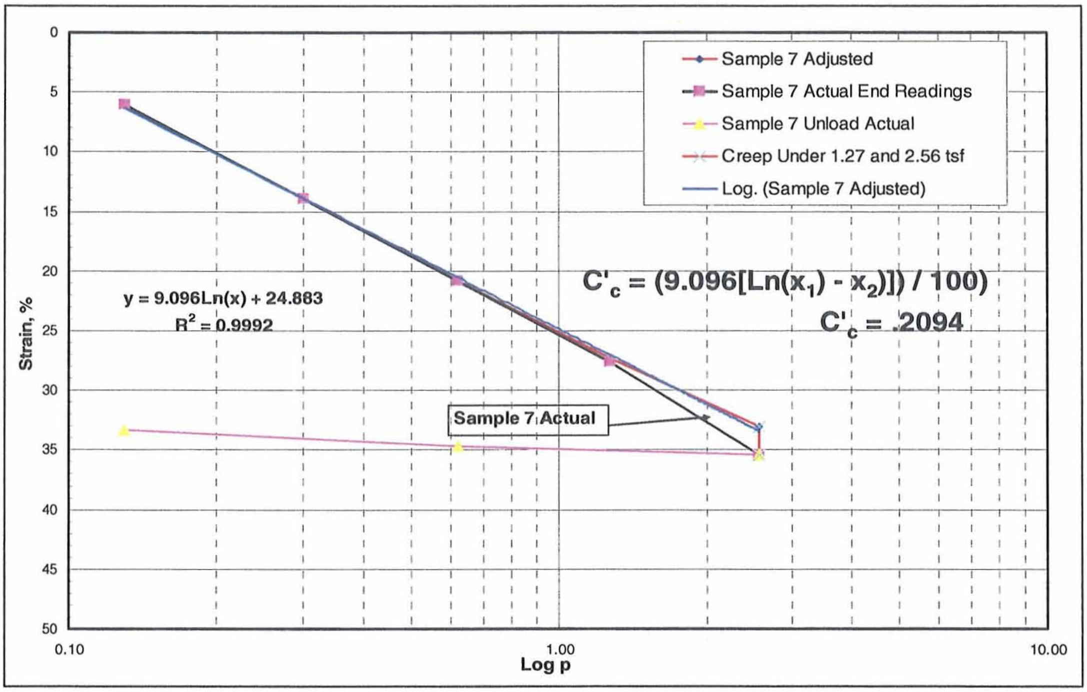

Figure 4.27 C'$_c$ Value for strain vs. load plots for Sample 7.

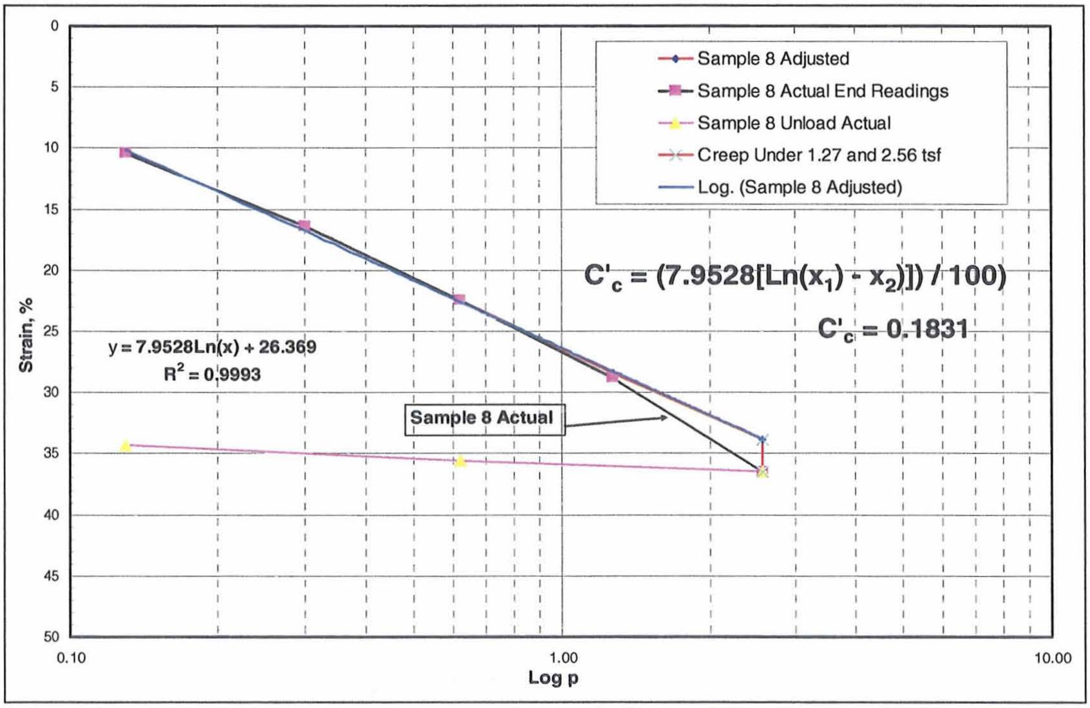

Figure 4.28 C'$_c$ Value for strain vs. load plots for Sample 8.

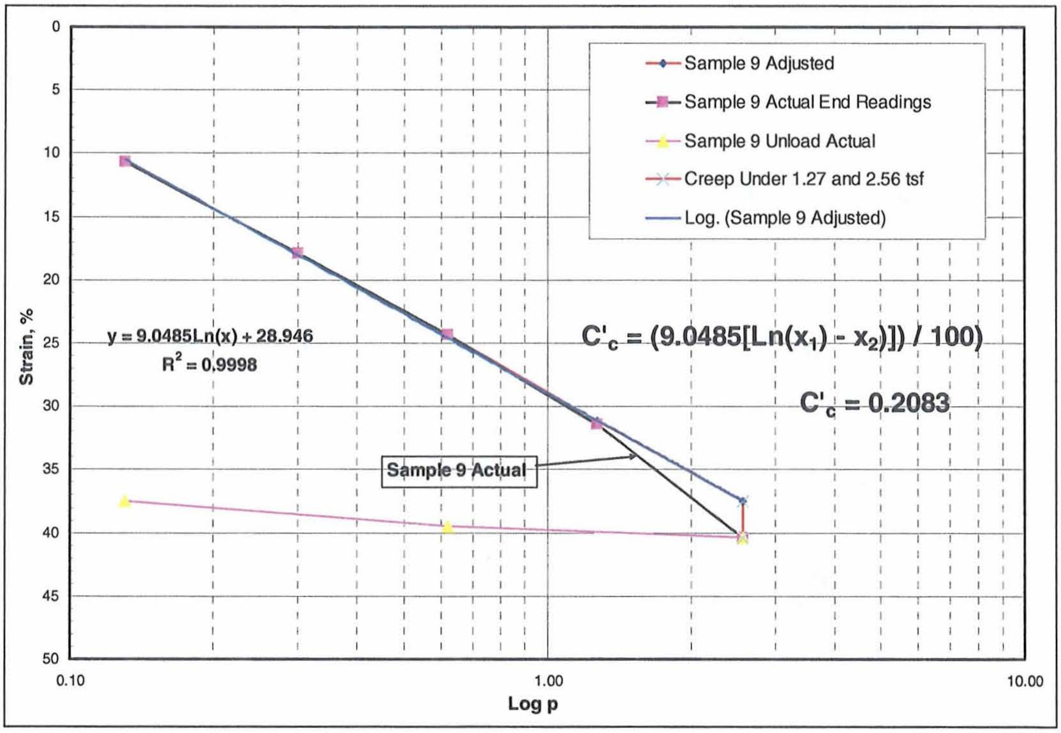

Figure 4.29 C'_c Value for strain vs. load plots for Sample 9.

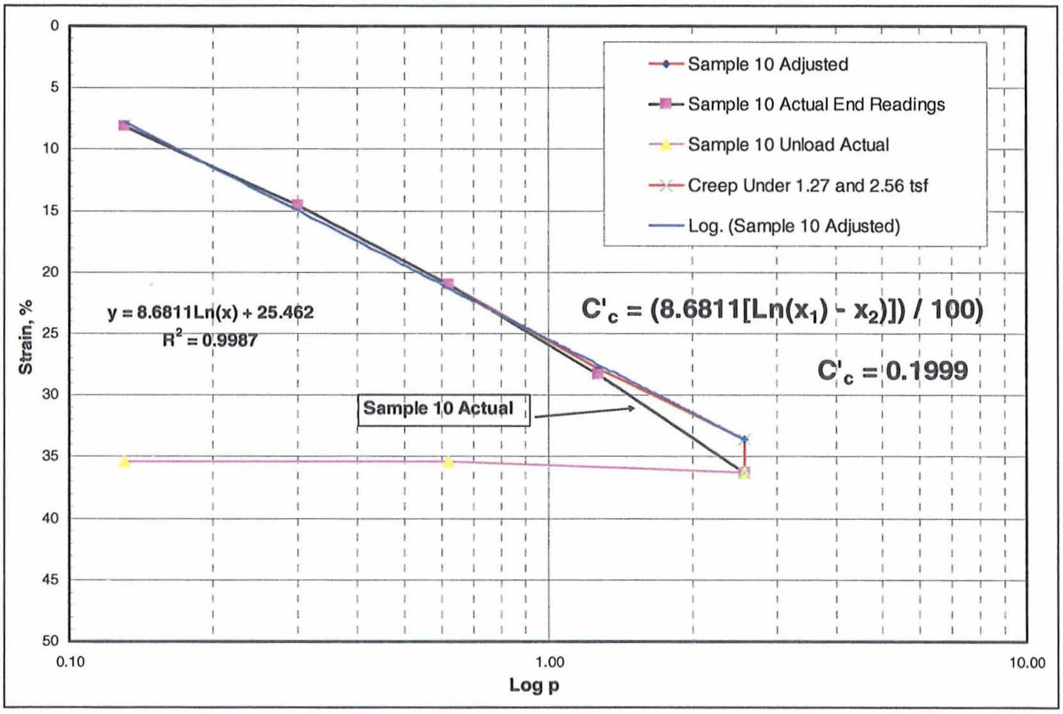

Figure 4.30 C'_c Value for strain vs. load plots for Sample 10.

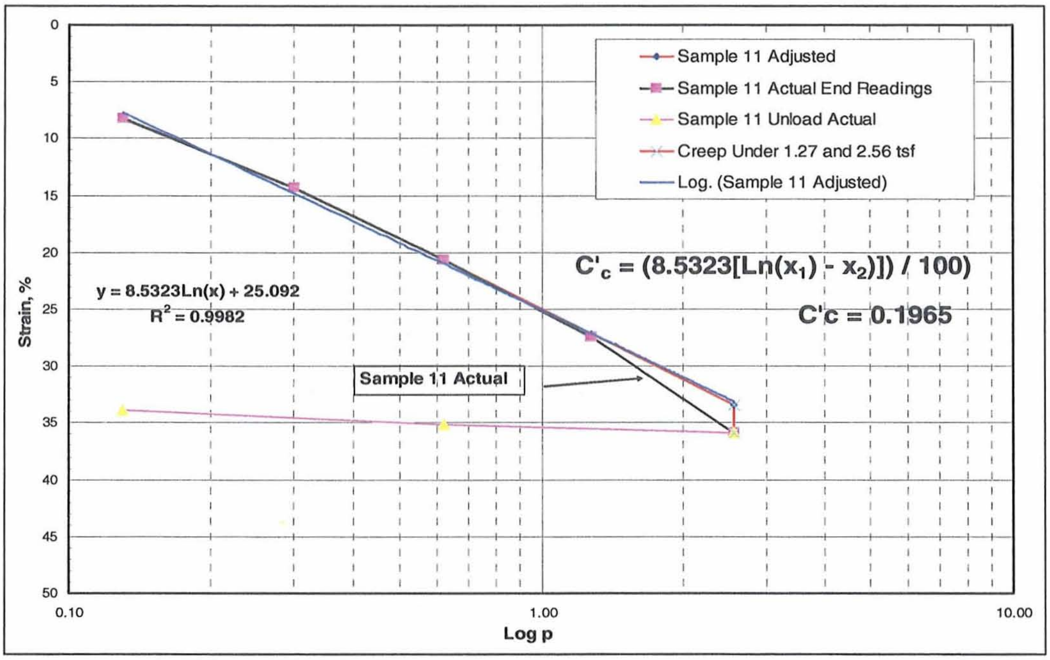

Figure 4.31 C'$_c$ Value for strain vs. load plots for Sample 11.

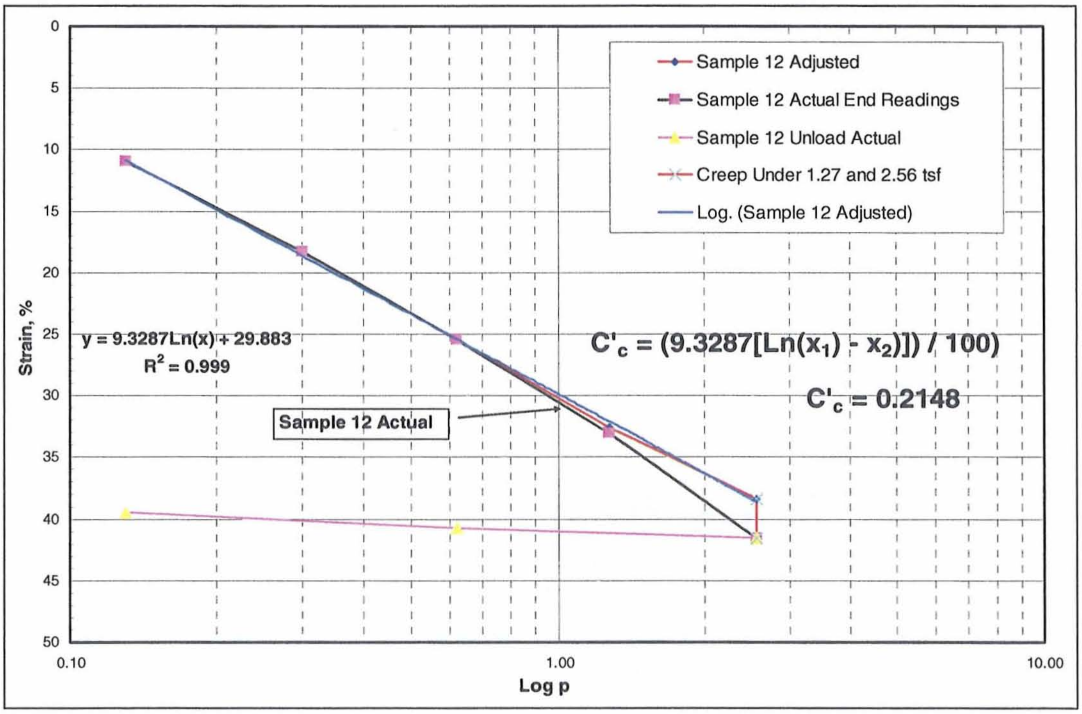

Figure 4.32 C'$_c$ Value for strain vs. load plots for Sample 12.

Figure 4.33 depicts a graph comparing C'_α and the (C + H)/L ratio for samples tested at 2.56 tsf loading increment. C'_α was averaged between sample testing pairs (e.g. samples A and B, 1 and 2, 3 and 4) and compared to averaged (C + H)/L ratios for the same testing pairs. Loading increment 2.56 tsf show an upward sloping trend for C'_α with respect to decreasing (C + H)/L. Figure 4.34 depicts a graph comparing C_β and the (C + H)/L ratio. The figure indicates that C_β decreases as (C + H)/L decreases, as expected. An exponential curve was fitted as the best choice to depict the changes in C_β between points since the value C_β depicts biodegradation effects which are modeled exponentially. This figure can be used to determine the C_β value of 0.0900 for gaps in data such as for (C + H)/L = 3.11 which is used to model a portion of the Kingsland Landfill in North Arlington, New Jersey later in this work.

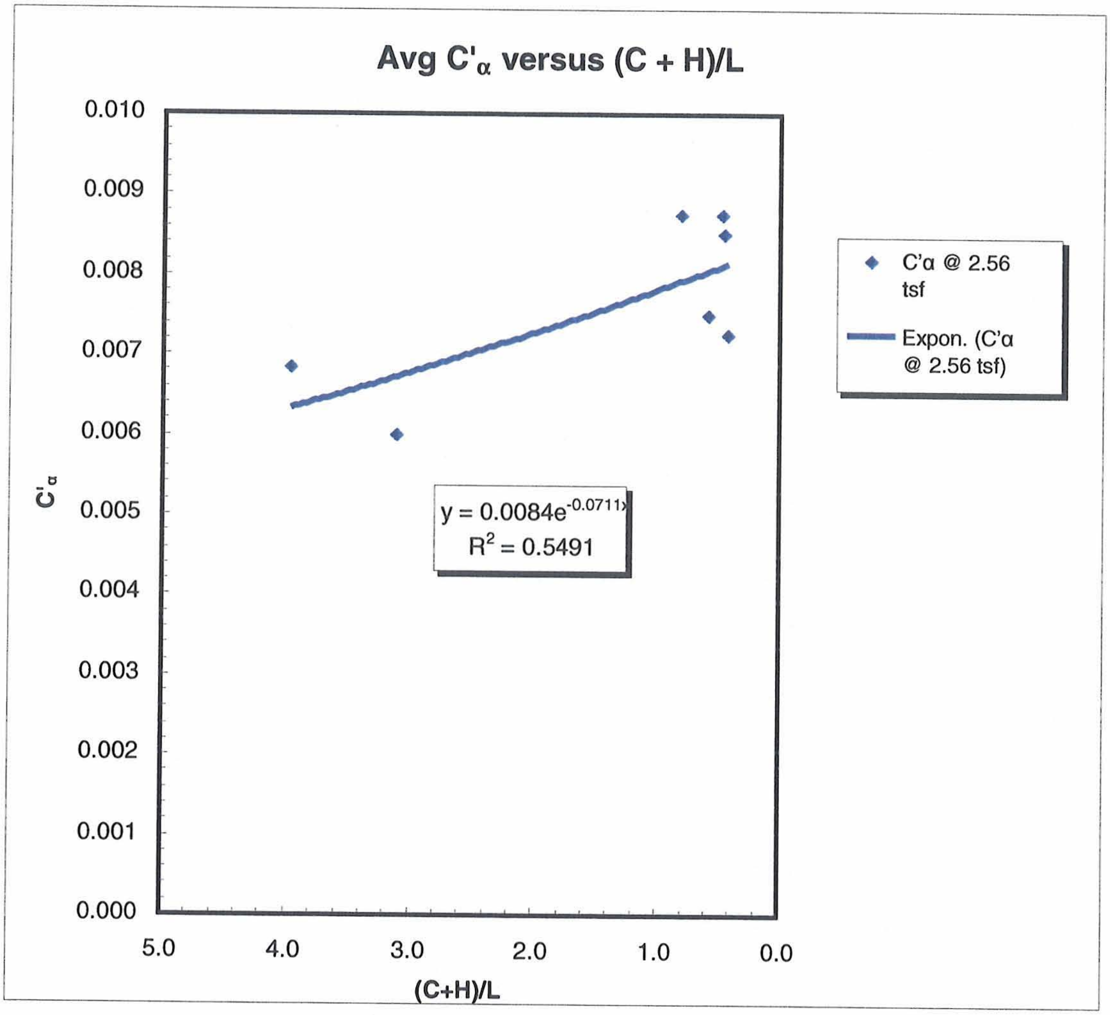

Figure 4.33 C'$_{\alpha}$values vs. (C + H)/L values.

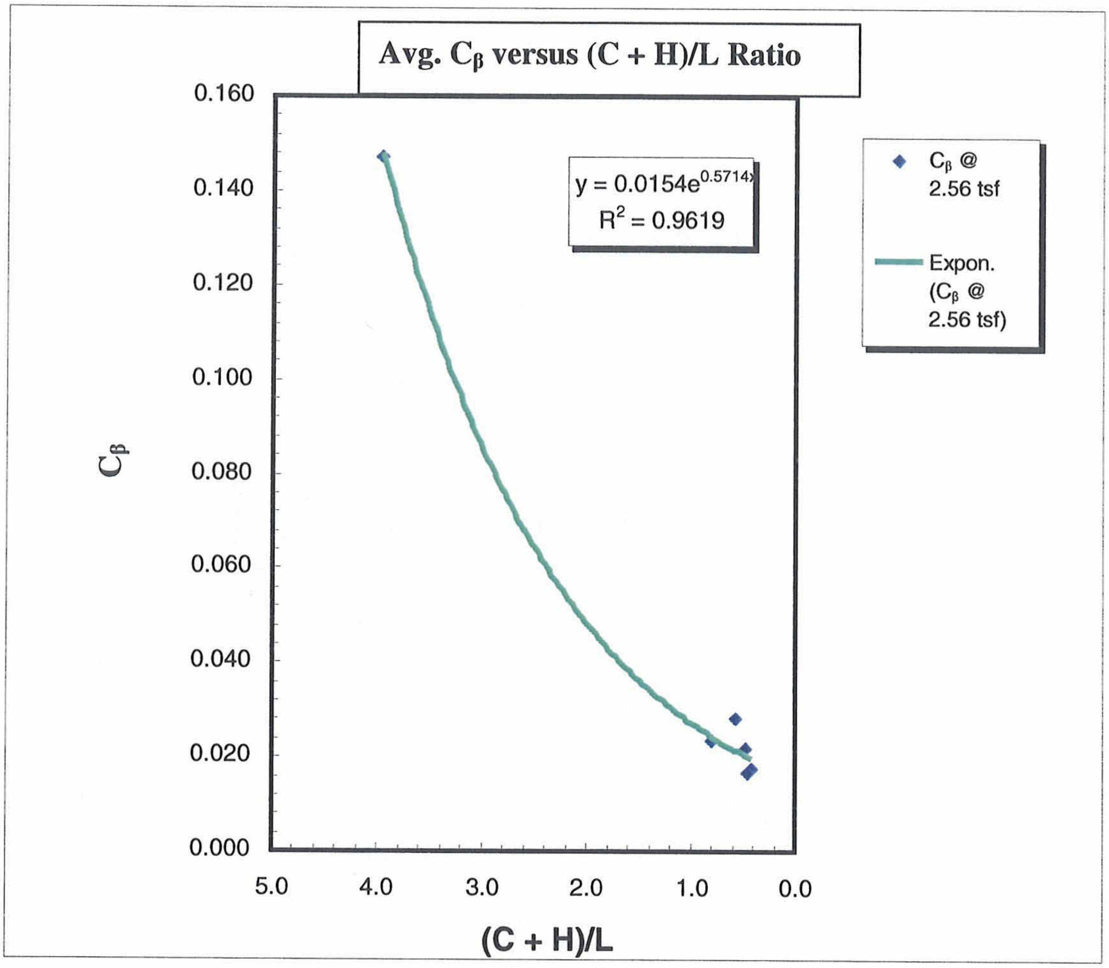

Figure 4.34 C_β values vs. (C + H)/L values.

Figure 4.35 depicts the relationship between the average Biodegradation Secant Modulus ($Secant_\beta$) which represents the slope of the curve from the onset of C'_α and the start of tertiary $C_{\alpha\beta}$ settlement versus the (C + H)/L ratio. This modulus may be used to determine long term settlement when the final time of interest is within the $C_{\alpha\beta}$ range of tertiary settlement.

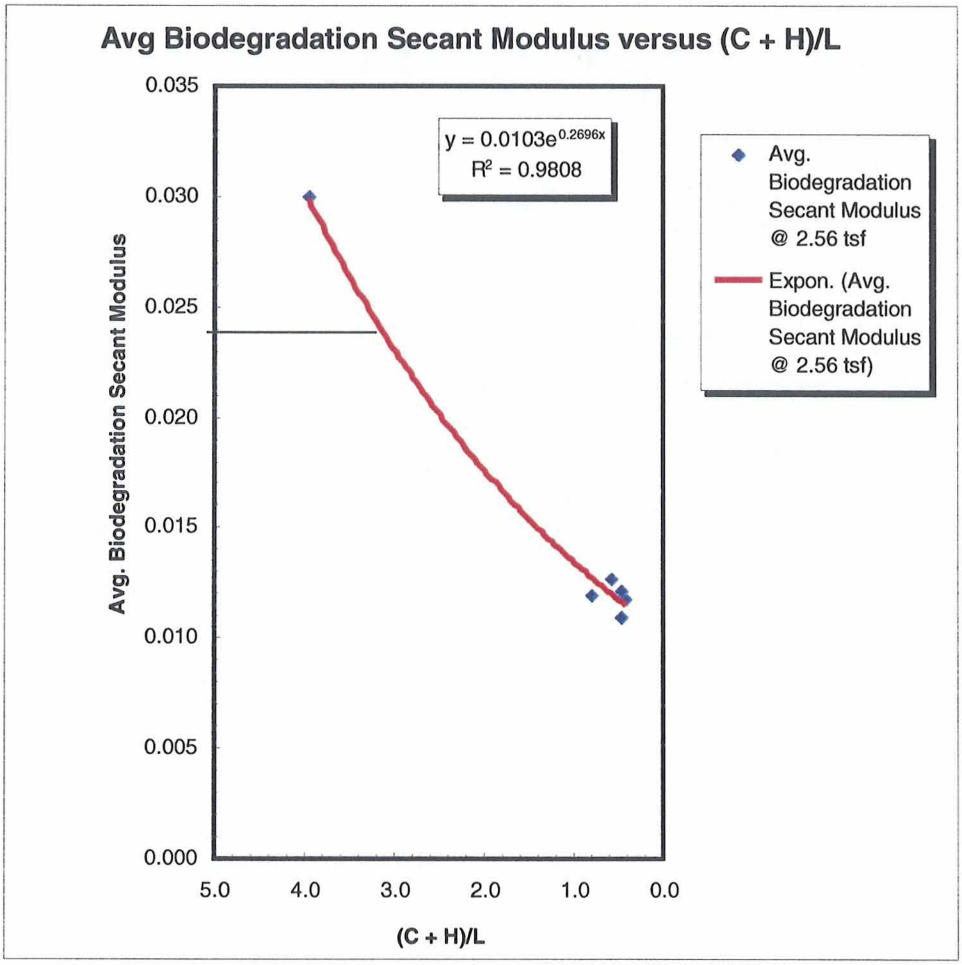

Figure 4.35 Secant$_\beta$ values vs. (C + H)/L values.

Figure 4.36 depicts the relationship between $C_{\alpha\beta}$ and the (C + H)/L ratio. The data indicate that the value of $C_{\alpha\beta}$ reduces as (C + H)/L reduces, as would be expected, approaching values similar to organic soils.

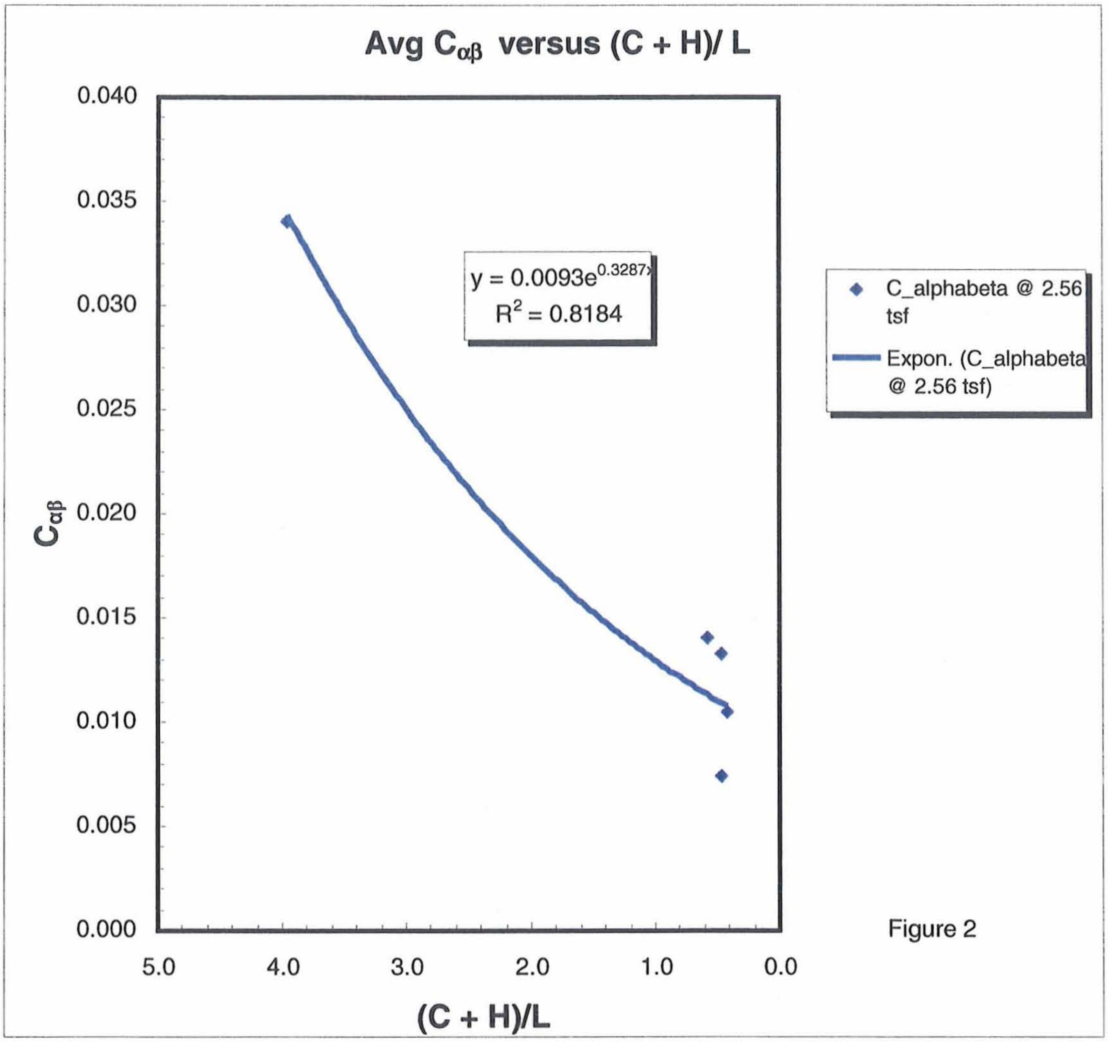

Figure 4.36 $C_{\alpha\beta}$ values vs. (C + H)/L values.

CHAPTER 5

DEVELOPMENT OF THE MODEL

The following discusses the development of a model to utilize the results of the testing.

5.1 Determination of End of Biodegradation

Findikakis et al (1979) and further refined by Durmesouglu et al (2005), developed exponent factors based upon half life decay factors for certain characters of waste dependent upon their observed overall rate of degradability which they identified by the descriptive modifiers, readily, moderately and slowly decomposable as discussed earlier. These descriptive modifier exponent decay factors are used in the basic first order exponential decay formula to calculate the volume of the original mass remaining after time t_i for each group of constituents. To accomplish this, prepared waste material was classified in accordance with their constituents, descriptive modifiers and percentages. Table 5.1 depicts the material used in this study, the waste constituents, their respective percentages and descriptive modifiers were as follows:

Table 5.1 Constituent Percentages and Descriptive Modifiers

Constituent	Percent of Total MSW		Descriptive Modifier
Food Waste	19%	19%	Readily
Garden Trimmings	6%		Moderately
Paper	38%		Moderately
Textiles	3%	47%	Moderately
Wood	2%		Slowly
Plastic	13%	15%	Slowly
Dirt, Ashes, Brick etc.	8%		Non-Decomposable
Glass	11%	19%	Non-Decomposable

Utilizing the following formula:

$$V_r = V_{rd} + V_{md} + V_{sd} + V_{nd} \tag{5.1}$$

where V_r is volume remaining, V_{rd} is the readily degradable original volume, V_{md} is the moderately degradable original volume, V_{sd} is the slowly degradable original volume, and V_{nd} is the non degradable original volume.

To theoretically determine the volume remaining for each of the descriptive modifier fraction of material, at any time, Findikakis et al. (1979) and Durmesouglu et. al. (2005) recommended that the following exponential decay formula and decay factors, ki be used for any given time ti:

$$V_r = V_o * e^{-k_i t_i} \tag{5.2}$$

where V_o is the original volume of the type of material, t_i is the time in question and k_i is varies with the state of decomposition of the waste in accordance with the following: readily degradable, $k_1 = 0.1386$; moderately degradable, $k_2 = 0.0231$; and, slowly degradable, $k_3 = 0.0173$.

To determine the time t_f, when almost the entire organic portion of the waste has degraded, an iterative process is adopted using the above formulae to determine when approximately 97 % of the organic portion of the waste remaining has been degraded.

Based upon the waste sample as a whole, this value equates to approximately 78.5 % of the waste mass, assuming that 81 % of the waste is degradable. This value was chosen to represent the practical limit of degradation and was based upon a point where further gas production becomes almost insignificant. Calculations to determine the time in years to approximate the portion degraded, and conversely the portion remaining, are performed using the following analyses and shown in Table 5.2 (modified from Tchobanoglous 1977) and Table 5.3:

Table 5.2 Typical Data on Ultimate Analysis of the Combustible Components in MSW

	Percent by Weight (dry basis)									
Component	W. In lbs	Percent Degradable Portion MSW	C	H	O_2	N	S	Ash	Degraded Portion %	V_r (%)
Food Waste	19	19%	48	6.4	37.6	2.6	0.4	5.4	94.6	0.010
Garden Trimmings	6	6%	47.8	6	38	3.4	0.3	4.8	95.2	0.003
Paper	38	38%	43.5	6	44	0.3	0.2	6.2	93.8	0.024
Wood	2	2%	49.5	6	42.7	0.2	0.1	1.6	98.4	0.000
Plastic	13	13%	60	7.2	22.8	0	0	10	90	0.013
Textiles	3	3%	55	6.6	31.2	4.6	0.15	2.6	97.4	0.001
Dirt, Ashes, Brick etc.	8	8%	26.3	3	2	0.5	0.2	68.2	31.8	0.055
Sub-total	89	89%								0.105
Non Combustible Portion										
Glass	11	11%								0.11
Sub-total	11	11%								0.11
Total MSW Remaining	100									0.215
Total MSW Combusted										78.5

Source: Tchobanoglous 1977

To determine the theoretical time at which the above amount of decomposition degradation occurs was determined and shown in Table 5.3 to be 138 years

Table 5.3 Determination of Time t_f Based Upon Findikakis et al (1979).

	V_o	V_r after 138 years	V_d%
$V_{rd} = 0.19*(e^{-0.1386t})$ (Food Waste)	0.19	0.00%	100.00%
$V_{md} = 0.44*(e^{-0.0231t})$ (Paper and Garden Trimmings Textiles)	0.47	1.94%	95.87%
$V_{sd} = 0.02 * (e^{-0.0173t})$ (Wood and Plastic)	0.15	0.62%	95.87%
$V_{nb} = 0.19\ V_o$ (Non Degradable Mass)	0.19	19.00%	0.00%
$V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$	1	21.56%	78.44%
		residual	decomposition
Therefore $V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$			
$V_{remaining} = V_r = 0.19V_o\ (e^{-0.1386t}) + 0.47\ V_o\ (e^{-0.0231t}) + 0..15\ V_o\ (e^{-0231t}) + 0.19\ V_o$			

5.2 Determination of Theoretical Gas Remaining

To determine the theoretical volume of gas remaining, the dry weight of the organic portion of the waste sample needs to be ascertained. Appendix E presents a typical sample computation to accomplish this. The total weight, W, needs to be adjusted by removing the weight of the non degradable portion of the waste, W_{nd} and the amount of water in the waste W_w. What remains is the dry weight of the organic portion of the waste, W_{org} (dry basis). By determining the percentage of material remaining using the formulae discussed above, for each modifier constituent, and multiplying those values by the original constituent percentage and the W_{org}, the degraded dry weight of each modifier constituent can be determined.

By utilizing the mass balance equation discussed in Chapter 2 (Equation 2.2.),

$$C_aH_bO_cN_d \rightarrow nC_wH_xO_yN_z{+}mCH_4{+}(a\text{-}nw\text{-}m)\ CO_2 + (c\text{-}ny\text{-}2a\ \text{-}2nw\text{-}m)H_2O{+}(d\text{-}nz)NH_3 \tag{2.2}$$

and the analysis presented in Table 2.1, one is able to theoretically determine the equation of the chemical formula for the overall waste material and the amount of gas remaining at any time of interest.

The following Figure 5.1 presents a graphical depiction of the theoretical gas produced and gas remaining versus time in years for the waste tested.

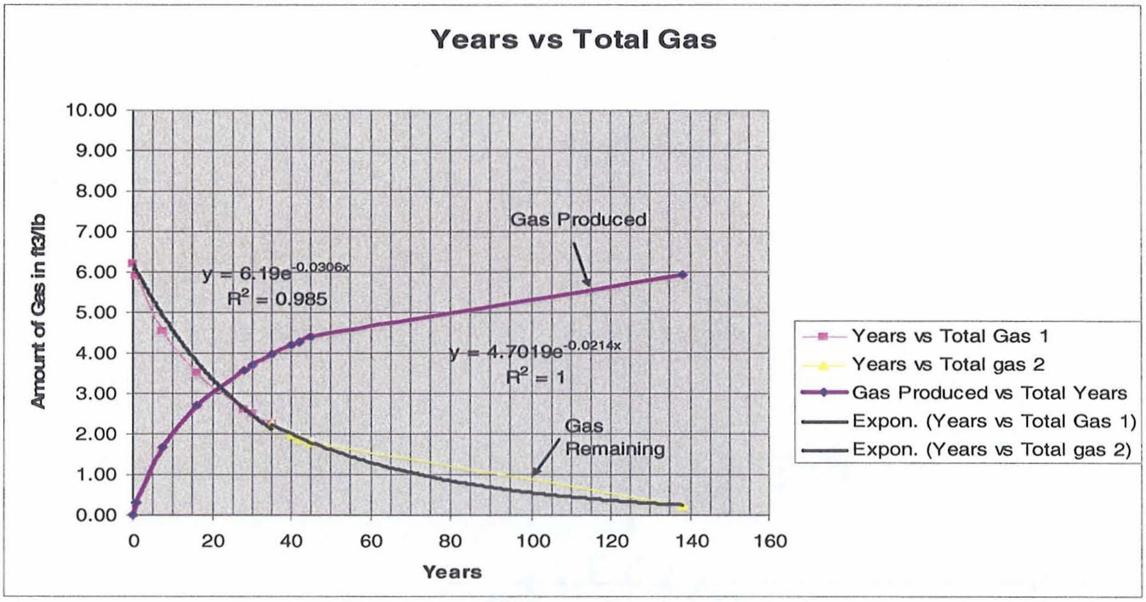

Figure 5.1 Theoretical gas produced and gas remaining vs. time.

Figure 5.2 shows the relationship between the laboratory determined values for (C + H)/L to the quantity of gas produced within the bioreactors and the time in days measured during the laboratory experiment at the time of (C + H)/L sample harvesting. By knowing the quantity of gas produced by the waste at each (C + H)/L value, a relationship between laboratory time and theoretical field time can be ascertained by using the relationships developed by Findikakis et.al. (1979) and Durmesouglu et al (2005), to determine the theoretical quantity of gas produced for time in years, as shown in Figure 5.1. This equates to comparing the quantity of gas produced per lb of waste in the laboratory to that computed theoretically in the field.

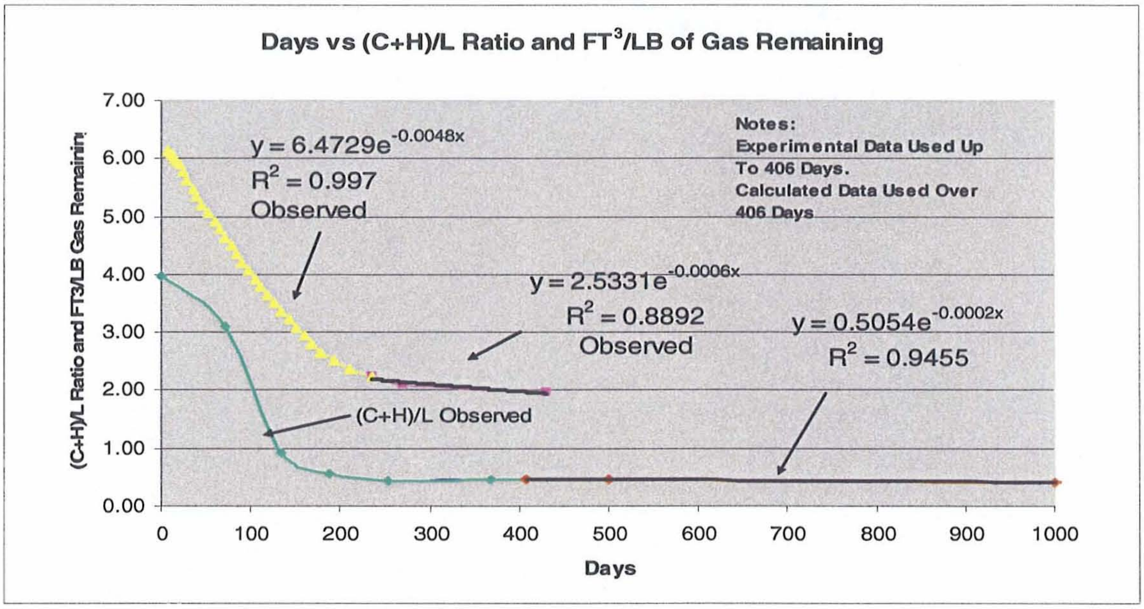

Figure 5.2 Observed (C + H)/L ratio and observed gas remaining vs. laboratory time.

5.3 Determination of (C + H)/L Ratio from C_{bio} and C_{ult}

The volume of waste remaining at t_f represents the lowest C_{bio}/C_{ult} ratio [(C + H)/L] that will occur for waste of this composition. C_{bio} is the quantity of food source in the waste available for degradation and C_{ult} represents the non degradable quantity of the waste. If C_{bio} is considered equivalent to the cellulose and hemicellulose portion of the waste, (C+H) and C_{ult} is considered equivalent to the lignin portion of the waste (L), then the C_{bio}/C_{ult} ratio can be considered to be equivalent to the (C + H)/L ratio. The (C + H)/L ratio at t_f equal to 138 years, represents the end point value of (C + H)/L ratio beyond which no further significant gas will be produced.

Table 5.4 depicts the ultimate analysis of the degradable portions of the waste tested herein. The values for carbon, hydrogen, oxygen and nitrogen have been normalized to account for the removal of the sulfur and ash content that were shown in Table 5.2.

Table 5.4 Typical Data on Ultimate Analysis of the Degradable Components in MSW (Modified from Tchobanogulous et al)

	Percent by Weight (dry basis)							
	Redistributed Content for C, H, O2, N w/o Sulfur and Ash							
Component	Percent Degradable Portion MSW	Carbon	Hydrogen	Oxygen	Nitrogen	Representative % of Total w/o ash content	% Ash	C_{ult} Carbon in Ash
Food Waste	19%	50.74	6.77	39.75	2.75	94.6	5.4	2.74
Garden Trimmings	6%	50.21	6.30	39.92	3.57	95.2	4.8	2.41
Paper	38%	46.38	6.40	46.91	0.32	93.8	6.2	2.88
Wood	2%	50.30	6.10	43.39	0.20	98.4	1.6	0.80
Plastic	13%	56.47	6.78	32.03	4.72	97.4	10	5.65
Textiles	3%	66.67	8.00	25.33	0.00	90	2.6	1.73
Dirt, Ashes, Brick, etc.	8%	82.70	9.43	6.29	1.57	31.8	68.2	56.40
	89%	403.47	49.77	233.62	13.14			
	Typical Data on Ultimate Analysis of the Degradable Components in MSW							
	Percent by Weight (dry basis excluding Sulfur and Ash)							

Source: Tchobanogulous et. al. 1977

Table 5.5 provides the data for the calculation of the theoretical C_{bio}/C_{ult} [(C + H)/L] ratio using the adjusted values depicted in Table 5.4 determined by removing the sulfur and ash contents. By multiplying the quantity of waste remaining by the redistributed quantity of carbon, shown in Table 5.4, the C_{bio} (C + H) for that constituent can be approximated. Similarly the carbon in the ash, determined by multiplying the total Carbon for each constituent by its respective percent ash yield the C_{ult}, Carbon in Ash for that constituent. This value approximates the C_{ult} (L) value for that constituent. By summing all the constituent C_{bio} and C_{ult} values the total (C + H) and L values for the waste at 138 years can be determined. By dividing C_{bio} by C_{ult} one obtains the (C + H)/L ratio for the waste at 138 years. The theoretical (C + H)/L value using this described method is 0.24.

Table 5.5 Determination of (C + H)/L Ratio at 138 Years

Constituents	% Decomposed after 138 years	Ult Remaining Ash Content	% Ash Left after 138 years	C_{ult} Carbon in Ash	Waste Remaining	C_{bio} Remaining	
Food Waste	1.000	5.4	5.40%	2.74	0.00000	0.00	
Garden Trimmings	0.959	4.8	4.60%	2.41	0.04126	2.07	
Paper	0.959	6.2	5.94%	2.88	0.04126	1.91	
Wood	0.908	1.6	1.45%	1.73	0.09187	4.62	
Plastic	0.908	10	9.08%	0.80	0.09187	6.12	
Textiles	0.959	2.6	2.49%	5.65	0.04126	2.33	
Dirt, Ashes, Brick etc.	1.000	68	68.00%	56.40	0.00000	0.00	
			Total	72.24		17.06	
						0.24	
							(C + H)/L
							0.24

Once the field time in years has been determined for the waste at various states of decomposition and utilizing a comparison between gas produced and the (C + H)/L ratio, the theoretical amount of waste remaining can be ascertained using the formulae (Equation 5.1) suggested by Findikakis et al (1979) and Durmesouglu et al (2005) as discussed above. After determining the weight of waste remaining, the amount of carbon available can be computed. Then, the values for C_{bio} and C_{ult} (C_{lignin}), shown in Table

5.6, may be determined for differing field times by using of the following formulae which are proved in Appendix F.

$$C_{bio} = (C + H)/L \;/\; 1+ [(C + H)/L] * \text{Total Carbon Available} \qquad (5.3)$$

$$C_{ult}\ (C_{lignin}) = \text{Total Carbon Available} - C_{bio} \qquad (5.4)$$

Table 5.6 Determination of C_{bio} and C_{ult} from (C + H)/L Ratio and Total Carbon Available

Field Time in Years	0	3.2	8	10.5	14.75	16	17	From Figures 5.1 and 5.2
C_{bio} / C_{lignin} Ratio	3.96	3.11	0.91	0.57	0.43	0.47	0.46	Laboratory Test
Total Carbon Available	403.47	368.09	328.53	312.17	288.76	282.68	278.03	Decay Formula
C_{bio}	322.12	278.53	156.52	113.34	86.83	90.38	87.60	Equation 5.3
C_{lignin}	81.34	89.56	172.00	198.84	201.93	192.30	190.43	Equation 5.4

5.4 Relationship Between Laboratory and Field Degradation Time

Using the relationships developed above that equate theoretical gas produced to years and actual gas produced to days, in the laboratory observed during this study, Figure 5.3 depicts the relationship between the time for degradation in the laboratory and the corresponding time for degradation in the field. This figure was prepared by equating the laboratory and field time in days to their common (C + H)/L ratios. By examining the curves shown in Figure 5.3 it can be determined that the ratio between rates of degradation in the laboratory bioreactors as compared to rates of degradation in the field, for the same (C + H)/L value varies from 5.2 to 21.6. This is based upon theoretical computations using the exponent ranges discussed by Findikakis (1979). Actual values observed in the field may vary as discussed later in the next chapter

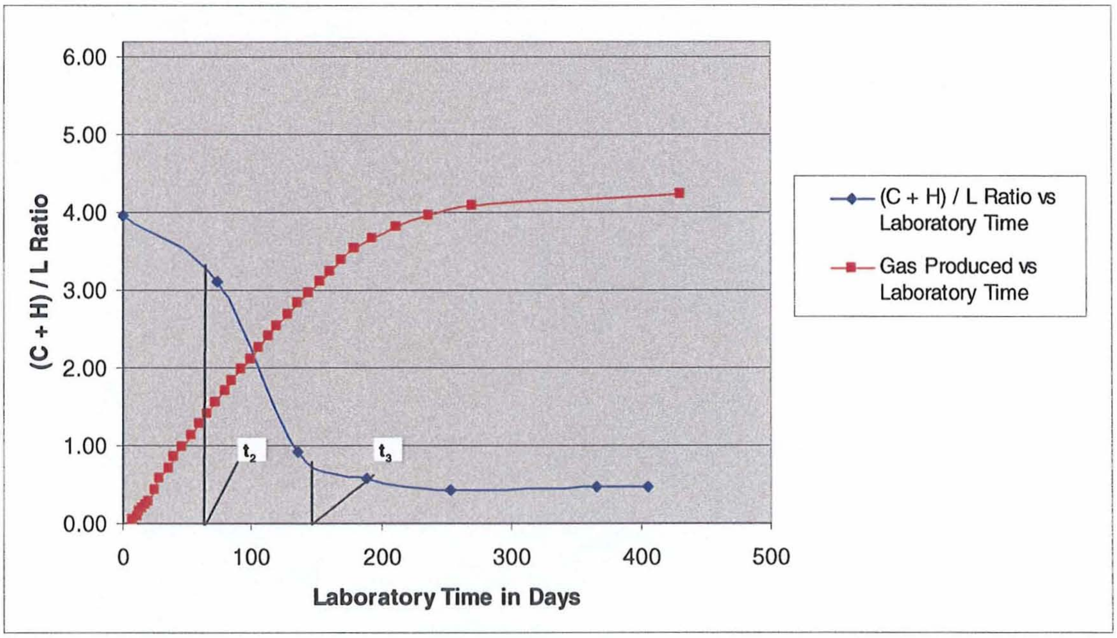

Figure 5.3 Relationship between laboratory time and field time vs. (C + H)/L ratio.

5.5 Development of the Model for Settlement

The proposed model utilizes conventional settlement models and considers the percent strain that can be predicted, dependent upon waste type, from the results of this study. This approach considers that volumetric strain is equal to vertical strain because the thickness of landfills is generally much smaller than their length and width. By characterizing the state of decomposition through the determination of the (C + H)/L ratio on recovered samples and utilizing the parameters listed here, it is possible to predict the settlement of the waste under external loading and/or under time dependent strain settlement from the time of application ,or filling, to the desired future time.

For settlement computation under external loading conditions, the primary settlement utilizing the C'_c values determined during the testing and shown on Table 4.8 and Figures 4.17 through 4.32 may be used in accordance with the following equation for each of the layers of waste exhibiting a different value of (C + H)/L:

$$\text{Primary Settlement } \rho_{\text{primary}} = H_o * C'_c * \text{Log } (p_o + \Delta p)/p_o \qquad (5.5)$$

where H_o is the thickness of the layer, C'_c is the Coefficient of Compression based upon strain, p_o is the existing overburden pressure at the center of the layer, and Δp is the change in pressure at the center of the layer caused by the external load.

When the actual value of C'_c for a given (C + H)/L ratio is not known from testing, an approximate value for C'_c may be obtained from Figure 4.16. The figure indicates that the average C'_c value varies from 0.220 to 0.195 for all values of (C + H)/L tested.

In accordance with Figure 4.15, primary settlement occurs quickly due to the expulsion of gas and water from within the void space of the relatively permeable waste material.

Following primary settlement, mechanical inorganic secondary settlement occurs until such time that biodegradation settlement begins. Inorganic mechanical settlement for each layer of waste, exhibiting a different (C + H)/L ratio, may be determined in accordance with the following equation:

$$\text{Secondary Inorganic Settlement } \rho_{\alpha} = H_o * C'_{\alpha} * \text{Log}(t_2/t_1) \tag{5.6}$$

where t_1 is the time defining the end of primary settlement and t_2 is the time at the start of biodegradation settlement.

When the actual value of C'_{α} for a given (C + H)/L ratio is not known from testing, an approximate value for C'_{α} may be obtained from Figure 4.33. The figure indicates that the average C'_{α} varies from 0.0065 to 0.0085 for all values of (C + H)/L tested.

Figure 4.15 indicates that t_1 (t_{90}) occurs within four minutes of application of the load increment during consolidometer testing. This equates to approximately 30 minutes, or 70 minutes in field time when extrapolated to actual settlement data observed at the Kingsland Landfill in North Arlington, New Jersey (PS&S 2001) or the comparison of theoretical (C + H)/L ratios shown in Figure 5.3. These values were determined by equating the laboratory curve for time at the beginning of biodegradation settlement to a parallel settlement plot that sets the beginning of biodegradation settlement to that actually observed in the field at the Kingsland Landfill (see Figure 5.4. or calculated from theoretical values for (C + H)/L in the field (Figure 5.3).

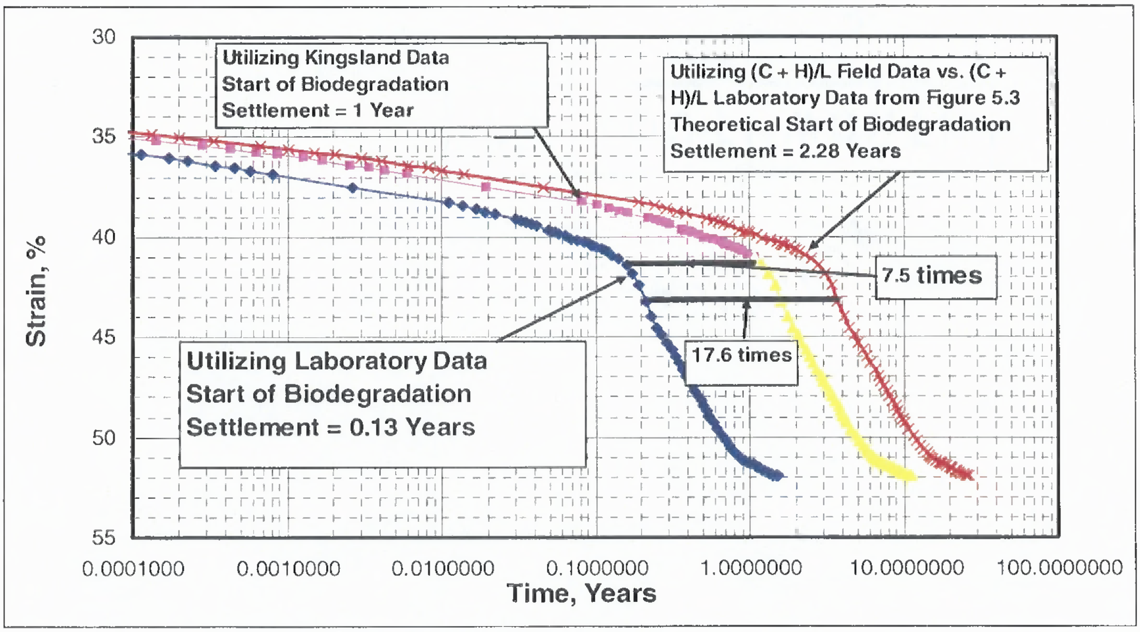

Figure 5.4 Relationship between start of biodegradation settlement for laboratory and field.

Observation of actual data at the Kingsland Landfill indicates that t_2, the beginning of biodegradation settlement, occurs about one year, following placement of waste.

After approximately one year, biodegradation settlement controls the behavior of the waste and the following formula may be used to model expected settlement:

$$\text{Biodegradation Settlement } \rho_\beta = H_o * C_\beta * \text{Log}(t_3/t_2) \qquad (5.7)$$

where t_3 is the start of final tertiary biodegradation settlement and others variables as discussed previously.

When the actual value of C_β for a given (C + H)/L ratio is not known from testing, an approximate value for C_β may be obtained from Figure 4.34. The figure indicates that the average C_β varies from 0.15 to 0.02 for all values of (C + H)/L tested.

If the desired settlement value is for a time that extends beyond t_3, then the Secant_β coefficient may be used as a surrogate for the C'_α and C_β portions of the settlement model equations in accordance with the following formula:

$$\text{Secant Modulus of Biodegradation Settlement } \rho_{\mathrm{Secant}\beta} = H_o * \mathrm{Secant}_\beta * \mathrm{Log}(t_3/t_1) \tag{5.8}$$

where values are defined as before

When the actual value of the Secant Modulus of Biodegradation, Secant_β, for a given (C + H)/L ratio is not known from testing, an approximate value for Secant_β may be obtained from Figure 4.35. The figure indicates that the average Secant_β value varies from 0.0240 to 0.0110 for all values of (C + H)/L tested. Use of the Secant_β coefficient outside of the suggested range of settlement time will over predict the quantity of settlement that will occur below time t_3.

Following ρ_β, beyond time t_3, tertiary biodegradation settlement $\rho_{\alpha\beta}$ begins and settlement is governed by this long term residual tertiary mechanism. To compute $\rho_{\alpha\beta}$, the following formula can be used:

Tertiary Biodegradation Settlement $\rho_{\alpha\beta} = H_o * C_{\alpha\beta} * \text{Log}(t_f/t_3)$ (5.9)

where t_f is the required time of settlement, others as before.

When the actual value of $C_{\alpha\beta}$ for a given (C + H)/L ratio is not known from testing, an approximate value for $C_{\alpha\beta}$ may be obtained from Figure 4.36. The figure indicates that the average $C_{\alpha\beta}$ value varies from 0.0340 to 0.0100 for all values of (C + H)/L tested.

The following series of equations may be used to obtain the value of anticipated settlement, at some time t_f, that is less than t_3 at a landfill that is subjected to an external loading

(At $t_f < t_3$):

$$\rho_f = \rho_{\text{primary}} + \rho_\alpha + \rho_\beta \tag{5.10}$$

or

$$\rho_f = H_o\,[(C'_c * \text{Log}\,(\,p_o + \Delta p)/p_o) + (C'_\alpha * \text{Log}(t_2/t_1)) + (C_\beta * \text{Log}(t_f/t_2))] \tag{5.11}$$

For anticipated settlement under the same conditions but without an external loading:

$$\rho_f = \rho_\alpha + \rho_\beta \tag{5.12}$$

or

$$\rho_f = H_o\,[(C'_\alpha * \mathrm{Log}(t_2/t_1)) + (C_\beta * \mathrm{Log}(t_f/t_2))] \tag{5.13}$$

The following series of equations should be used to approximate the value of anticipated settlement at some time t_f that is greater than t_3 at a landfill that is subjected to an external loading

(At $t_f > t_3$):

$$\rho_f = \rho_{primary} + \rho_{Secant\beta} + \rho_{\alpha\beta} \tag{5.14}$$

or

$$\rho_f = H_o\,[(C'_c * \mathrm{Log}\,(\,p_o + \Delta p)/p_o) + (\mathrm{Secant}_\beta * \mathrm{Log}(t_3/t_1)\ + (C_{\alpha\beta} * \mathrm{Log}(t_f/t_3))] \tag{5.15}$$

For anticipated settlement under the same conditions but without an external loading:

$$\rho_f = \rho_{Secant\beta} + \rho_{\alpha\beta} \tag{5.16}$$

or

$$\rho_f = H_o[(Secant_\beta * Log(t_3/t_1)) + (C_{\alpha\beta} * Log(t_f/t_3))] \tag{5.17}$$

CHAPTER 6

VALIDATION OF THE MODEL

6.1 Validation of Developed Model on Actual Landfill Data

This section discusses the validation of the model and the relationship between the types of settlement anticipated and the phases of landfill decomposition. Figure 6.1 depicts these phases of decomposition and their associated settlement processes utilizing a square root of time plot versus percent strain from Sample A (LT) at a loading increment of 2.56 tsf. This figure, based upon actual laboratory data serves to validate the hypothesis present in Section 1.2 and Figure 1.1.

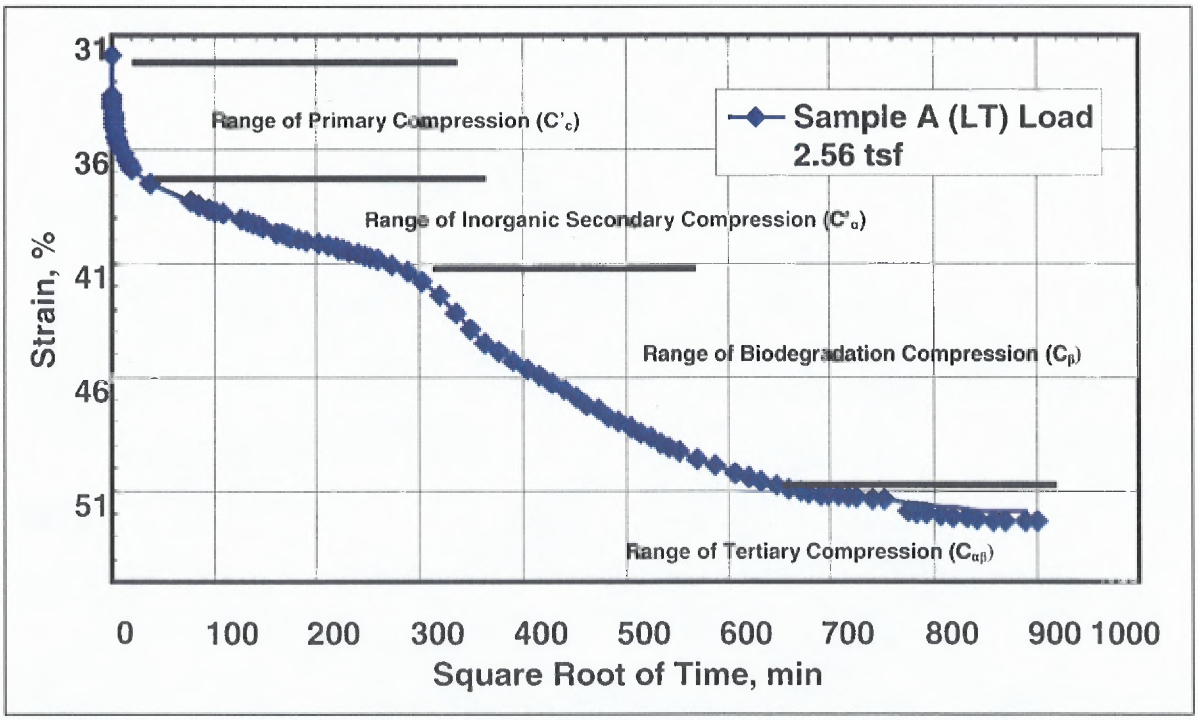

Figure 6.1 Phases of decomposition and associated settlement processes.

To further validate the model developed, observed field settlement data was utilized from several sources obtained from the literature search and from actual data observed from topographic surveys performed by Paulus, Sokolowski and Sartor, LLC on the Kingsland Landfill from 1992 to 2008. The pattern of settlement shown in Figure 6.1 was also observed in field data obtained from the above sources.

6.2 Field Validation Example #1

Figure 6.2 depicts the settlement of 16 selected points from the topographic surveys performed for 1992, 1993, 2008 and 2008 at the Kingsland, Landfill, North Arlington, NJ. Since the Landfill was closed in 1987 and the settlement data observed began in 1992, an initial (C + H)/L value of 3.11 was selected as representative. This value was selected because a five year old waste in the field is equivalent to a three to six month old waste in the laboratory (using a field time to laboratory time ratio that varies from 7.5 to 17.6 observed and theoretical, respectively). The settlement data from Points 9 and 10 indicate a possible slope failure condition, which did occur at the landfill in this area as the result of excessive filling. Point 1 may also indicate possible slope failure conditions, since it is in the same general location of the reported failure area. Other points, where the slope is flat or turns upward, are most likely the result of filling of the landfill between 2000 and 2008 as a result of composting and construction activities. Also presented in this figure are the plots computed from data obtained from the laboratory plots extended 7.5 and 17.6 times as discussed previously.

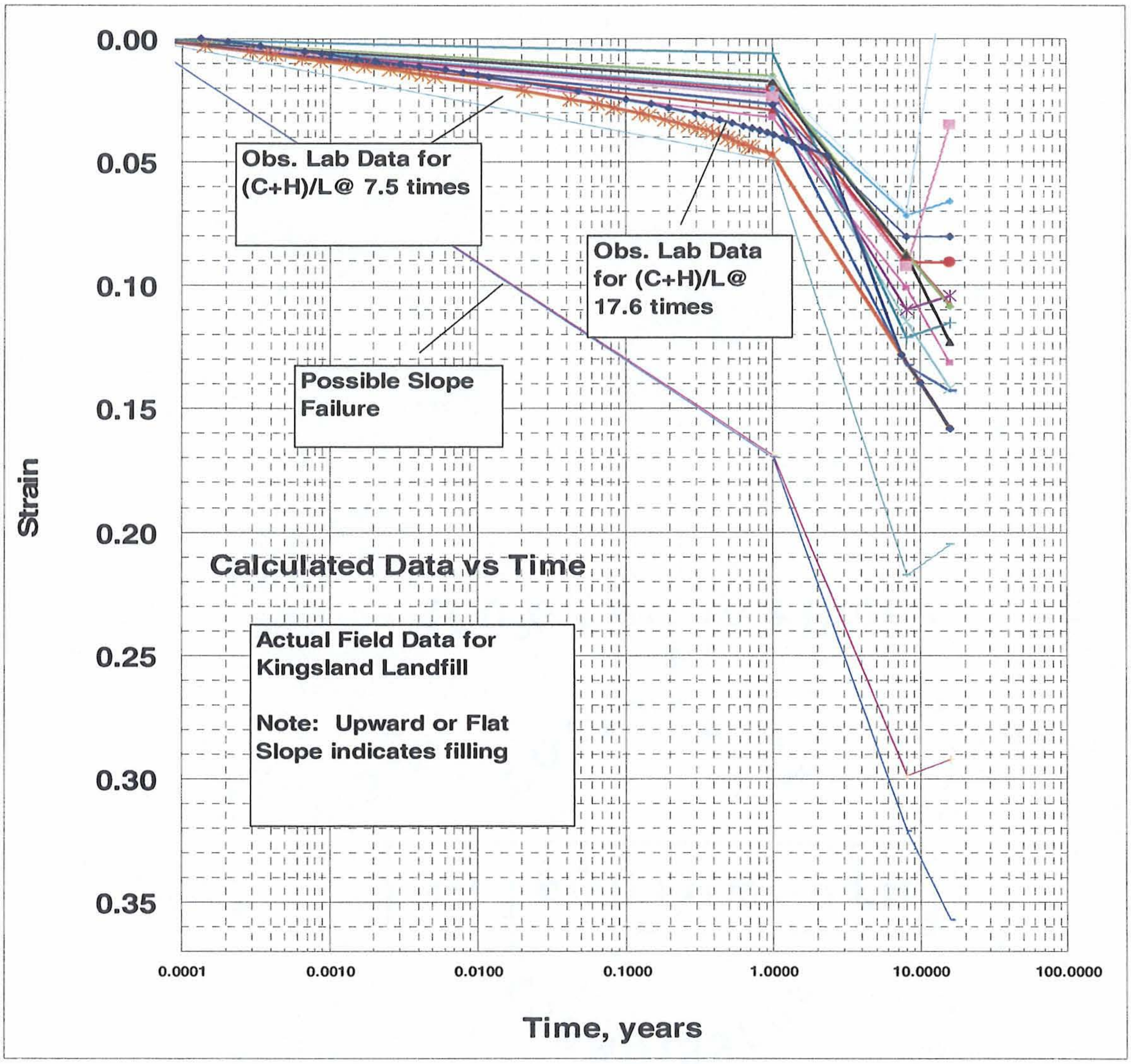

Figure 6.2 Settlement data for Kingsland Landfill 1992 to 2008.
Source: PS&S, LLC topographic surveys 1992, 1993, 2000 and 2008

Table 6.1 depicts the actual elevation and strain data observed during the surveys performed in 1992, 1993, 2000 and 2008. Figure 6.3 depicts the four surveys utilized and are shown enlarged in Appendix G. Strains were calculated based upon the observed settlements using the elevation at that point as the original height H_o.

Table 6.1 Observed Settlement and Strain for Kingsland Landfill

Location Point	1992	1993	2000	2008	Comments
	Elevation (ft)	Elevation (ft)	Elevation (ft)	Elevation (ft)	
A	115.7	112	104	100.5	
B	117.8	116	107.5	105	
C	104.7	102.2	95	101	Some spot filling between 2005 and 2008
D	114	112	104	100	
E	112	109	103	103	Some spot filling between 2005 and 2008
F	92.5	91	86	96	
1	80.5	76.5	63	64	Some spot filling between 2005 and 2008
2	86.5	84	79	77.2	
3	86.2	84.2	76.3	74	
4	90.5	89	81	81.5	Some spot filling between 2005 and 2008
5	98.6	98	91	91	Some spot filling between 2005 and 2008
6	82.5	82	72.5	73	Some spot filling between 2005 and 2008
7	94.5	92	82	81	
8	83.5	81.8	77.5	78	Some spot filling between 2005 and 2008
9	77	64	54	54.5	Some spot filling between 2005 and 2008
10	82.5	68.5	56	53	

Table 6.1 Continued Observed Settlement and Strain for Kingsland Landfill

Location Point	Strain ε %	Strain ε %	Strain ε %	Strain ε %	
	1992	1993	2000	2008	Comments
	0.00005	1	8	16	Year of Interest
A	0	3%	10%	13%	
B	0	2%	9%	11%	
C	0	2%	9%	4%	
D	0	2%	9%	12%	
E	0	3%	8%	8%	
F	0	2%	7%	-4%	
1	0	5%	22%	20%	Possible Slope failure
2	0	3%	9%	11%	
3	0	2%	11%	14%	
4	0	2%	11%	10%	
5	0	2%	9%	9%	
6	0	1%	12%	12%	
7	0	3%	13%	14%	
8	0	2%	7%	7%	
9	0	17%	30%	29%	Possible Slope failure
10	0	17%	32%	36%	Possible Slope failure

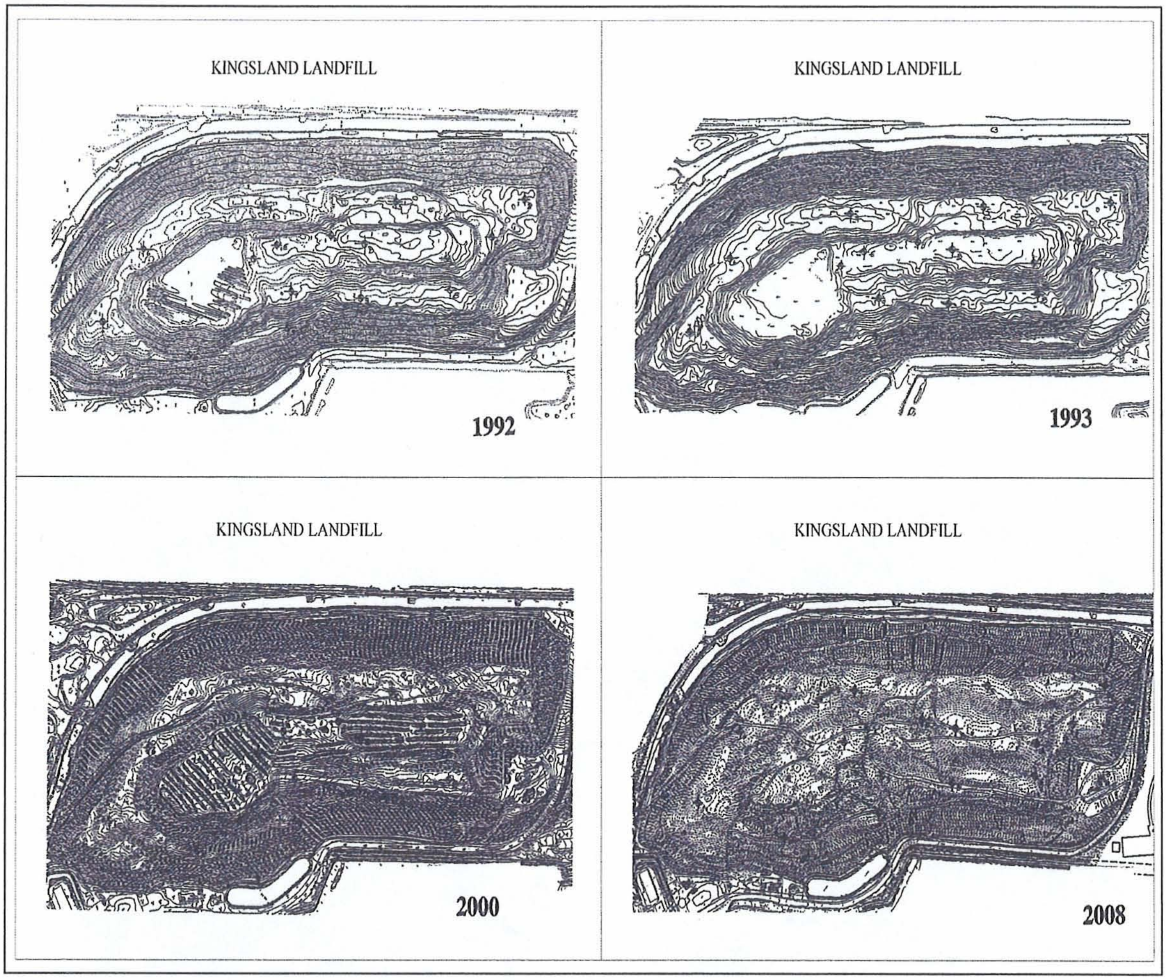

Figure 6.3 1992, 1993, 2000 and 2008 topographic plots Kingsland Landfill.
Source: PS&S, LLC topographic surveys 1992, 1993, 2000 and 2008

Table 6.2 depicts the calculation for settlement after 16 years using the developed model for a landfill thickness, H_o of 85 feet.

Table 6.2 Calculation Using Data and Model

Landfill 1965 to 1987 = 22 years in operation					
Using This Work with (C + H)/L values of 3.11:					
t_p = 30 min	t_2 = 4204800 min				
t_1 =525600 min	t_f = 8409600 min				
Example Calculation for 16 years					
$\rho_{16} = C_{\alpha\ @3.11}$ x $\text{Log}(\ t1/\ t_o) + C_{\beta\ @3.11}$ x $\text{Log}(\ t_f\ /\ t_1)$					
$\rho_{16} =$	0.006*LOG(525600/30)+0.090*LOG(8409600/525600)				
$\rho_{16} =$	0.1338	times landfill 1992 thickness (85) =		11.38	feet

Settlement for years 1, 8 and 16 was computed using the information shown in Table 6.3 and the developed model: These values were computed for a field to laboratory time ratio of 7.5. Similar computations can be made for a field to laboratory time ratio of 17.6 and for a (C + H)/L ratio value of 2.50 at time ratio of 7.5. The calculations are shown in Appendices H and I, respectively. A comparison of the percent differences between observed and calculated settlements, for similar years between (C + H)/L ratio values of 3.11 and 2.50 indicate that the choice of a (C + H)/L ratio value of 3.11 yields a better correlation. This comparison is shown as Table I.7 in Appendix I.

Table 6.3 Comparison of Calculated and Observed Settlement Values in Feet for Field to Laboratory Time Ratio of 7.5

	Calculated Strains			$t_p = 30$ minutes					
	Years	0	1		8		16		
		0	0.025		0.107		0.1338		
Landfill Depth	Calc ρ								
from Elev.	Point		Calc	Obs	Calc	Obs	Calc	Obs	
115.70	A	0	2.95	3.70	12.35	11.70	15.48	15.20	
117.80	B	0	3.00	1.80	12.57	10.30	15.77	12.80	
104.70	C	0	2.67	2.50	11.18	9.70	14.01	3.70	Some spot filling
114.00	D	0	2.90	2.00	12.17	10.00	15.26	14.00	
112.00	E	0	2.85	3.00	11.95	9.00	14.99	9.00	Some spot filling
92.50	F	0	2.36	1.50	9.87	6.50	12.38	-3.50	Some spot filling
80.50	1	0	2.05	4.00	8.59	17.50	10.77	16.50	Indicates possible slope failure
86.50	2	0	2.20	2.50	9.23	7.50	11.58	9.30	
86.20	3	0	2.19	2.00	9.20	9.90	11.54	12.20	
91.00	4	0	2.32	2.00	9.71	10.00	12.18	9.50	Some spot filling
100.10	5	0	2.55	2.10	10.68	9.10	13.40	9.10	Some spot filling
82.50	6	0	2.10	0.50	8.81	10.00	11.04	9.50	Some spot filling
94.50	7	0	2.41	2.50	10.09	12.50	12.65	13.50	
83.50	8	0	2.13	1.70	8.91	6.00	11.17	5.50	Some spot filling
77.00	9	0	1.96	13.00	8.22	23.00	10.31	22.50	Indicates slope failure
82.50	10	0	2.10	14.00	8.81	26.50	11.04	29.50	Indicates slope failure

The difference between the calculated and observed values are shown in Table 6.4

Table 6.4 Percent Difference between Calculated and Observed Settlement

Point	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
A	2.95	3.70	20%	12.35	11.70	-6%	15.48	15.20	-2%
B	3.00	1.80	-67%	12.57	10.30	-22%	15.77	12.80	-23%
C	2.67	2.50	-7%	11.18	9.70	-15%	14.01	3.70	-279%
D	2.90	2.00	-45%	12.17	10.00	-22%	15.26	14.00	-9%
E	2.85	3.00	5%	11.95	9.00	-33%	14.99	9.00	-67%
F	2.36	1.50	-57%	9.87	6.50	-52%	12.38	-3.50	454%
1	2.05	4.00	49%	8.59	17.50	51%	10.77	16.50	35%
2	2.20	2.50	12%	9.23	7.50	-23%	11.58	9.30	-24%
3	2.19	2.00	-10%	9.20	9.90	7%	11.54	12.20	5%
4	2.32	2.00	-16%	9.71	10.00	3%	12.18	9.50	-28%
5	2.55	2.10	-21%	10.68	9.10	-17%	13.40	9.10	-47%
6	2.10	0.50	-320%	8.81	10.00	12%	11.04	9.50	-16%
7	2.41	2.50	4%	10.09	12.50	19%	12.65	13.50	6%
8	2.13	1.70	-25%	8.91	6.00	-49%	11.17	5.50	-103%
9	1.96	13.00	85%	8.22	23.00	64%	10.31	22.50	54%
10	2.10	14.00	85%	8.81	26.50	67%	11.04	29.50	63%

For all data, except Points A, B, D, 2, 3 and 7, possible slope failure and or spot filling at various times may have occurred. At Points C, E, F, 4, 5, 6, and 8 some filling may have occurred between observation years 2000 and 2008. For Points A, B, D, 2, 3 and 7, where no slope failure or reported filling occurred and Points C, 4, 5, 6, and 8, where filling only occurred between years 2000 and 2008, the following Table 6.5 indicates the percentage difference between points over the four time durations observed.

Comparing this table to Table H.6 in Appendix H, shifting the start of biodegradation an additional 1.29 years yields smaller calculated settlement values which result in approximately 20 percent reductions compared to the previously calculated values.

Table 6.5 Percent Difference between Calculated and Observed Settlement for Points A, B, C, D, 2, 3, 4, 5, 6, 7 and 8

Point	1993			2000			2008		
	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
A	2.95	3.70	20%	12.35	11.70	-6%	15.48	15.20	-2%
B	3.00	1.80	-67%	12.57	10.30	-22%	15.77	12.80	-23%
C	2.67	2.50	-7%	11.18	9.70	-15%	Filling 2000 - 2008		
D	2.90	2.00	-45%	12.17	10.00	-22%	15.26	14.00	-9%
2	2.20	2.50	12%	9.23	7.50	-23%	11.58	9.30	-24%
3	2.19	2.00	-10%	9.20	9.90	7%	11.54	12.20	5%
4	2.32	2.00	-16%	9.71	10.00	3%	Filling 2000 - 2008		
5	2.55	2.10	-21%	10.68	9.10	-17%	Filling 2000 - 2008		
6	2.10	0.50	-320%	8.81	10.00	12%	Filling 2000 - 2008		
7	2.41	2.50	4%	10.09	12.50	19%	12.65	13.50	6%
8	2.13	1.70	-25%	8.91	6.00	-49%	Filling 2000 - 2008		

Except for some discrete areas where arching or non reported filling may have occurred, Table 6.5 shows a good relationship between actual observed results and actual results.

6.3 Field Validation Example #2

The following example was obtained from a Converse Consultants report dated May 5, 2000 and entitled “Stability Assessment of Kingsland Park Sanitary Landfill (KPSL)". The report says that “the elevation of the landfill was +125 feet in 1987” when the landfill was closed and “has settled at least 15 feet to Elevation +110 or +100”. Utilizing this data, it would appear that the landfill was observed to settle between 15 and 25 feet from 1987 to 2000. Depending upon the (C + H)/L ratio of the placed waste differing values of settlement would be computed. The computed settlement, using the developed model, would be as shown in Table 6.6, assuming that the waste exhibited a (C + H)/L ratio of 3.96 or 3.11. Figures 6.4 and 6.5 depict the various (C + H)/L plots that would be utilized for the computations.

Table 6.6 Calculation of Landfill Settlement

Using Developed Model with (C + H)/L values of 3.11 and 3.96				
t_p =30 min	t_2 = 3258720			
t_1 = 525600	t_f = 6832800 min			
t_1 is start of biodegradation				
t_2 is start of tertiary biodegradation creep				
$\rho_{13\ at3.11} = C'_{\alpha\ at3.11}$ x $Log(t_1/t_p)+C_{\beta\ at3.11}$ x $Log(t_2/t_1)+C_{\alpha\beta\ at3.11}$ x $Log(t_f/t_2)$				
$\rho_{13\ at3..96} = C'_{\alpha\ at3.96}$ x $Log(t_2/t_o)+C_{\beta\ at3.96}$ x $Log(t_2/t_1)+C_{\alpha\beta\ at3.96}$ x $Log(t_f/t_2)$				
$\rho_{13\ at3.11}$ =	0.006*LOG(525600/30)+0.0900*LOG(3258720/525600)+.0260*LOG(6632800/3258720)			
$\rho_{13\ at3.11}$ =	0.104801353	times landfill 1987 thickness (125) =	13.10	ft
Use Secant Modulus				
$\rho_{13\ at3.11} = Secant_{\beta\ at3.11}$ x $Log(t_2/t_o)+C_{\alpha\beta\ at3.11}$ x $Log(t_f/t_2)$				
$\rho_{13\ at3.11}$ =	0.0236*LOG(3258720/30)+.0260*LOG(6632800/3258720)			
$\rho_{13\ at3.11}$ =	0.126872745	times landfill 1987 thickness (125) =	15.86	ft
$\rho_{13\ at3.96}$ =	0.009*LOG(525600/30)+0.1470*LOG(3258720/525600)+.0340*LOG(6632800/3258720)			
$\rho_{13\ at3.96}$ =	0.174509142	times landfill 1987 thickness (125) =	21.81	ft
Use Secant Modulus				
$\rho_{13\ at3.96} = Secant_{\beta\ at3.96}$ x $Log(t_2/t_o)+C_{\alpha\beta\ at3.96}$ x $Log(t_f/t_2)$				
$\rho_{13\ at3.96}$ =	0.0300*LOG(3258720/30)+.0340*LOG(6632800/3258720)			
$\rho_{13\ at3.96}$ =	0.164349718	times landfill 1987 thickness (125) =	20.54	ft

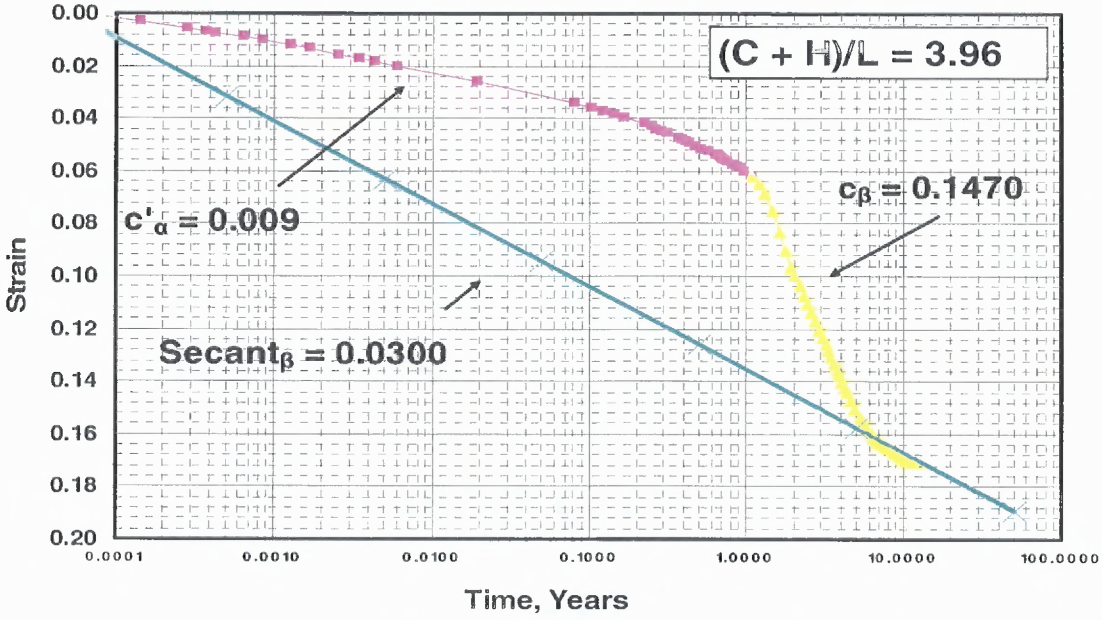

Figure 6.4 Settlement plot of waste at (C + H)/L = 3.96.

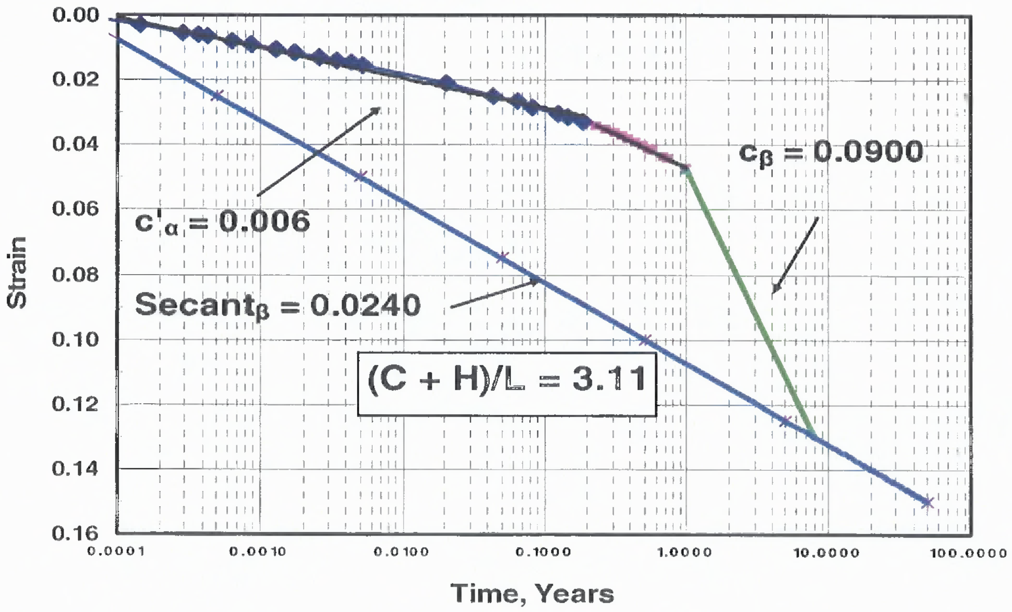

Figure 6.5 Settlement plot of waste at (C + H)/L = 3.11.

The calculated values for settlement appear to agree favorably with the estimates made by Converse Consultants in their report.

6.4 Field Validation Example #3

The following example is from an old landfill in Connecticut called Site C that is 40 to 50 years old and cited by Edil, Ranguette and Wuellner (1990). The waste was excavated and re-deposited and compacted in another location. A value of (C + H)/L = 0.58 was used, because of the age of the waste, and the consolidation properties for that (C + H)/L value utilized. Because the waste was re-deposited and re-compacted this example should not experience large settlements due to biodegradation or void collapse and should give closer computed settlement values to those calculated. To determine the settlement use was made of Figure 6.6 below, and strain values selected from the graph at the various times observed by Edil et al (1990).

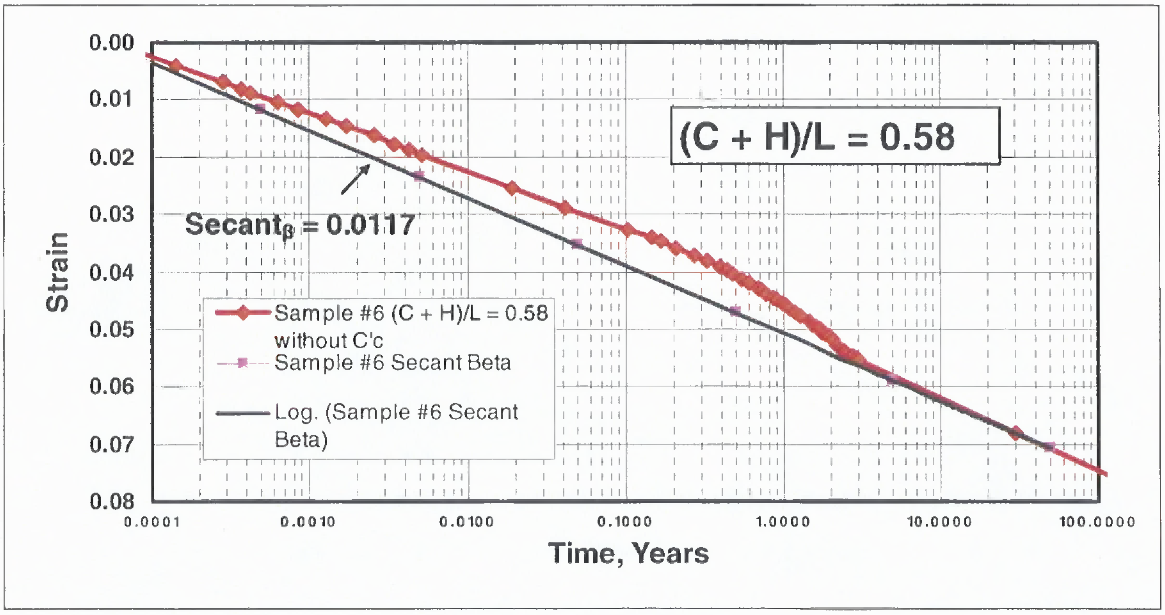

Figure 6.6 Plot of waste at (C + H)/L = 0.58.

Table 6.7 depicts the settlements, observed by Edil et al (1990), at six locations on a landfill that the authors labeled SP#2 through SP#7. Settlement readings were taken, under self weigh, t for time durations ranging from 3.3 to 4.1 years. The value for t_1 was taken as equal to 30 minutes as previously.

Table 6.7 Settlement Observations Made by Edil et.al. (1990) in Connecticut

SP #	H_o in meters	Obs. ρ	Duration years	Obs. Strain	Calc. ρ (m)	Calc. /Obs %	% Difference
84-2	10.06	0.65	4	0.057	0.5734	88%	-12%
84-3	10.06	0.58	4	0.057	0.5734	99%	-1%
84-4	11.58	0.6	4.1	0.058	0.6716	112%	12%
84-5	5.49	0.33	4.1	0.058	0.3184	96%	-4%
84-6	10.06	0.61	3.9	0.056	0.5634	92%	-8%
84-7	11.58	0.52	3.3	0.055	0.6369	122%	22%

A detailed step by step calculation example for this problem is shown in Appendix J. The values calculated using the model described herein agree favorably with the settlement values observed by Edil et al.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The work performed herein utilized the data obtained from the results of oedometer (consolidometer) testing on 13 identical waste samples that were prepared in the laboratory based upon typical northeast region waste characterization studies performed by the author as a part of his work for Paulus, Sokolowski and Sartor, LLC. A sample of Humus, Sample H-10, was also prepared and placed within an oedometer for testing. The samples were allowed to degrade (decompose) within bioreactors that were kept within a water bath at approximately 110 ^{o}F to simulate conditions within a landfill (see Appendix A).

Generated gas was collected in SKC (tedlar-like) sample collection bags and measured. The state of biodegradation was determined utilizing collected gas volume measurements as well as by testing for the (C + H)/L ratio of the sample just prior to oedometer testing. The samples were sent to a laboratory in the University of North Carolina for the required testing.

The sample of Humus, Sample H-10, was held at a constant stress of 2.56 tsf for 593 days and its consolidation coefficients values of C'_c, C'_α, C_β, $Secant_\beta$, and $C_{\alpha\beta}$ were determined. Sample A(LT) was left in the oedometer, under a stress of 2.56 tons per square foot (tsf), for up to 627 days (see Appendix B). Samples 5, 6, 7, 8, 9, 10, 11 and 12 were left in the oedometer, under a stress of 2.56 tons per square foot (tsf), for 155 to 173 days, to determine the consolidation coefficients C'_c, C'_α, C_β, $Secant_\beta$, and $C_{\alpha\beta}$ that would be needed for subsequent settlement analyses. Samples A, B, 1, 2, 3 and 4 were left in the oedometer for 56 to 63 days, not a sufficient length of time to determine all of the coefficients listed above. However, charts and graphs were established from the data acquired that was sufficient to estimate the values that could be used for the coefficients not determined by laboratory testing.

7.2 Conclusions

Based upon the results of the laboratory testing and the validation of the model the following conclusions can be made:

1) The results of this research study have shown that there are four distinct phases of compression. These phases consist of primary compression, secondary inorganic compression, biodegradation compression and tertiary compression. The results of the time versus strain deformation tests conducted in this study allow for the identification and quantification of the beginning and end of these phases.

2) Based upon the results of the study, it is possible to determine the rate parameter and settlement magnitude due to biodegradation using (C + H)/L ratio values. As an example, it was observed that a distinct value of the (C + H)/L ratio may be assigned to the beginning and end of the biodegradation compression phase. For the waste tested within this study, these values were observed to be approximately 3.00 and 0.50, respectively. These values may vary depending upon the composition and nature of the waste tested.

3) The results indicate that C'_c varies from 0.2445 to 0.1831 for the MSW samples and 0.2145 for the Humus H-10 sample. An exponential comparison of C'_c and the (C + H)/L ratio indicates that the value of C'_c decreases with decreasing (C + H)/L

within this narrow range. Earlier work by Hossain, Barlaz and Gabr (2003) indicated that C'_c increased with decreasing (C + H)/L. In their work they only tested samples with a (C + H)/L value of less than 1.29.

4) The values for C'_α, obtained under a constant stress of 2.56 tsf, range from 0.0050 to 0.0095 for the waste samples and 0.0056 for the Humus. Graphical comparisons between the (C + H)/L ratio and C'_α for samples tested were made. The values of C'_α were averaged between sample testing pairs (e.g. samples A and B, 1 and 2, 3 and 4) and compared to averaged (C + H)/L ratios for the same testing pairs. The results for the loading increment 2.56 tsf show an upward sloping trend for C'_α with respect to decreasing (C + H)/L.

5) The value for the coefficient C_β at 2.56 tsf is 0.0.1470, for Sample A (LT), and 0.0540 for Sample H-10. Graphical comparisons between C_β and the (C + H)/L ratio were similarly made. The values for C_β ranged from 0.1470 to 0.0150 for the waste samples. As expected, C_β was observed to decrease as (C + H)/L decreased. To fill in a gap in the data, caused by the removal of samples from the oedometer too early, an exponential curve was fitted, as a best choice, to depict the changes in C_β between known points. This method was chosen because the coefficient value C_β depicts biodegradation effects which are generally modeled exponentially. The results yielded good estimates for calculation purposes which were confirmed by field data.

6) The results of the testing indicate that a coefficient, termed the Biodegradation Secant Modulus, Secant_β, can be used to determine settlement estimates for long-term settlement that exceeds the time value t_3, the time when tertiary biodegradation creep settlement begins. The Biodegradation Secant Modulus represents

the slope of the curve from the onset of C'_{α}, determined to be 30 minutes in the field (four minutes in the laboratory) and the start of tertiary $C_{\alpha\beta}$ settlement versus the (C + H)/L ratio. The values of Secant_{β} were observed to be directly proportional to the (C + H)/L ratio, varying from 0.0300 to 0.0109. Exponential curve fitting methods were used similar to that for C_{β}.

7) The value for $C_{\alpha\beta}$ is 0.0340 for Sample A (LT) and 0.0235 for Sample H-10. Graphical relationships between $C_{\alpha\beta}$ and the (C + H)/L ratio indicate that the value of $C_{\alpha\beta}$ range from 0.0055 to 0.0340 decreasing as (C + H)/L decreases, as would be expected, approaching values similar to those of organic soils, which was the original premise of this work. Exponential curve fitting methods were used similar to that for C_{β}.

8) The results of the study make it possible to determine a relationship between the start of biodegradation in the laboratory and the field based upon the measured (C + H)/L ratio values determined during testing and the theoretically computed values in the field. This relationship would be dependent upon the nature and type of waste.

9) The validation examples generally show good correlation between the observed settlements and the predicted model settlements for waste similar to the characterization of the waste tested. Some discrepancies exist between the two and most likely can be attributed to the lack of compaction of the waste and the presence and collapse of voids and nested material within the landfill. It is readily apparent that when the waste material is compacted, the correlations between the observed and the predicted settlements are much better. These results are for the sample of waste with a (C + H)/L ratio of 0.58 utilizing a time ratio for the start of biodegradation between field and

observed laboratory values of 5.2. Using a higher value of 17.6 for this ratio, which was derived from a theoretical comparison of the laboratory and Findikakis' et al (1979) method, yields smaller calculated settlement values which result in approximately 20 percent reductions compared to the previously calculated values for 5.2.

CHAPTER 8

RECOMMENDATIONS

8.1 Suggested Methodology for Estimating Biodegradation Settlement of MSW of Varying Characterization

To further refine and develop a model that may be used for waste material of differing characterization percentages and not just for waste material of the same characterization as that tested herein, testing similar to that performed as part of this work, should be performed on samples of the individual constituents that make up a typical waste material. In this way, the consolidation coefficients of each of the waste constituents can be determined. Once determined, it should be theoretically possible to determine the consolidation coefficients of any mixed waste material by calculating suitably weighted average of the values of the coefficients obtained for each of the individual constituents based upon their percentages within any desired waste material characterization.

In the event the recommended testing discussed above has not yet been performed, the following discusses a procedure that may yield a reasonable settlement assessment within a landfill containing waste that is not similar to the waste material that was tested herein. Firstly, samples of the unknown waste should be collected from various depths throughout the landfill and tested to determine its composition as well as its (C + H)/L ratio value to ascertain its approximate state of decomposition throughout the landfill profile. It is important that the characterization procedure be performed utilizing samples large enough to be representative of the percentages of the individual constituents present in the waste. This should be done for a sufficient number of waste samples that will yield statistically relevant results. The collected samples used to determine the (C + H)/L ratio should be prepared as discussed in Chapter 4. The sample testing should be done at pressures corresponding to overburden pressures in the field or loading conditions for anticipated future construction. These tests should be held in consolidation until it is apparent that the tertiary compression is well underway.

The consolidation parameters, C'_c, the total secondary coefficients C'_α, C_β, Secant_β and long-term residual tertiary coefficient $C_{\alpha\beta}$, for each waste sample tested can then be determined at its specific state of decomposition. The initial settlement of the sample occurs very rapidly usually within two minutes of initial load placement. The values of the creep rate of secondary compression, C'_α, the rates related to biodegradation decomposition, C_β, the Secant Modulus of Biodegradation Secantβ and the residual tertiary settlement, $C_{\alpha\beta}$, are determined by holding the load for the longer time periods discussed. These coefficient values are dependent upon the (C + H)/L ratio (state of decomposition of waste) and will vary for each (C + H)/L ratio observed.

Following the determination of the consolidation coefficients, charts of these various coefficients versus their respective observed (C + H)/L ratio values can be constructed using an exponential relationship to account for the reduction in mass in accordance with half life exponential decay theory. Along with estimates of the time for the start and end of the various phases of settlement and decomposition, t_1, t_2, t_3 and

t_f, the observed coefficients may then be used within the formulae cited in Chapter 6 above to compute an estimate of anticipated settlement.

In the event that time does not permit the testing of the waste samples in consolidation for the time durations recommended above, the unknown waste can be generally described by utilizing its relative percentages of its volume of waste associated with the descriptive modifiers determined by Findikakis et al (1979). Once the volume percentage of each of the Findikakis descriptive modifiers (Readily Biodegradable; Moderately Biodegradable; and, Slowly Biodegradable) is determined, then the Findikakis' methods for determining volume remaining and gas produced can be employed. With these, along with the value of the (C + H)/L ratio, observed from the testing on the unknown waste, an assessment of the current state of decomposition versus the observed (C + H)/L ratio can be made. The theoretical field time for volume remaining, gas remaining and the (C + H)/L values for the unknown waste should be determined. Once these values are determined they should be compared to the (C + H)/L ratio values, of the samples from this study, and the time at which the same volume of waste remaining and gas remaining, for the tested waste from this study, also occurs. A correlation between the (C + H)/L values for the unknown waste and the waste tested during this research can then be developed. Utilizing these values of (C + H)/L, Figure 8.1 and the figures presented in Chapter 4, the percent biodegradation remaining and the parameters for the coefficients C'_c, C'_α, C_β, Secant_β, and $C_{\alpha\beta}$ for the unknown waste can be approximated and estimates of settlement at any given time can be made as discussed above. The method suggested in this paragraph will yield only approximate estimates of the settlement characteristics of the unknown waste.

Figure 8.1 can be used to assess the percent of material yet to biodegrade at any given time t.

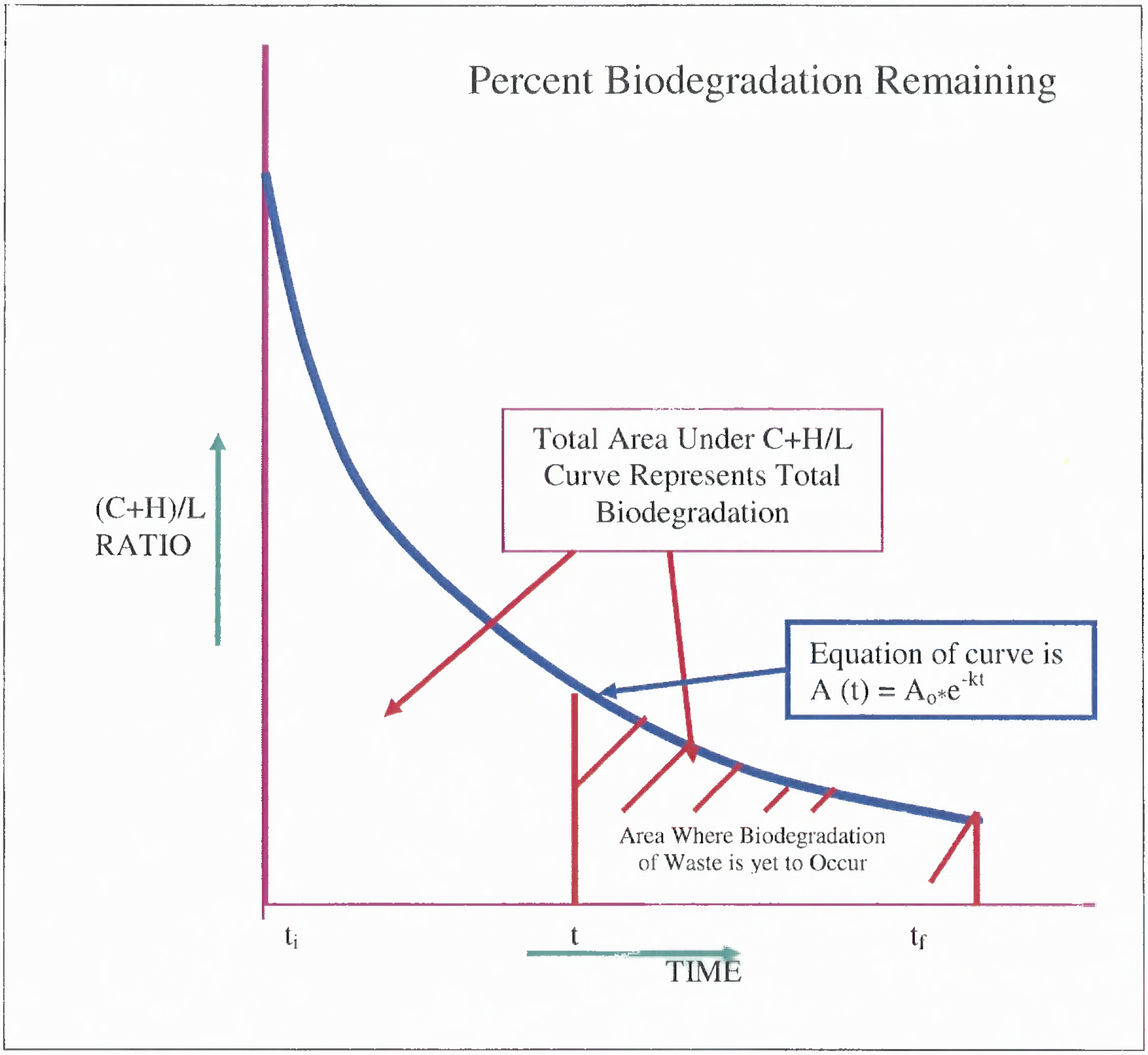

Figure 8.1 Percent biodegradation remaining.

Figure 8.1 shows the relationship of the (C + H)/L ratio to time. The area under the curve, represented by the equation:

$$A\,(t) = A_o * e^{-kt} \tag{8.1}$$

represents the total biodegradation that will occur, B_{100}, for a given material from time period $t = t_i$ to $t = t_f$:

$$B_{100} = \text{Area Under the entire Curve } B = \int A\ (t)\ dt = \int A_o * e^{-kt}\ dt \qquad (8.2)$$

The area under the portion of the curve between some time t and t_f, end of biodegradation, represents the remaining amount of biodegradation yet to occur, B_r. at time $t = t_i$

$$B_r = \text{Area Under the curve from } t_i \text{ to } t = \int A\ (t)\ dt = \int A_o * e^{-kt}\ dt \qquad (8.3)$$

The following analysis determines the percent of biodegradation remaining, B_t, at any given time $t = t_f$:

$$\text{Biodegradation Remaining } B_t(\%) = (B_t/B_{100}) * 100 \qquad (8.4)$$

By plotting the (C + H)/L ratio for a waste with similar characteristics to that tested, one should be able to make a determination of the magnitude of the remaining decomposition and hence the potential remaining settlement utilizing the consolidation parameter coefficients C'_c, C'_α, C_β, Secant_β and $C_{\alpha\beta}$ for each layer exhibiting a different (C + H)/L ratio.

8.2 Recommendations for Future Work

As a result of this work, some questions and recommendations for future work have arisen.

1) It can be observed from Figures 4.16 and 4.33 through 4.36 that data regarding settlement parameters were not available between the (C + H)/L ratio values of 3.00 and 1.00. It is recommended that testing should be performed to fill in these gaps in the data by conducting the consolidation tests for a sufficient period of time to determine the settlement parameters.

2) To better refine the rates and the quantity of gas generated, a gas volume flow meter should be used to determine gas volumes generated rather than the SKC Sample bags. In addition, the gas samples may be tested for their CH_4 and CO_2 contents so that better predictions of overall theoretical gas generation can be facilitated

3) It is not possible to simulate the effects of the collapse of voids that occur in the waste material in the field by the model developed for this work. To assess the effects of this mechanism, settlement observations for landfills that have been subject to dynamic compaction or have undergone an engineered compaction program during placement should be made to see if predictive settlement and observed settlement have a better correlation. By performing this type of compaction, the voids within the landfill would collapse and the settlement behavior of the landfill material would be more representative of only biodegradation settlements in the field.

APPENDIX A

WATER BATH TEMPERATURES AND LEACHATE RECYCLING SCHEDULE

Figure A.1 shows the water bath temperature readings maintained throughout the research experimentation. A water bath at an average temperature of 110 ^oF was used to simulate ambient temperatures within a landfill and enhance mesophilic reactions. The temperature was maintained using a commercial water heater and the water was circulated throughout the duration of testing to promote uniformity of temperature.

Table A.1 Record of Water Bath Temperatures

Solid Waste Study			
Water Bath Temperature Record			
Date	**Cum. Days**	**Temp °F**	
		AM	**PM**
12/14/2007	7	90.2	98.3
12/17/2007	10	108.9	111.6
12/18/2007	11	113.3	106.1
12/19/2007	12	111.1	105.6
12/20/2007	13	104.7	107.7
12/21/2007	14	107.9	108.8
12/22/2007	15	108.2	108.3
12/23/2007	16	107.3	NA
12/24/2007	17	106.3	108.7
12/26/2007	19	109.1	109.3
12/27/2007	20	110.0	108.3
12/28/2007	21	111.1	108.1
12/29/2007	22	105.5	106.4
12/31/2007	24	105.5	106.7
1/2/2008	26	104.2	105.2
1/3/2008	27	106.3	107.0
1/4/2008	28	109.6	111.3
1/7/2008	31	107.1	108.1
1/8/2008	32	108.2	NA
1/9/2008	33	108.4	108.3
1/10/2008	34	109.7	110.0
1/11/2008	35	110.6	108.3
1/12/2008	36	109.2	NA
1/13/2008	37	108.8	108.1
1/14/2008	38	108.4	108.7
1/15/2008	39	107.9	107.9
1/16/2008	40	NA	109.1
1/17/2008	41	107.7	107.6
1/18/2008	42	108.0	107.9
1/21/2008	45	109.1	108.6
1/22/2008	46	109.2	109.6
1/23/2008	47	109.7	108.2
1/24/2008	48	107.8	106.1
1/25/2008	49	109.1	109.0
1/28/2008	52	108.9	108.5
1/29/2008	53	110.0	110.1
1/30/2008	54	108.7	109.6
1/31/2008	55	110.1	110.4

Table A.2 Record of Water Bath Temperatures, Continued

Solid Waste Study			
Water Bath Temperature Record Continued			
Date	**Cum. Days**	**Temp ^{o}F**	
		AM	**PM**
2/1/2008	56	110.9	110.0
2/4/2008	59	109.0	109.3
2/5/2008	60	110.3	NA
2/6/2008	61	NA	109.1
2/7/2008	62	110.1	109.7
2/9/2008	64	109.2	NA
2/11/2008	66	NA	107.2
2/12/2008	67	110.9	110.8
2/13/2008	68	111.7	NA
2/15/2008	70	109.8	108.7
2/17/2008	72	108.7	NA
2/19/2008	74	110.0	109.9
2/20/2008	75	109.8	NA
2/21/2008	76	NA	109.5
2/23/2008	78	109.6	NA
2/25/2008	80	110.3	NA
2/26/2008	81	NA	109.0
2/27/2008	82	108.8	NA
2/28/2008	83	NA	108.9
2/29/2008	84	108.7	NA
3/1/2008	85	NA	109.1
3/2/2008	86	110.1	NA
3/3/2008	87	110.1	109.2
3/4/2008	88	109.3	109.7
3/6/2008	90	110.1	110.2
3/7/2008	91	110.3	NA
3/8/2008	92	109.7	110.0
3/9/2008	93	110.3	NA
3/10/2008	94	NA	NA
3/11/2008	95	109.9	110.1
3/12/2008	96	109.6	109.5
3/13/2008	97	110.1	109.7
3/14/2008	98	NA	NA
3/15/2008	99	110.4	110
3/16/2008	100	110.1	109.5
3/18/2008	102	109.8	110.0
3/20/2008	104	110.1	109.7
3/21/2008	105	109.1	109.9

Table A.3 Record of Water Bath Temperatures, Continued

Solid Waste Study			
Water Bath Temperature Record Continued			
Date	Cum. Days	Temp ^{o}F	
		AM	PM
3/22/2008	106	110.9	110.8
3/24/2008	108	111.6	NA
3/25/2008	109	108.3	107.8
3/27/2008	111	109.7	109.2
3/28/2008	112	109.0	110.3
3/29/2008	113	111.7	111.2
3/30/2008	114	111.5	NA
3/31/2008	115	111.1	111.3
4/1/2008	116	111.4	NA
4/2/2008	117	111.7	110.7
4/3/2008	118	110.1	110.6
4/4/2008	119	110.8	110.3
4/5/2008	120	110.7	110.7
4/6/2008	121	110.5	109.9
4/7/2008	122	110.1	109.8
4/8/2008	123	109.7	109.5
4/9/2008	124	111.2	NA
4/10/2008	125	111.7	NA
4/11/2008	126	NA	110.8
4/13/2008	128	NA	111.4
4/14/2008	129	110.6	110.0
4/15/2008	130	110.8	110.3
4/16/2008	131	109.8	109.3
4/17/2008	132	109.9	NA
4/18/2008	133	109.1	109.8
4/19/2008	134	110.5	110.3
4/20/2008	135	110.3	NA
4/21/2008	136	111.2	110.5
4/22/2008	137	110.5	NA
4/23/2008	138	110.1	NA
4/24/2008	139	111.7	NA
4/25/2008	140	109.5	NA
4/26/2008	141	109.8	109.7
4/27/2008	142	110.7	NA
4/28/2008	143	111.0	110.5
4/29/2008	144	110.8	109.9

Table A.4 Record of Water Bath Temperatures, Continued

Solid Waste Study			
Water Bath Temperature Record Continued			
Date	**Cum. Days**	**Temp ^{0}F**	
		AM	**PM**
4/30/2008	145	110.3	110.3
5/1/2008	146	110.7	109.1
5/2/2008	147	109.9	110.0
5/4/2008	149	111.1	110.4
5/5/2008	150	109.9	NA
5/6/2008	151	110.6	109.9
5/7/2008	152	110.4	110.8
5/8/2008	153	110.5	109.7
5/9/2008	154	110.2	109.1
5/10/2008	155	109.8	NA
5/12/2008	157	110.2	109.6
5/13/2008	158	111.1	NA
5/14/2008	159	110.3	109.8
5/15/2008	160	110.2	110.2
5/16/2008	161	111.7	110.9
5/17/2008	162	110.8	111.0
5/18/2008	163	110.9	110.1
5/19/2008	164	110.7	110.2
5/20/2008	165	110.5	NA
5/08	176	110.4	110.1
6/08	206	110.7	110.0
7/08	237	110.5	110.0
8/08	268	110.4	110.0
9/08	298	110.5	110.0
10/08	329	110.5	110.1
11/08	359	110.6	110.0
12/08	390	110.6	110.1
1/09	421	110.6	110.1
2/09	449	110.4	109.0
3/09	480	110.6	109.9
4/09	510	110.6	110.0
5/09	541	110.5	110.0
6/09	571	110.6	110.1
7/09	602	110.5	109.9
8/09	633	110.6	110.0
9/09	663	110.6	110.0

Table A.5 Leachate Recycling Schedule

Leachate Recycling Schedule		
Date	Interval in Days	Cumulative Days Between Changes
1/8/2008		25
2/20/2008	43	68
3/22/2008	31	99
4/17/2008	26	125
5/17/2008	30	155
6/25/2008	39	194
7/15/2008	20	214
8/11/2008	27	241
9/10/2008	30	271
10/14/2008	34	305
11/11/2008	28	333
12/10/2008	29	362
1/19/2009	34	396
2/15/2009	33	429
3/17/2009	30	459
4/16/2009	30	489
5/13/2009	27	516
6/16/2009	34	550
7/25/2009	39	589
8/29/2009	35	624
9/30/2009	32	656

APPENDIX B

LISTING OF CONSOLIDATION TESTING DATA FOR SAMPLE A (LT)

The following tables list the data obtained from the oedometer during consolidation testing for Sample A (LT). Sample A (LT) was left in the oedometer the longest of all samples to determine the long-term consolidation behavior of the waste sample.

Table B.1 Sample A (LT) Consolidation Data Readings

	CONSOLIDATION TEST	
Sample No.	A (LT)	
Visual Classification:	Homogenized Solid Waste	
Apparatus Measurements		
Diameter of Ring	6.35 cm	
Area of Ring	31.67 cm^2	
Height of Ring, Z_1	1.0 inch	
Soil and Ring Weights	**Initial**	
W of Ring and wet soil	604.95 gms	
Weight of Ring	521.34 gms	
W of wet soil	83.61 gms	
W of dry soil, W_s = W/1+w (gms)	31.3 gms	
Water Content		
W of Cont. + wet soil	117.88 gms	
W of Cont. + dry soil	77.10 gms	

Table B.2 Sample A (LT) Consolidation Data Readings Continued

W of Water W_w	40.78 gms	
W of cont.	52.7 gms	
W of dry soil, W_s	24.40 gms	
Water Content, w in %	167.1	
Initial W of wet soil	83.61 gms	
Initial W of dry soil	31.3 gms	

Table B.3 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**0.13**	**tsf**	
Date Applied:	**12/12/2007**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
11:30:00	00:00	0.00	0.0000
	00:03	0.22	0.0369
	00:06	0.32	0.0381
	00:12	0.45	0.0408
	00:30	0.71	0.0435
11:31:00	01:00	1.00	0.0457
11:31:30	01:30	1.22	0.0466
11:32:00	02:00	1.41	0.0475
11:34:00	04:00	2.00	0.0495
11:36:00	06:00	2.45	0.0506
11:40:00	10:00	3.16	0.0525
11:50:00	20:00	4.47	0.0546
12:00:00	30:00	5.48	0.0558
12:15:00	45:00	6.71	0.0575
12:30:00	60:00	7.75	0.0585
13:00:00	90:00	9.49	0.0600
13:30:00	120:00	10.95	0.0613
14:30:00	180:00	13.42	0.0636
15:30:00	240:00	15.49	0.0649
16:30:00	300:00	17.32	0.0662
17:30:00	360:00	18.97	0.0672
7:30:00	1200:00	34.64	0.0740
11:30:00	1440:00	37.95	0.0455
9:00:00	2730:00	52.25	0.0802
16:30:00	3180:00	56.39	0.0815
12:00:00	4350:00	65.95	0.0840
9:30:00	7080:00	84.14	0.0884

Table B.4 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**0.30**	**tsf**	
Date Applied:	**12/17/2007**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
9:30	00:00	0.00	0.0884
	00:03	0.22	0.1050
	00:06	0.32	0.1058
	00:12	0.45	0.1069
	00:30	0.71	0.1086
9:31	01:00	1.00	0.1098
	01:30	1.22	0.1106
9:32	02:00	1.41	0.1113
9:34	04:00	2.00	0.1129
9:36	06:00	2.45	0.1139
9:40	10:00	3.16	0.1151
9:50	20:00	4.47	0.1168
10:00	30:00	5.48	0.1180
10:15	45:00	6.71	0.1193
10:30	60:00	7.75	0.1203
11:00	90:00	9.49	0.1218
11:30	120:00	10.95	0.1230
12:30	180:00	13.42	0.1247
13:30	240:00	15.49	0.1263
14:30	300:00	17.32	0.1275
15:30	360:00	18.97	0.1286
16:30	420:00	20.49	0.1295
9:30	1440:00	37.95	0.1360
17:00	1890:00	43.47	0.1381
9:30	2880:00	53.67	0.1412
9:30	4350:00	65.95	0.1450
9:30	5760:00	75.89	0.1482
8:00	7100:00	84.32	0.1506

Table B.5 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**0.62**	**tsf**	
Date Applied:	**12/22/2007**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
8:00	00:00	0.00	0.1506
	00:03	0.22	0.1698
	00:06	0.32	0.1709
	00:12	0.45	0.1723
	00:30	0.71	0.1745
8:01	01:00	1.00	0.1762
	01:30	1.22	
8:02	02:00	1.41	0.1782
8:04	04:00	2.00	0.1803
8:06	06:00	2.45	0.1818
8:10	10:00	3.16	0.1834
8:20	20:00	4.47	0.1860
8:30	30:00	5.48	0.1876
8:45	45:00	6.71	0.1893
9:00	60:00	7.75	0.1907
9:30	90:00	9.49	0.1926
10:00	120:00	10.95	0.1941
11:00	180:00	13.42	0.1962
12:00	240:00	15.49	0.1978
13:00	300:00	17.32	0.1991
14:00	360:00	18.97	0.2002
15:00	420:00	20.49	
11:30	1650:00	40.62	0.2102
9:00	2940:00	54.22	0.2153
9:00	5820:00	76.29	0.2220
9:00	7260:00	85.21	0.2245

Table B.6 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	A (LT)		
Visual Classification:	Homogenized Solid Waste		
Load:	1.27	tsf	
Date Applied:	12/27/2007		
Applied by:	LL, SL		
Time	Elapsed Time min:sec	√t in √min	Dial Reading
9:00	00:00	0.00	0.2245
	00:03	0.22	0.243
	00:06	0.32	0.2457
	00:12	0.45	0.2478
	00:30	0.71	0.2507
9:01	01:00	1.00	0.253
	01:30	1.22	0.2544
9:02	02:00	1.41	0.2553
9:04	04:00	2.00	0.2578
9:06	06:00	2.45	0.2594
9:10	10:00	3.16	0.2613
9:20	20:00	4.47	0.264
9:30	30:00	5.48	0.2665
9:45	45:00	6.71	0.2686
10:00	60:00	7.75	0.2701
10:30	90:00	9.49	0.2721
11:00	120:00	10.95	0.2737
12:00	180:00	13.42	0.276
13:00	240:00	15.49	0.2777
14:00	300:00	17.32	0.2791
15:00	360:00	18.97	0.2803
16:00	420:00	20.49	0.2813
10:00	1500:00	38.73	0.2903
8:00	2820:00	53.10	0.2953
8:00	5700:00	75.50	0.3008
9:00	8640:00	92.95	0.3045
9:00	100840:00	100.40	0.3057
9:00	11520:00	107.33	0.3072
9:00	15840:00	125.86	0.3115
9:00	17280:00	131.45	0.3122
9:00	18720:00	136.82	0.3131
9:00	20160:00	141.99	0.3141
9:00	21600:00	146.97	0.3151
9:00	23040:00	151.79	0.3159
9:00	24480:00	156.46	0.3165
9:00	28800:00	169.71	0.3186
9:00	30240:00	173.90	0.3192

Table B.7 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**2.56**	**tsf**	
Date Applied:	**1/17/2008**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
9:00	00:00	0.00	0.3192
	00:03	0.22	0.3360
	00:06	0.32	0.3378
	00:12	0.45	0.3395
	00:30	0.71	0.3420
9:01	01:00	1.00	0.3443
	01:30	1.22	0.3457
9:02	02:00	1.41	0.3466
9:04	04:00	2.00	0.3489
9:06	06:00	2.45	0.3504
9:10	10:00	3.16	0.3522
9:20	20:00	4.47	0.3548
9:30	30:00	5.48	0.3562
9:45	45:00	6.71	0.3577
10:00	60:00	7.75	0.3589
10:30	90:00	9.49	0.3607
11:00	120:00	10.95	0.3622
12:00	180:00	13.42	0.3645
13:00	240:00	15.49	0.3657
14:00	300:00	17.32	0.3670
16:00	420:00	20.49	0.3690
8:00	1380:00	37.15	0.3750
9:00	5760:00	75.89	0.3831
9:00	7200:00	84.85	0.3848
10:00	8700:00	93.27	0.3864
9:00	10080:00	100.40	0.3876
10:00	11580:00	107.61	0.3886
9:00	15840:00	125.86	0.3909
10:00	17340:00	131.68	0.3920
9:00	18720:00	136.82	0.3929
9:00	20160:00	141.99	0.3938
10:00	21660:00	147.17	0.3945
9:00	25920:00	161.00	0.3966
9:00	27360:00	165.41	0.3973
9:00	28800:00	169.71	0.3979
9:00	30240:00	173.89	0.3985
11:00	33240:00	182.32	0.3997

Table B.8 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**2.56**	**tsf**	
Date Applied:	**1/17/2008**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
9:00	00:00	0.00	0.3192
	00:03	0.22	0.3360
	00:06	0.32	0.3378
	00:12	0.45	0.3395
	00:30	0.71	0.3420
9:01	01:00	1.00	0.3443
	01:30	1.22	0.3457
9:02	02:00	1.41	0.3466
9:04	04:00	2.00	0.3489
9:06	06:00	2.45	0.3504
9:10	10:00	3.16	0.3522
9:20	20:00	4.47	0.3548
9:30	30:00	5.48	0.3562
9:45	45:00	6.71	0.3577
10:00	60:00	7.75	0.3589
10:30	90:00	9.49	0.3607
11:00	120:00	10.95	0.3622
12:00	180:00	13.42	0.3645
13:00	240:00	15.49	0.3657
14:00	300:00	17.32	0.3670
16:00	420:00	20.49	0.3690
8:00	1380:00	37.15	0.3750
9:00	5760:00	75.89	0.3831
9:00	7200:00	84.85	0.3848
10:00	8700:00	93.27	0.3864
9:00	10080:00	100.40	0.3876
10:00	11580:00	107.61	0.3886
9:00	15840:00	125.86	0.3909
10:00	17340:00	131.68	0.3920
9:00	18720:00	136.82	0.3929
9:00	20160:00	141.99	0.3938
10:00	21660:00	147.17	0.3945
9:00	25920:00	161.00	0.3966
9:00	27360:00	165.41	0.3973
9:00	28800:00	169.71	0.3979
9:00	30240:00	173.89	0.3985
11:00	33240:00	182.32	0.3997

Table B.9 Sample A (LT) Consolidation Data Readings Continued

	CONSOLIDATION TEST Continued		
Sample No.	**A (LT)**		
Visual Classification:	**Homogenized Solid Waste**		
Load:	**2.56**	**tsf**	
Date Applied:	**1/17/2008**		
Applied by:	**LL, SL**		
Time	**Elapsed Time min:sec**	**√t in √min**	**Dial Reading**
9:00	36000:00	189.74	0.4006
9:00	40320:00	200.80	0.4017
9:00	44640:00	211.28	0.4025
9:00	47520:00	217.99	0.4035
9:00	48960:00	221.27	0.4040
9:00	50400:00	224.50	0.4043
9:00	53280:00	230.82	0.4051
9:00	57600:00	240.00	0.4062
9:00	60480:00	245.93	0.4070
9:00	63360:00	251.71	0.4077
10:00	67740:00	260.27	0.4089
08:00/07:00 DST	74760:00	273.42	0.4108
10:00	83520:00	289.00	0.4139
10:00	92160:00	303.58	0.4180
10:00	102240:00	319.75	0.4244
9:00	112260:00	335.05	0.4322
9:00	122340:00	349.77	0.4395
9:00	132420:00	363.89	0.4455
9:00	142500:00	377.49	0.4492
9:00	152580:00	390.61	0.4529
9:00	164100:00	405.09	0.4566
9:00	172740:00	415.62	0.4598
9:00	182820:00	427.65	0.4627
9:00	192900:00	439.20	0.4660
9:00	204420:00	452.13	0.4695
9:00	213060:00	461.58	0.4722
9:00	223140:00	472.38	0.4747
9:00	233220:00	482.93	0.4775
9:00	241860:00	491.79	0.4796
9:00	253380:00	503.37	0.4825
9:00	263460:00	513.28	0.4848
9:00	273540:00	523.01	0.4871
9:00	283620:00	532.56	0.4895
9:00	293700:00	541.94	0.4913
9:00	303780:00	551.16	0.4931
9:00	322500:00	567.89	0.4963
9:00	344100:00	586.60	0.4993

APPENDIX C

EXTENSOMETER DATA RESULTS FROM NORTHERN NJ LANDFILL

This Appendix depicts figures of settlement versus time for five extensometers installed within an orphaned landfill located in northern New Jersey. These figures are utilized to determine, from the observed data, using the field measurements that the time for primary compression and the duration of the C'_c parameter occurs rapidly following the application of external load. The initial portions of the curves obtained after the application of loading from the placement of fill material to raise grade can be seen to be very short in duration and that C'_α is the governing mechanism, within the non – biodegradation settlement immediately following fill placement.

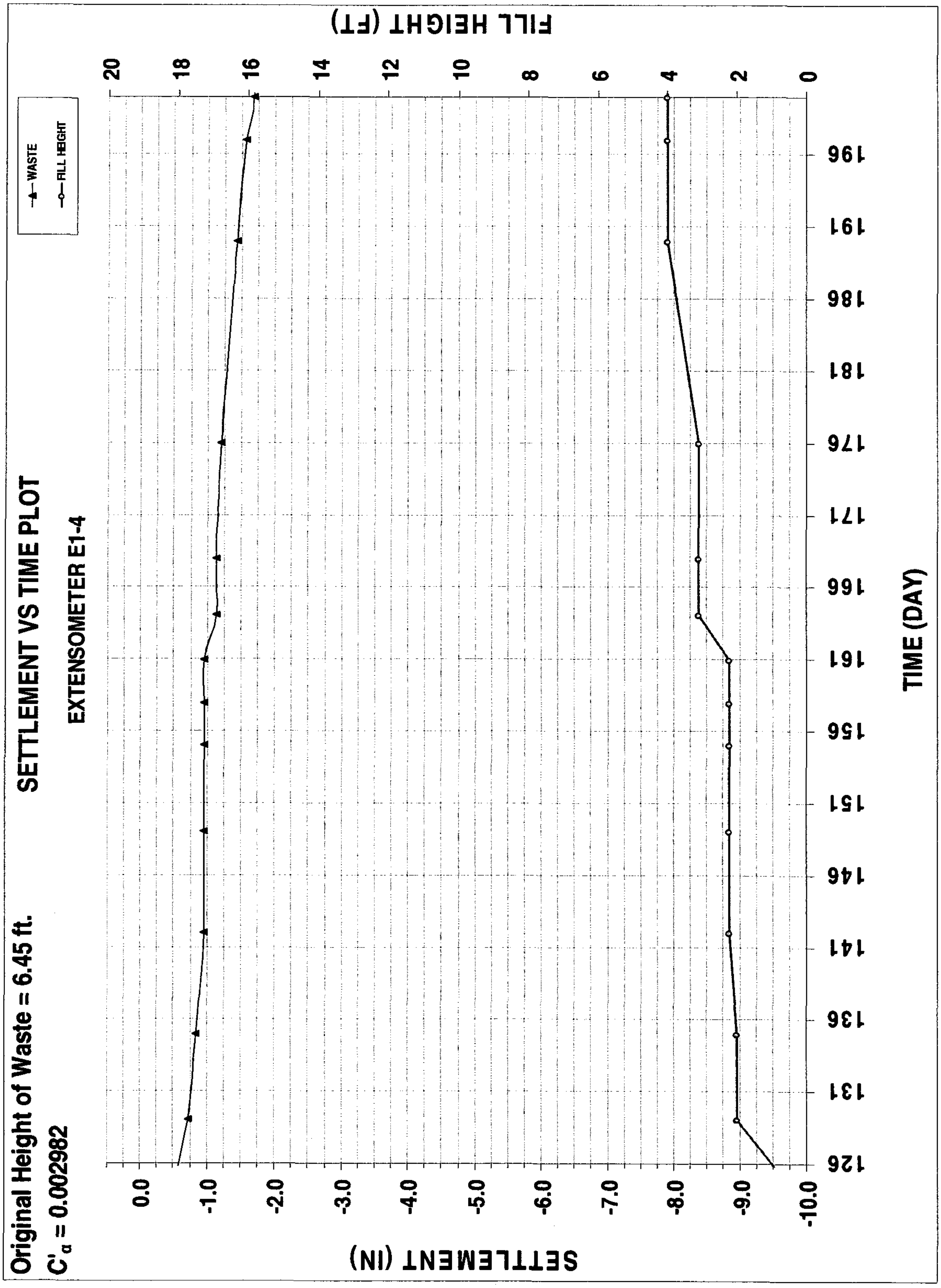

Figure C.1 Extensometer E1-4 settlement versus time record from northern NJ Landfill

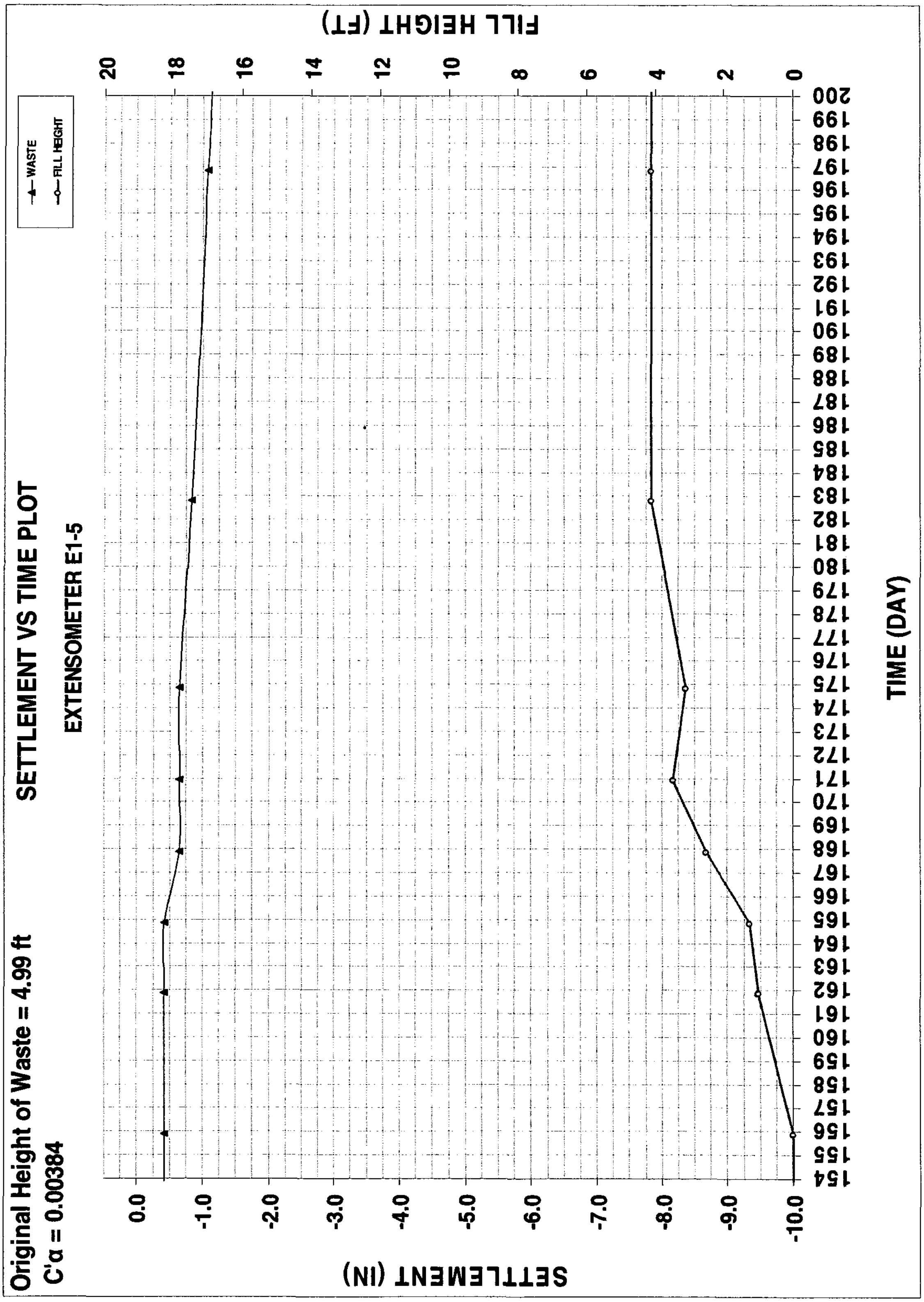

Figure C.2 Extensometer E1-5 settlement versus time record from northern NJ Landfill

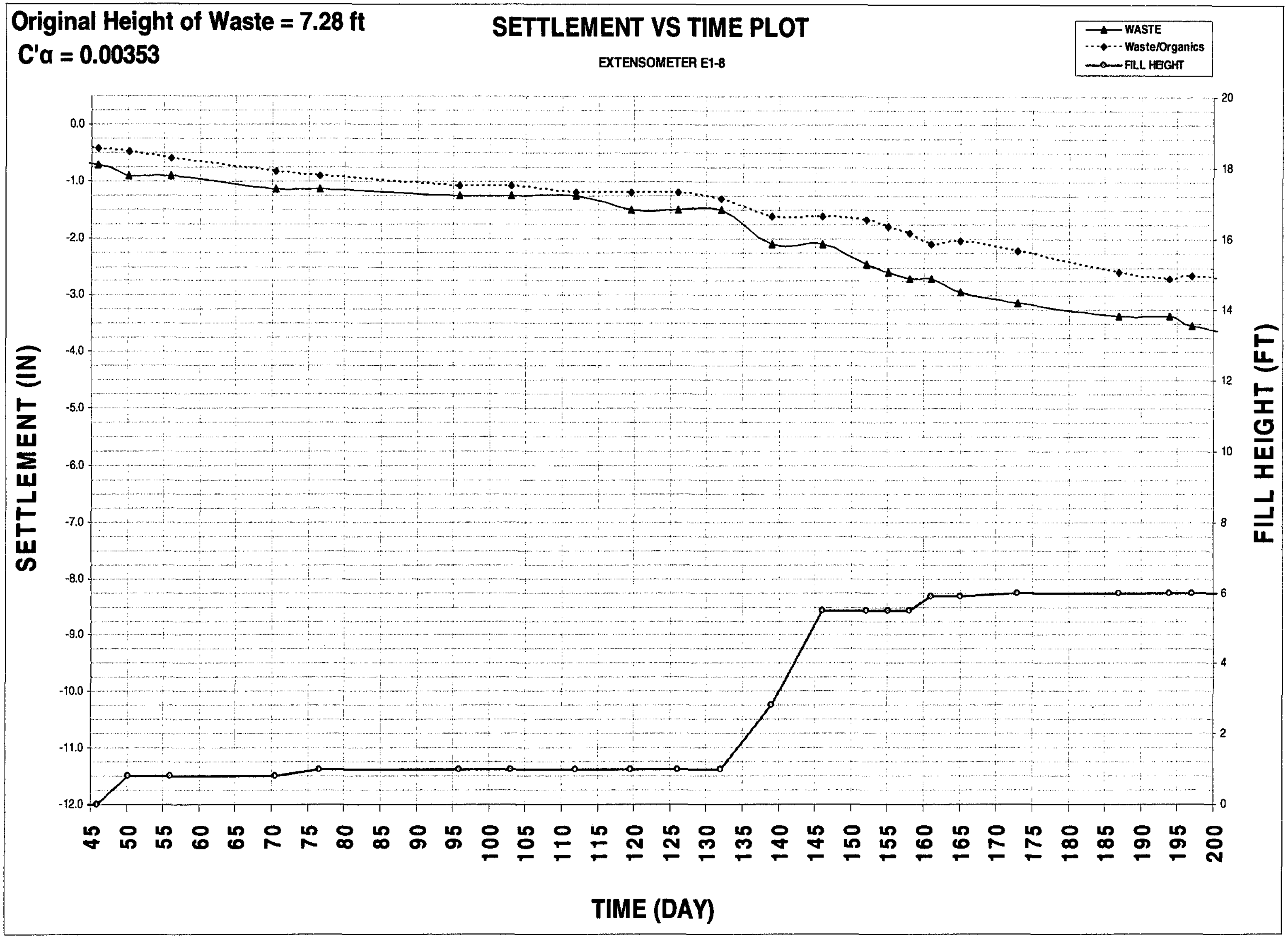

Figure C.3 Extensometer E1-8 settlement versus time record from northern NJ Landfill

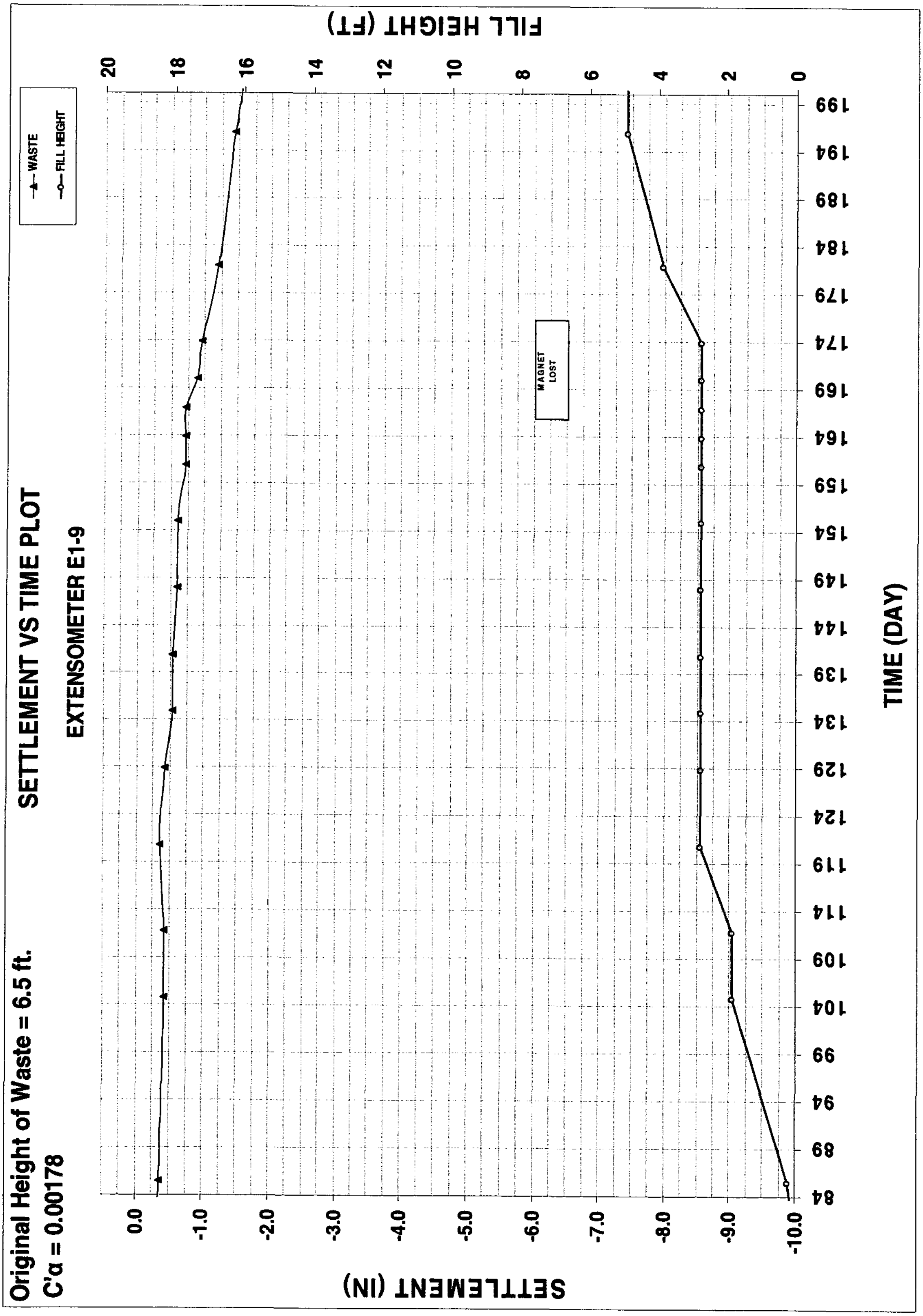

Figure C.4 Extensometer E1-9 settlement versus time record from northern NJ Landfill

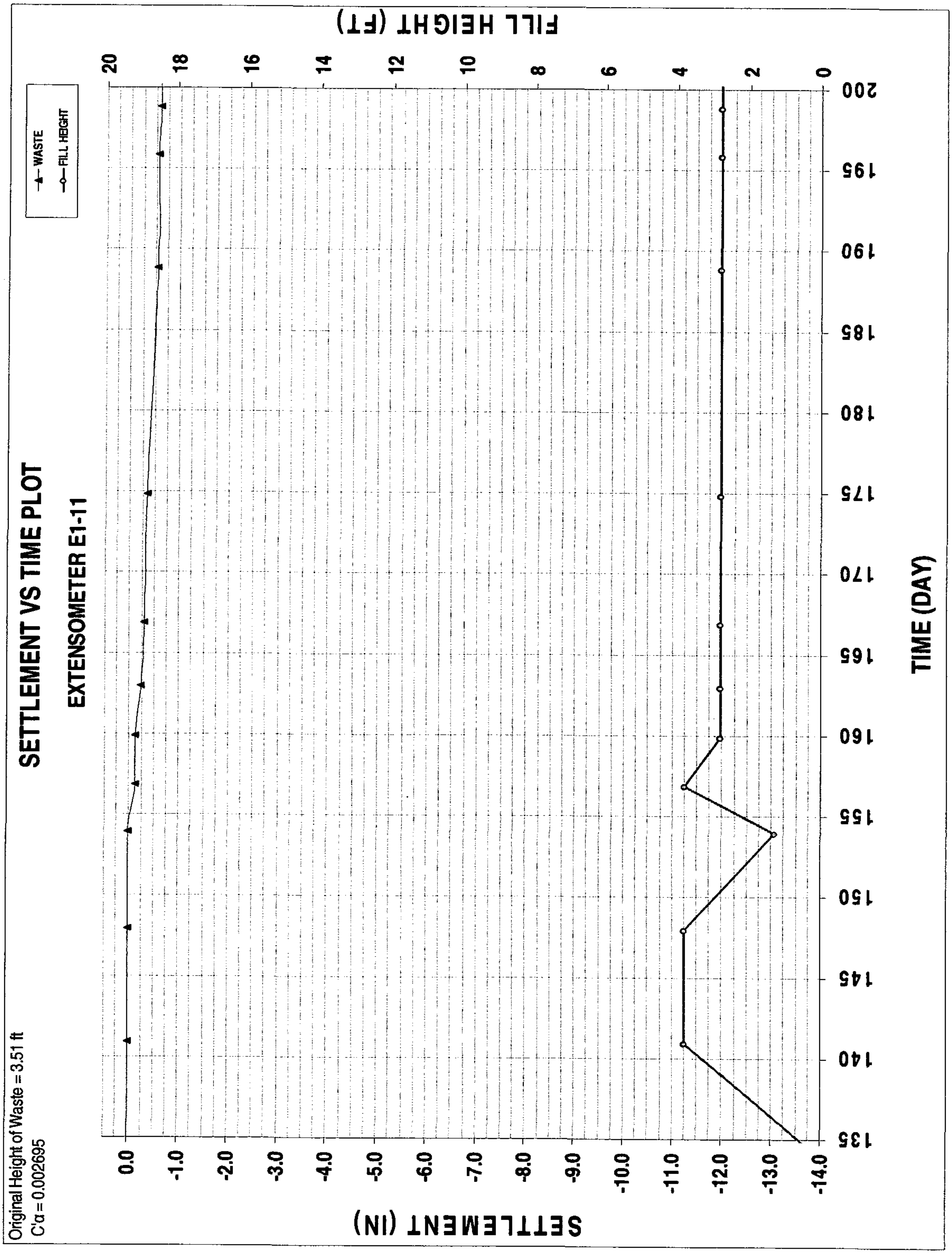

Figure C.5 Extensometer E1-11 settlement versus time record from northern NJ Landfill

APPENDIX D

EXPLANATION OF GRAPHICAL METHODS TO DETERMINE LABORATORY TEST DATA GAPS

Appendix D contains graphical representations of the comparison between the (C + H)/L ratio and the values for C'_c, C'_α, C_β, Secant_β, and $C_{\alpha\beta}$. These graphs were utilized to fill in some gaps in the data which developed because Samples 1, 2, 3 and 4 did not consolidate long enough within the oedometers to enable values to be constructed for some of these coefficients for the cited samples only. All the graphs were constructed utilizing an exponential relationship between the (C + H)/L ratio and the various coefficients. An exponential curve fitting approach was selected for the development of the missing data based upon the results of comparisons between the curve fitting methods shown below.

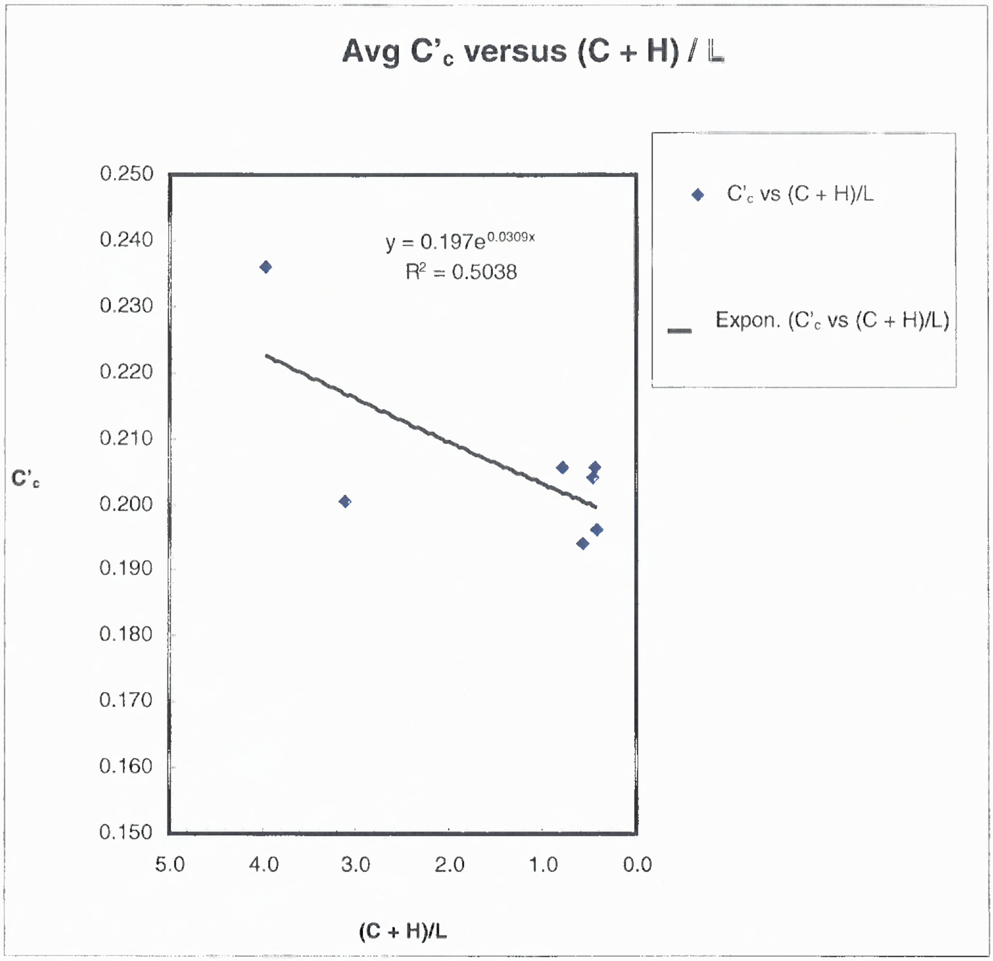

Figure D.1 Curve used to construct missing data for C'_c

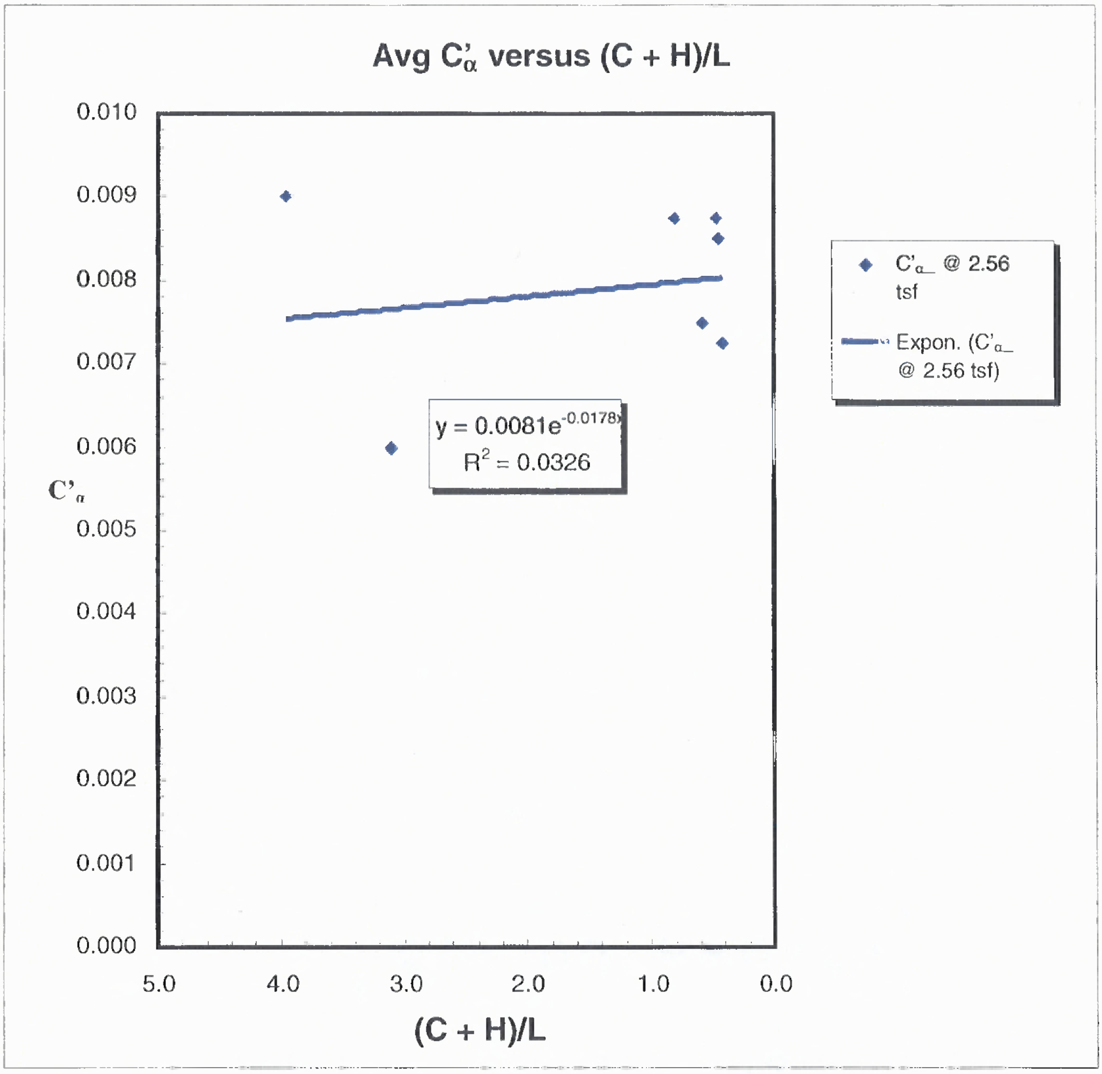

Figure D.2 Curve used to construct missing data for C'$_\alpha$

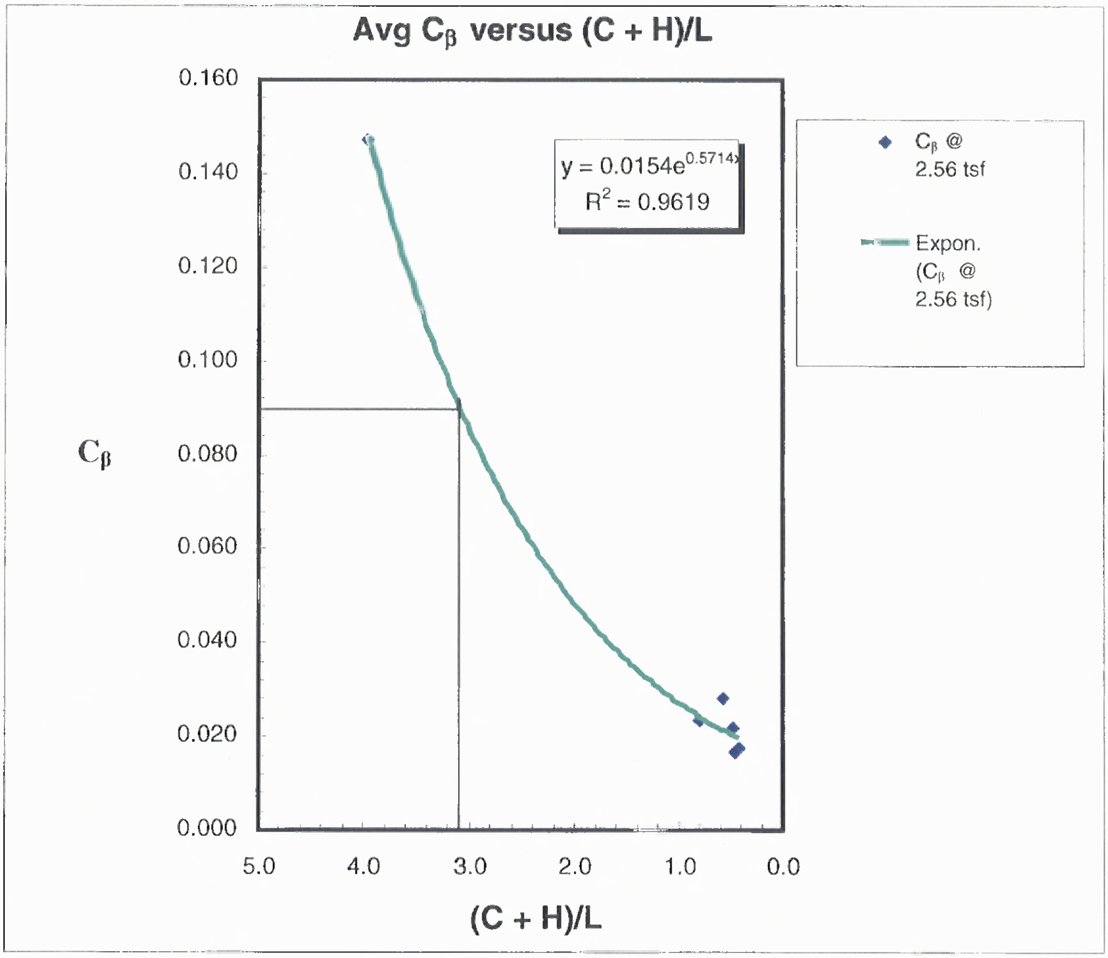

Figure D.3 Curve used to construct missing data for C_β

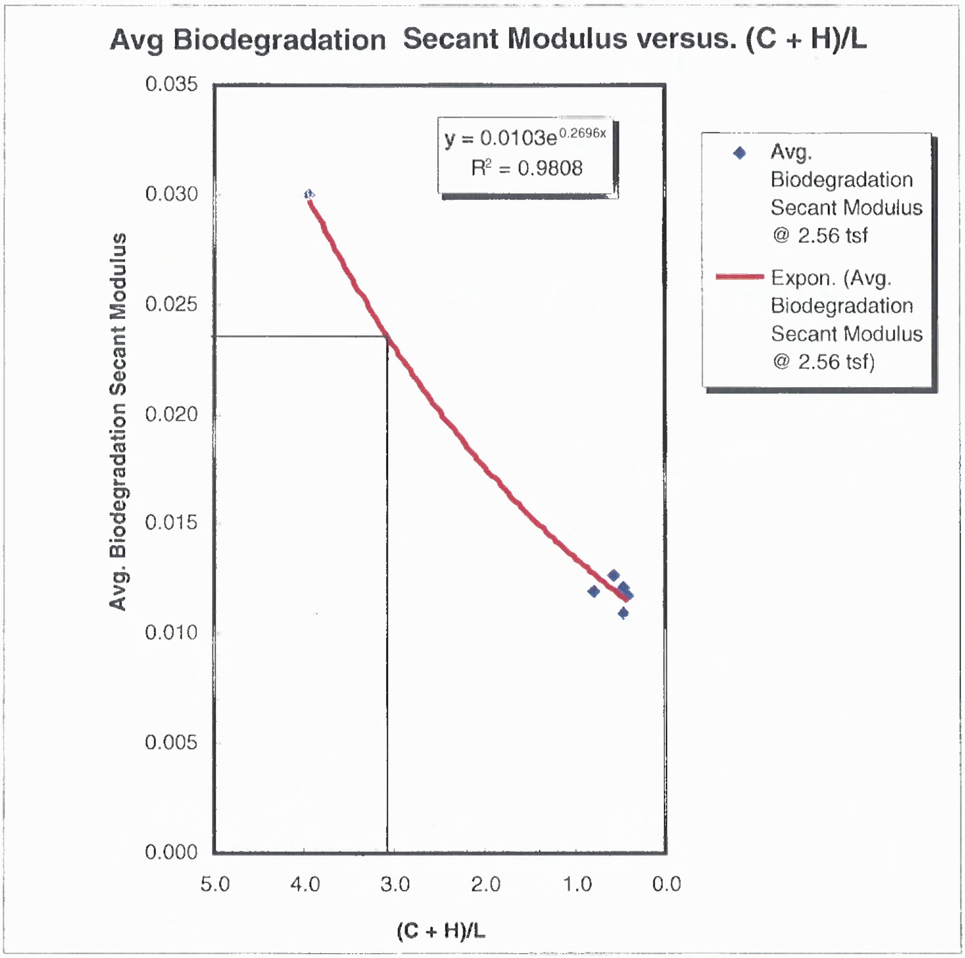

Figure D.4 Curve used to construct missing data for Secant$_{\beta}$

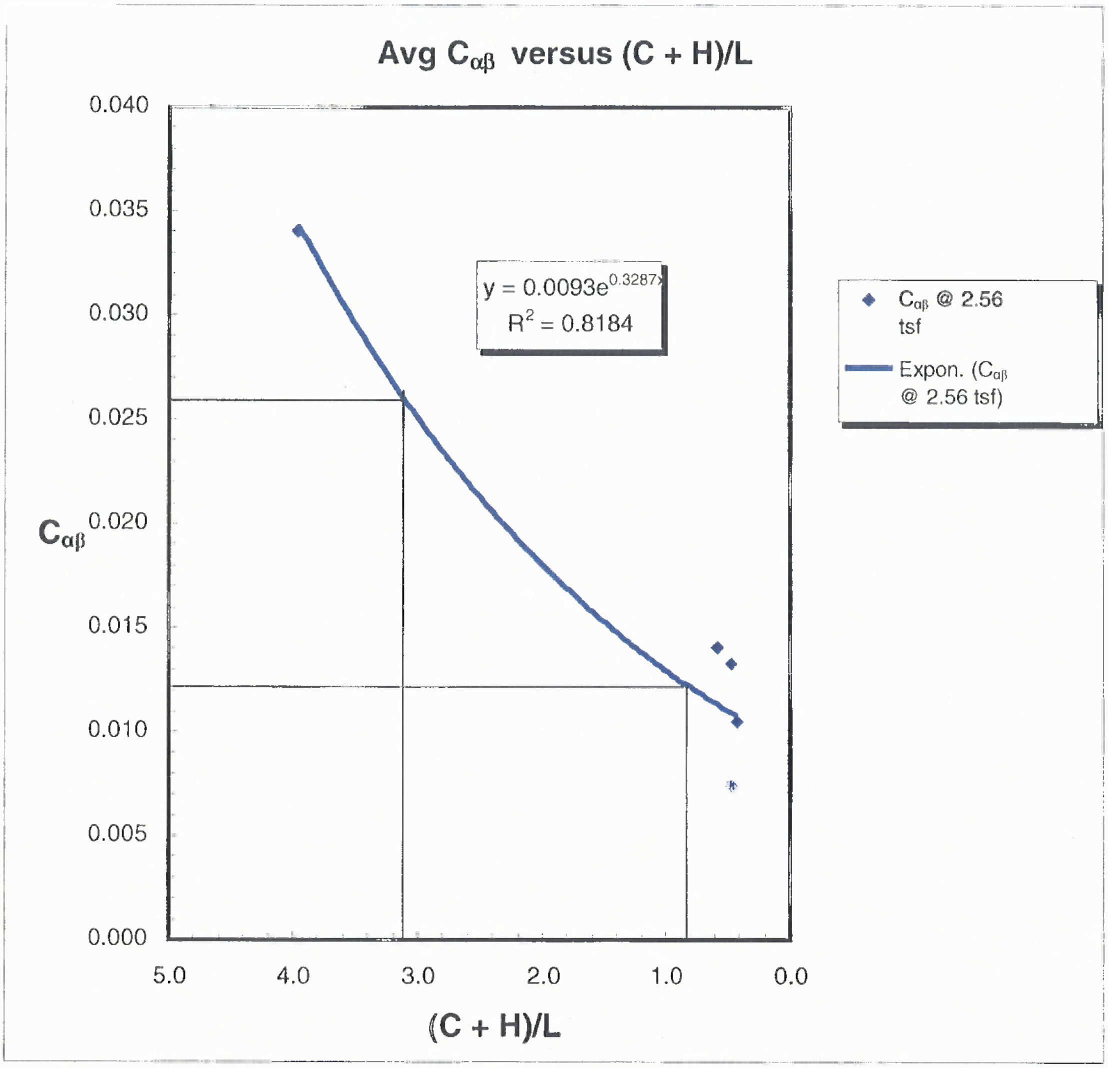

Figure D.5 Curve used to construct missing data for $C_{\alpha\beta}$

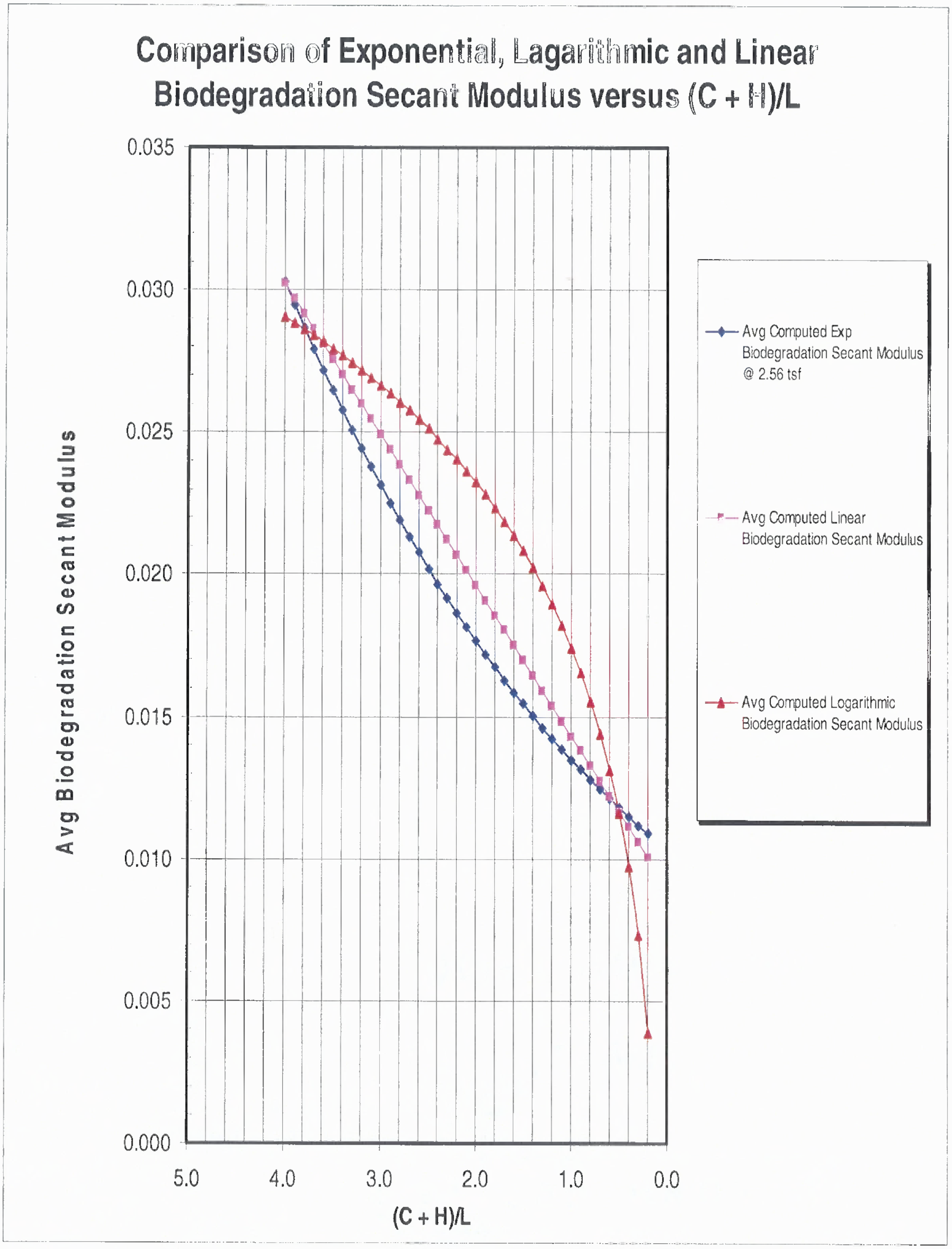

Figure D.6 Comparison of exponential, logarithmic and linear plots of Secant$_\beta$ Modulus versus (C + H)/L

APPENDIX E

SAMPLE CALCULATIONS FOR COMPUTATION OF GAS PRODUCED

Appendix E contains a procedure for computing the amount of gases that are yet to be produced for a waste at any given time t. Table E1 below lists the constituents and the relative percentages within the waste.

Table E.1 Sample Calculation for Computation of Gas Produced – Step 1

Step 1				
$V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$ (Findikakis 1979)				
Component	Percent of Total MSW		Descriptive	
Food Waste	19%	19%	Readily	
Garden Trimmings	6%	6%	Moderately	
Paper	38%	38%	Moderately	
Textiles	3%	3%	Moderately	
Plastic	13%	13%	Slowly	
Wood	2%	2%	Slowly	
Dirt, Ashes, Brick etc.	8%	8%	Non-Decomposable	
Glass	11%	11	Non-Decomposable	
100 lbs = $3.6\ \text{ft}^3$				

In the following table, the computations for volume remaining, V_r, and conversely volume decomposed, V_d, are shown utilizing Findikakis's theoretical relationships.

Table E.2 Sample Calculation for Computation of Gas Produced – Step 2

Step 2					
$V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$					
			V_o	V_r after 7.5 years	V_d%
$V_{rd} = 0.19*(e^{-0.1386t})$		Food Waste	0.19	6.72%	64.64%
$V_{md} = 0.44*(e^{-0.0231t})$		Paper and Garden Trimmings Textiles	0.47	39.52%	15.91%
$V_{sd} = 0.02 * (e^{-0.0173t})$		Wood and Plastic	0.15	12.61%	15.91%
$V_{nb} = 0.19 V_o$			0.19	19.00%	0.00%
$V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$			1	77.86%	22.14%
Therefore $V_r = V_{rd} + V_{md} + V_{sd} + V_{nd}$					
$V_r = 0.19V_o (e^{-0.1386t}) + 0.47 V_o (e^{-0.0231t}) + 0.15 V_o (e^{-0231t}) + 0.19 V_o$					
Volume of Decomposed Waste					
$V_d =$	0.779	ft^3			
Volume of remaining Degradable Waste					
$V_{rb} =$	0.2214	ft^3			
Percent of Original Organic Matter Remaining (P_{rb})					
P_{rb}	27.34%				

Step 3 determines the weight of decomposed wastes on a dry basis for one cubic foot (ft^3) of waste volume.

Table E.3 Sample Calculation for Computation of Gas Produced – Step 3

Step 3							
$C_{50.07}H_{78.17}O_{29.60}N$ +16.47H_2O ---> 27.03CH4 + 22.54CO_2 + NH_3							
If we assume that the organic portion of waste is the							
at a moisture content of 30.5% then the dry organic fraction weighs:							
decomposable portion and the initial weight of Total MSW is 100 lbs.							
81 lbs - 100lbs* 0.305 =		50.5	LBS	Dry Basis	(Wet Organic portion 89 lbs - 8 lbs = 81 lbs)		
		Ultimate Gas Yield is	6.189	ft^3/lb			
Determine how much of waste decomposes over 7.5 years:			V_o				
	Volume = 1.0 ft^3	Findikakis Values for V_r	% Decomposed Over 7.5 years	Percent of Total MSW	Decomposed Wastes (dry basis) (lbs)	Descriptive	k
Food Waste		0.067190023	65%	0.19	6.201903831	Readily	0.1386
Garden Trimmings		0.050455647	16%	0.06	0.481989812	Moderately	0.0231
Paper		0.319552433	16%	0.38	3.052602144	Moderately	0.0231
Wood		0.017566301	12%	0.02	0.122901791	Moderately	0.0173
Textiles		0.025227824	16%	0.03	0.240994906	Moderately	0.0231
Plastic		0.114180958	12%	0.13	0.798861638	Slowly	0.0173
Dirt, Ashes, Brick etc.		0.08	0%	0.08	0	Non-Decomposable	0
Total remaining decomposed waste		0.236975082			10.89925412		

In the following table, the amount of gas produced is computed. The total weight of decomposed waste on a dry basis was computed to be 10.9 lbs per 50.5 lbs of dry weight of organic fraction of waste (corresponding to the original wet weight of 100 lbs for the mixed waste material). Thus, it represents 21.58% of the original dry organic material. For 100 lbs of waste at a density of 27.8 lbs/ft^3, the total volume of original waste is 3.6 ft^3. For one ft^3 of waste, the amount of dry waste remaining after 7.5 years is 10.9 /3.6 = 3.03 lbs.

Table E.4 Sample Calculation for Computation of Gas Produced – Step 4

Step 4						
10.8992541		21.58%	of decomposable material decomposed over 7.5 years			
3.02757059		lbs decomposed per ft^3 of waste over 7.5 years				
100 lbs = 3.6 ft^3						
Determine Weight of Methane and Carbon Dioxide						
Balancing Equations						
Methane		(432.48/1166.7)*10.9=	4.037	lbs.		Moles of CH_4 / Total Moles of MSW * Weight of Decomposed MSW
Carbon Dioxide	Left Side	(991.76/1166.7)*10.9 =	9.265	lbs.		Moles of CO_2 / Total Moles of MSW * Weight of Decomposed MSW
Ammonia		(17/1166.7)*10.9 =	0.159	lbs.		Moles of NH_3 / Total Moles of MSW * Weight of Decomposed MSW
					13.461	
Water	Right Side	(296.46/1167.7)*10.9 =	2.767	lbs.		Moles of H_2O / Total Moles of MSW * Weight of Decomposed MSW
Waste		(1166.7/1166.7)*10.9 =	10.899	lbs.		Moles of $C_aH_bO_cN_d$ / Total Moles of MSW * Wgt of Decomposed MSW
					13.666	
Convert Weight of Gases to Volume:						
		100 lbs of waste =	3.597	ft^3 waste =	27.8 lbs/ ft^3 waste	
Methane		4.04 lbs/0.0448 lbs/ft^3 =		90.106	ft^3 =	55% of total gas produced
Carbon Dioxide		9.265lbs/0.1235 lbs/ft^3 =		75.020	ft^3 =	45% of total gas produced
				165.126 ft^3 of gas produced	per 3.6 ft^3 of waste	
				45.868	ft^3/ft^3	of waste is equiv to 21.58% of decomposable material decomposed over 7.5 years
				165.126 /100 = 1.651	ft^3/lb	of total gases for sample of solid waste used
				4.539	ft^3/lb	of total gases remaining

For the example shown above, t is set at 7.5 years and the amount of gases remaining to be produced is 4.539 ft^3 per lb. For the example waste, the total amount of gases that can be produced is 6.189 ft^3 per lb. of waste.

APPENDIX F

DERIVATION OF EQUATION 5.3

$C_{bio} = (C + H)/L / 1+ [(C + H)/L] * \text{Total Carbon Available}$ (Equation 5.3)

$C_{bio} = (C + H)$

$C_{ult} = L$

Total Carbon Available = $C_{bio} + C_{ult}$

By substituting for C_{bio}, C_{ult} and Total Carbon Available from above in the right hand side of Equation 5.3, the relationship is derived.

APPENDIX G

ENLARGED FIGURES OF KINGSLAND LANDFILL SURVEYS

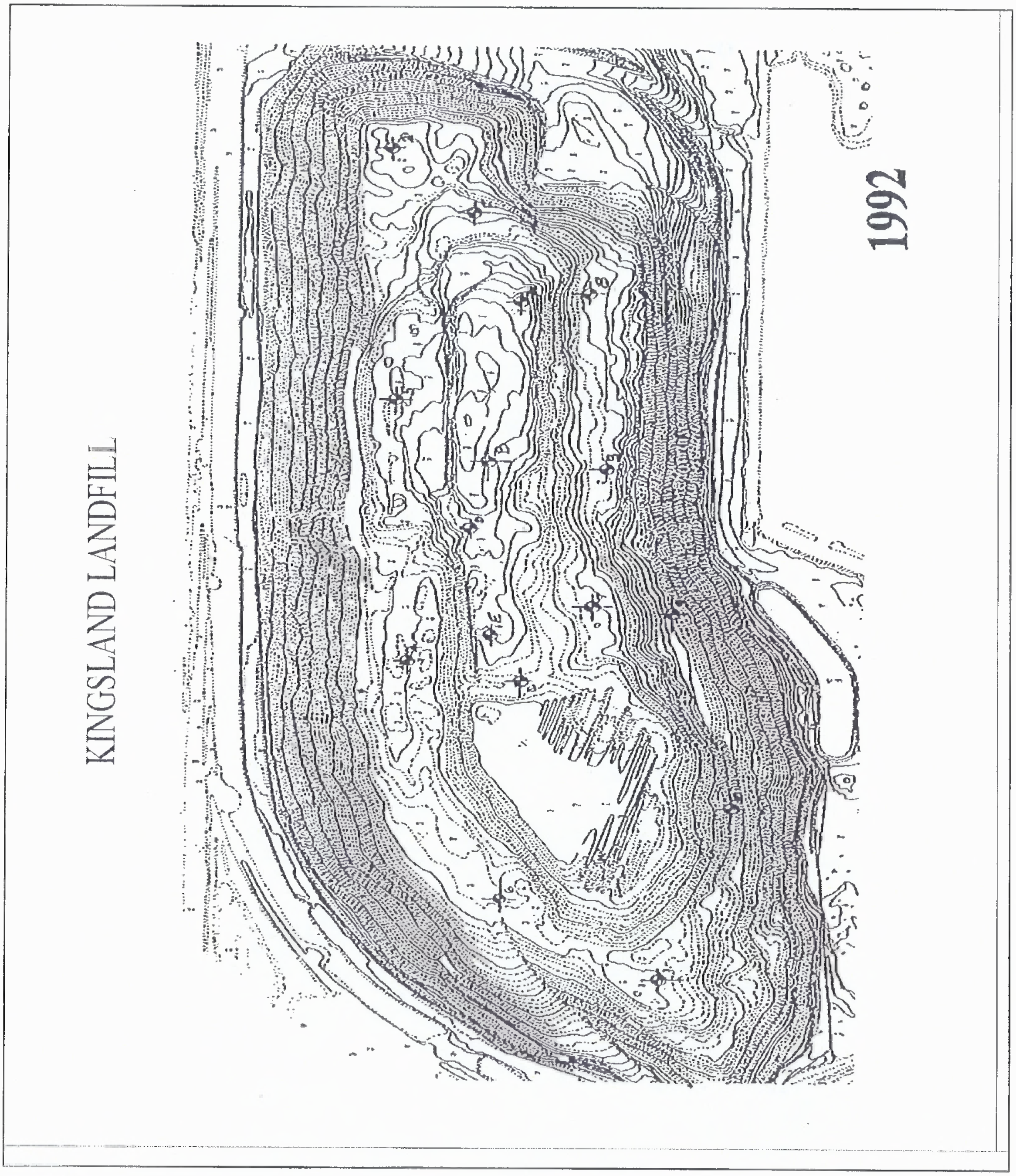

Figure G.1 Topographic survey Kingsland Landfill 1992

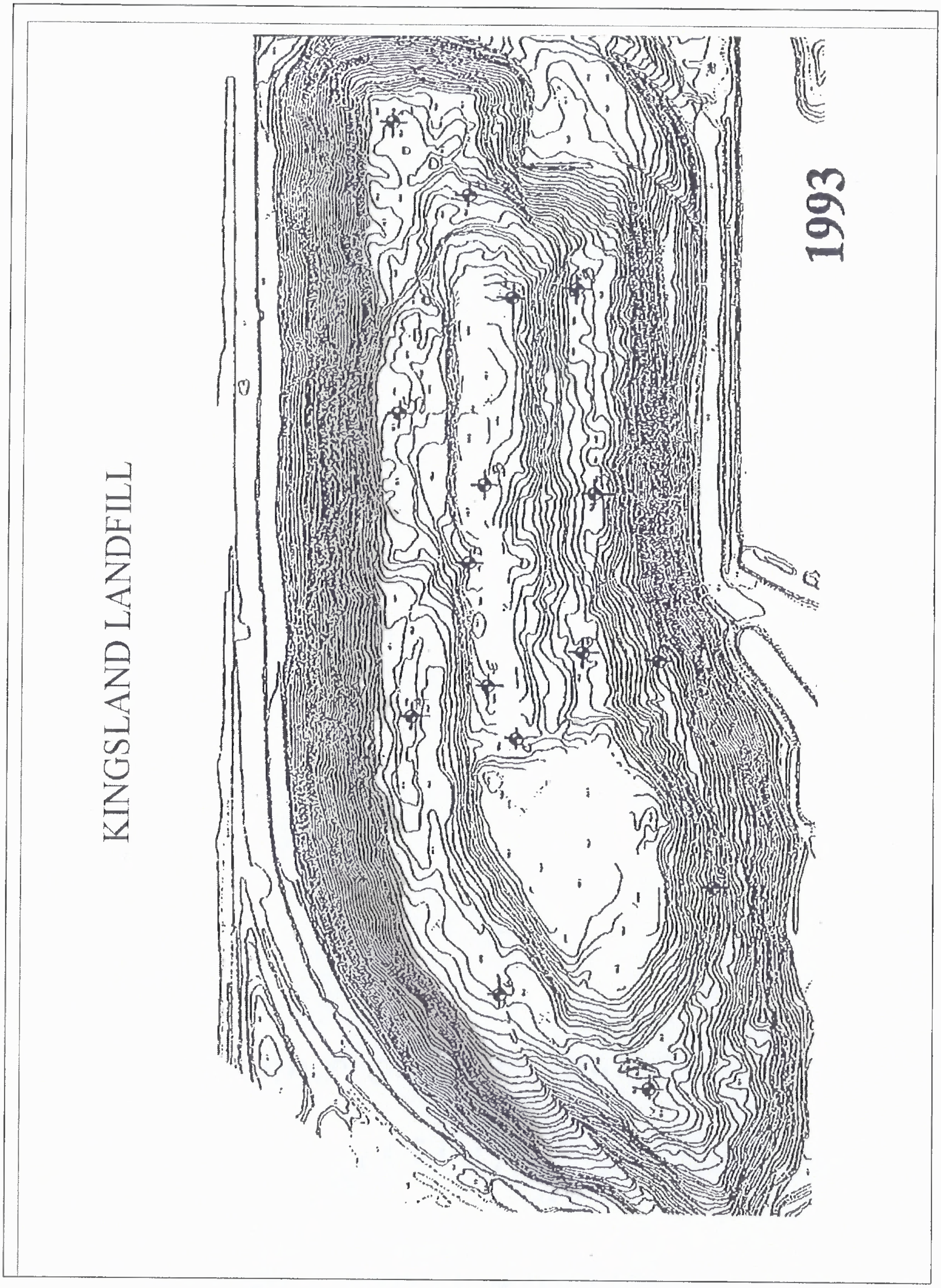

Figure G.2 Topographic survey Kingsland Landfill 1993.

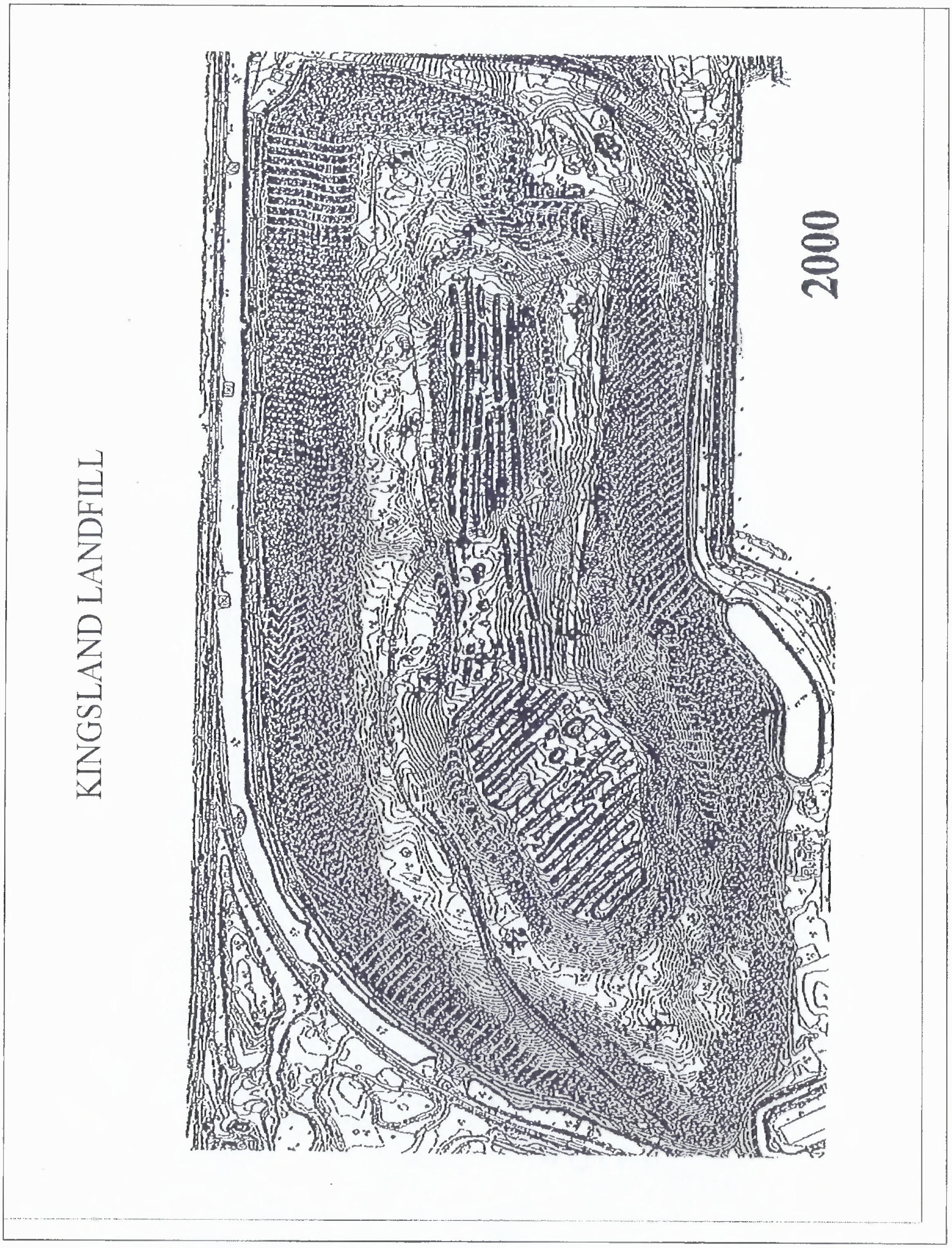

Figure G.3 Topographic survey Kingsland Landfill 2000.

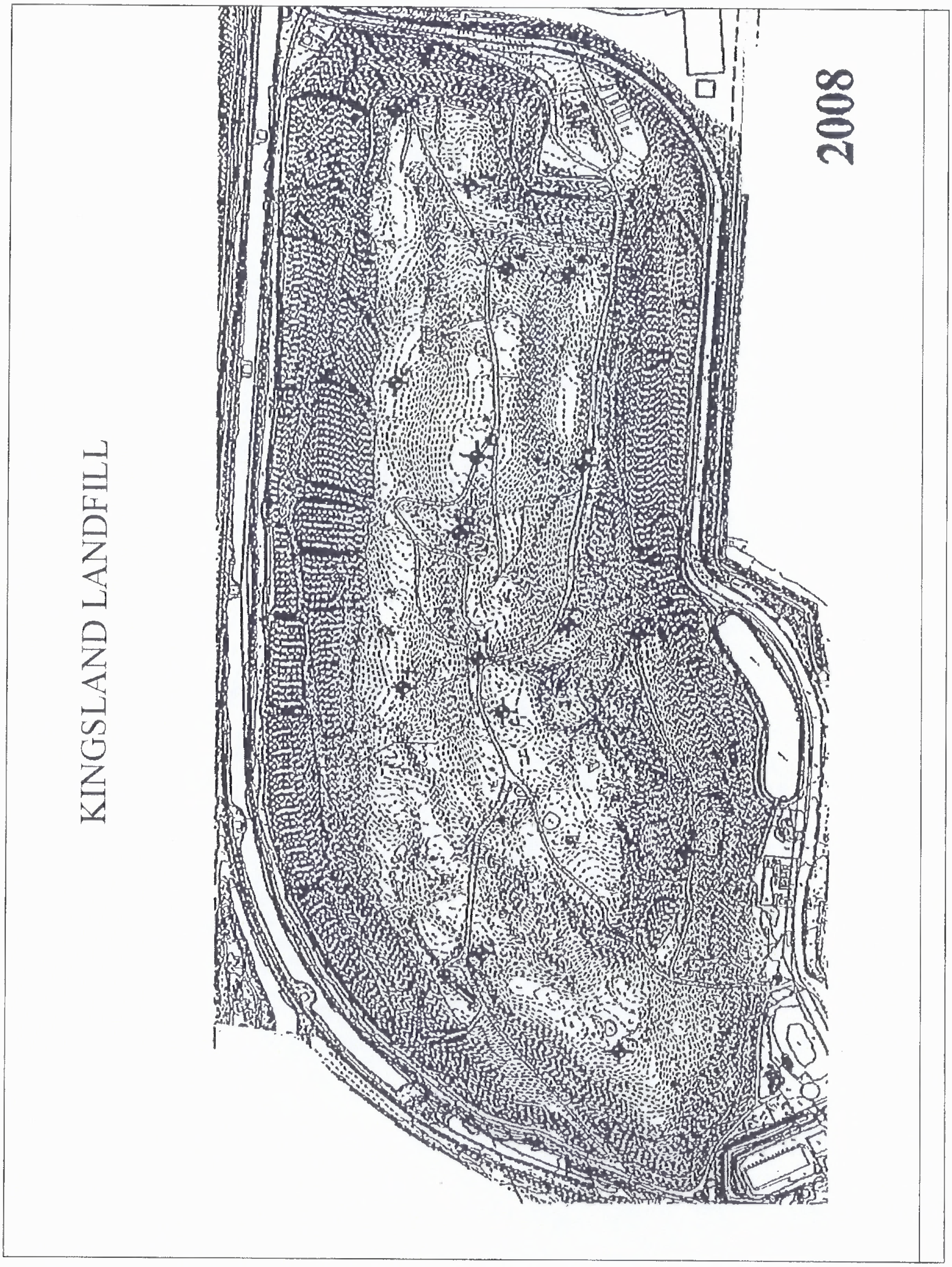

Figure G.4 Topographic survey Kingsland Landfill 2008.

APPENDIX H

OBSERVED AND CALCULATED SETTLEMENT FOR KINGSLAND LANDFILL AT 17.6 TIME RATIO

Table H.1 Observed Settlement for Kingsland Landfill

Location Point	1992	1993	2000	2008	Comments
	Elevation (ft)	Elevation (ft)	Elevation (ft)	Elevation (ft)	
A	115.7	112	104	100.5	
B	117.8	116	107.5	105	
C	104.7	102.2	95	101	Some spot filling between 2005 and 2008
D	114	112	104	100	
E	112	109	103	103	Some spot filling between 2005 and 2008
F	92.5	91	86	96	
1	80.5	76.5	63	64	Some spot filling between 2005 and 2008
2	86.5	84	79	77.2	
3	86.2	84.2	76.3	74	
4	90.5	89	81	81.5	Some spot filling between 2005 and 2008
5	98.6	98	91	91	Some spot filling between 2005 and 2008
6	82.5	82	72.5	73	Some spot filling between 2005 and 2008
7	94.5	92	82	81	
8	83.5	81.8	77.5	78	Some spot filling between 2005 and 2008
9	77	64	54	54.5	Some spot filling between 2005 and 2008
10	82.5	68.5	56	53	

Table H.2 Observed Strain for Kingsland Landfill

Location Point	Strain ε %	Strain ε %	Strain ε %	Strain ε %	
	1992	1993	2000	2008	Comments
	0.00005	1	8	16	Year of Interest
A	0	3%	10%	13%	
B	0	2%	9%	11%	
C	0	2%	9%	4%	
D	0	2%	9%	12%	
E	0	3%	8%	8%	
F	0	2%	7%	-4%	
1	0	5%	22%	20%	Possible Slope failure
2	0	3%	9%	11%	
3	0	2%	11%	14%	
4	0	2%	11%	10%	
5	0	2%	9%	9%	
6	0	1%	12%	12%	
7	0	3%	13%	14%	
8	0	2%	7%	7%	
9	0	17%	30%	29%	Possible Slope failure
10	0	17%	32%	36%	Possible Slope failure

Table H.3 Calculation Using Data and Model

Landfill 1965 to 1987 = 22 years in operation					
Landfill 1965 to 1987 = 22 years in operation					
Using PhD Work with (C + H)/L values of:					
t_p = 70 min	t_2 = 4204800 min				
t_1 =1203624 min	t_f = 8409600 min				
Example Calculation for 16 years					
$\rho_{16} = C_{\alpha 3.11}$ x Log(t_1/ t_o) + $C_{\beta 3.11}$ x Log(t_f / t_1)					
ρ_{16} =	0.006*LOG(1203624/70)+0.090*LOG(8409600/1203624)				
ρ_{16} =	0.0954	times landfill 1992 thickness (85) =		8.11	feet

Table H.4 Comparison of Calculated and Observed Settlement Values in Feet

	Calculated Strains			t_p = 70 minutes					
	Years	0	1		8		16		
		0	0.019		0.07431		0.101		
Landfill Depth	Calc p								
from Elev.	Point		Calc	Obs	Calc	Obs	Calc	Obs	
115.70	A	0	2.25	3.70	8.60	11.70	11.73	15.20	
117.80	B	0	2.29	1.80	8.75	10.30	11.94	12.80	
104.70	C	0	2.03	2.50	7.78	9.70	10.62	3.70	Some spot filling
114.00	D	0	2.21	2.00	8.47	10.00	11.56	14.00	
112.00	E	0	2.17	3.00	8.32	9.00	11.36	9.00	Some spot filling
92.50	F	0	1.80	1.50	6.87	6.50	9.38	-3.50	
80.50	1	0	1.563	4.00	5.98	17.50	8.16	16.50	Indicates possible slope failure
86.50	2	0	1.68	2.50	6.43	7.50	8.77	9.30	
86.20	3	0	1.67	2.00	6.41	9.90	8.74	12.20	
91.00	4	0	1.77	2.00	6.76	10.00	9.23	9.50	Some spot filling
100.10	5	0	1.94	2.10	7.44	9.10	10.15	9.10	Some spot filling
82.50	6	0	1.60	0.50	6.13	10.00	8.37	9.50	Some spot filling
94.50	7	0	1.83	2.50	7.02	12.50	9.58	13.50	
83.50	8	0	1.62	1.70	6.20	6.00	8.47	5.50	Some spot filling
77.00	9	0	1.49	13.00	5.72	23.00	7.81	22.50	Indicates slope failure
82.50	10	0	1.60	14.00	6.13018	26.5	8.37	29.50	Indicates slope failure

Table H.5 Percent Difference between Calculated and Observed Settlement

Point	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
A	2.25	3.70	39%	8.60	11.70	27%	11.73	15.20	0.2282
B	2.29	1.80	-27%	8.75	10.30	15%	11.94	12.80	0.0668
C	2.03	2.50	19%	7.78	9.70	20%	10.62	3.70	-1.869
D	2.21	2.00	-11%	8.47	10.00	15%	11.56	14.00	0.1743
E	2.17	3.00	28%	8.32	9.00	8%	11.36	9.00	-0.262
F	1.80	1.50	-20%	6.87	6.50	-6%	9.38	-3.50	3.6798
1	1.56	4.00	61%	5.98	17.50	66%	8.16	16.50	0.5053
2	1.68	2.50	33%	6.43	7.50	14%	8.77	9.30	0.0569
3	1.67	2.00	16%	6.41	9.90	35%	8.74	12.20	0.2836
4	1.77	2.00	12%	6.76	10.00	32%	9.23	9.50	0.0287
5	1.94	2.10	7%	7.44	9.10	18%	10.15	9.10	-0.115
6	1.60	0.50	-220%	6.13	10.00	39%	8.37	9.50	0.1194
7	1.83	2.50	27%	7.02	12.50	44%	9.58	13.50	0.2902
8	1.62	1.70	5%	6.20	6.00	-3%	8.47	5.50	-0.539
9	1.49	13.00	89%	5.72	23.00	75%	7.81	22.50	0.653
10	1.60	14.00	89%	6.13	26.50	77%	8.37	29.50	0.7164

Table H.6 Percent Difference between Calculated and Observed Settlement for Points A, B, C, D, 2, 3, 4, 5, 6, 7 and 8

Point	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
A	2.25	3.70	39%	8.60	11.70	27%	11.73	15.20	23%
B	2.29	1.80	-27%	8.75	10.30	15%	11.94	12.80	7%
C	2.03	2.50	19%	7.78	9.70	20%	Filling 2000 - 2008		
D	2.21	2.00	-11%	8.47	10.00	15%	11.56	14.00	17%
2	1.68	2.50	33%	6.43	7.50	14%	8.77	9.30	6%
3	1.67	2.00	16%	6.41	9.90	35%	8.74	12.20	28%
4	1.77	2.00	12%	6.76	10.00	32%	Filling 2000 - 2008		
5	1.94	2.10	7%	7.44	9.10	18%	Filling 2000 - 2008		
6	1.60	0.50	-220%	6.13	10.00	39%	Filling 2000 - 2008		
7	1.83	2.50	27%	7.02	12.50	44%	9.58	13.50	29%
8	1.62	1.70	5%	6.20	6.00	-3%	Filling 2000 - 2008		

APPENDIX I

OBSERVED AND CALCULATED SETTLEMENT FOR KINGSLAND LANDFILL AT (C + H)/L RATIO OF 2.50

Table I.1 Observed Settlement for Kingsland Landfill at (C + H)/L Ratio of 2.50

Location Point	1992	1993	2000	2008	Comments
	Elevation (ft)	Elevation (ft)	Elevation (ft)	Elevation (ft)	
A	115.7	112	104	100.5	
B	117.8	116	107.5	105	
C	104.7	102.2	95	101	Some spot filling between 2005 and 2008
D	114	112	104	100	
E	112	109	103	103	Some spot filling between 2005 and 2008
F	92.5	91	86	96	
1	80.5	76.5	63	64	Some spot filling between 2005 and 2008
2	86.5	84	79	77.2	
3	86.2	84.2	76.3	74	
4	90.5	89	81	81.5	Some spot filling between 2005 and 2008
5	98.6	98	91	91	Some spot filling between 2005 and 2008
6	82.5	82	72.5	73	Some spot filling between 2005 and 2008
7	94.5	92	82	81	
8	83.5	81.8	77.5	78	Some spot filling between 2005 and 2008
9	77	64	54	54.5	Some spot filling between 2005 and 2008
10	82.5	68.5	56	53	

Table I.2 Observed Strain for Kingsland Landfill for (C + H)/L Ratio of 2.50

Location Point	Strain ε %	Strain ε %	Strain ε %	Strain ε %	
	1992	1993	2000	2008	Comments
	0.00005	1	8	16	Year of Interest
A	0	3%	10%	13%	
B	0	2%	9%	11%	
C	0	2%	9%	4%	
D	0	2%	9%	12%	
E	0	3%	8%	8%	
F	0	2%	7%	-4%	
1	0	5%	22%	20%	Possible Slope failure
2	0	3%	9%	11%	
3	0	2%	11%	14%	
4	0	2%	11%	10%	
5	0	2%	9%	9%	
6	0	1%	12%	12%	
7	0	3%	13%	14%	
8	0	2%	7%	7%	
9	0	17%	30%	29%	Possible Slope failure
10	0	17%	32%	36%	Possible Slope failure

Table I.3 Calculation Using Data and Model for (C + H)/L Ratio of 2.50

Landfill 1965 to 1987 = 22 years in operation					
Landfill 1965 to 1987 = 22 years in operation					
Using PhD Work with (C + H)/L values of:					
t_p = 70 min	t_2 = 4204800 min				
t_1 =525600 min	t_f = 8409600 min				
Example Calculation for 16 years					
$\rho_{16} = C_{\alpha 2.50}\mathrm{x}\ \mathrm{Log}(t_1/t_o) + C_{\beta 2.50}\mathrm{x}\ \mathrm{Log}(t_f/t_1)$					
ρ_{16} =	0.0078*LOG(525600/70)+0.064*LOG(8409600/525600)				
ρ_{16} =	0.1102	times landfill 1992 thickness (85) =		9.36	feet

Table I.4 Comparison of Calculated and Observed Settlement Values in Feet for (C + H)/L Ratio of 2.50

	Calculated Strains			t_p = 70 minutes					
	Years	0	1		8		16		
		0	0.019		0.07431		0.101		
Landfill Depth	Calc p								
from Elev.	Point		Calc	Obs	Calc	Obs	Calc	Obs	
115.70	A	0	3.83	3.70	10.52	11.70	12.78	15.20	
117.80	B	0	3.90	1.80	10.71	10.30	13.01	12.80	
104.70	C	0	3.47	2.50	9.52	9.70	11.56	3.70	Some spot filling
114.00	D	0	3.77	2.00	10.36	10.00	12.59	14.00	
112.00	E	0	3.71	3.00	10.18	9.00	12.37	9.00	Some spot filling
92.50	F	0	3.06	1.50	8.41	6.50	10.21	-3.50	
80.50	1	0	2.66	4.00	7.32	17.50	8.89	16.50	Indicates possible slope failure
86.50	2	0	2.86	2.50	7.86	7.50	9.55	9.30	
86.20	3	0	2.85	2.00	7.84	9.90	9.52	12.20	
91.00	4	0	3.01	2.00	8.27	10.00	10.05	9.50	Some spot filling
100.10	5	0	3.31	2.10	9.10	9.10	11.05	9.10	Some spot filling
82.50	6	0	2.73	0.50	7.50	10.00	9.11	9.50	Some spot filling
			3.13		8.59		10.43		
			2.76		7.59		9.22		
94.50	7	0	2.55	2.50	7.00	12.50	8.50	13.50	
83.50	8	0	2.73	1.70	7.50	6.00	9.11	5.50	Some spot filling
77.00	9	0	3.83	13.00	10.52	23.00	12.78	22.50	Indicates slope failure
82.50	10	0	3.90	14.00	10.71	26.5	13.01	29.50	Indicates slope failure

Table I.5 Percent Difference Between Calculated and Observed Settlement for (C + H)/L Ratio of 2.50

Point	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
	1993			2000			2008		
A	3.83	3.70	-4%	10.52	11.70	10%	12.78	15.20	16%
B	3.90	1.80	-117%	10.71	10.30	-4%	13.01	12.80	-2%
C	3.47	2.50	-39%	9.52	9.70	2%	11.56	3.70	-212%
D	3.77	2.00	-89%	10.36	10.00	-4%	12.59	14.00	10%
E	3.71	3.00	-24%	10.18	9.00	-13%	12.37	9.00	-37%
F	3.06	1.50	-104%	8.41	6.50	-29%	10.21	-3.50	392%
1	2.66	4.00	33%	7.32	17.50	58%	8.89	16.50	46%
2	2.86	2.50	-15%	7.86	7.50	-5%	9.55	9.30	-3%
3	2.85	2.00	-43%	7.84	9.90	21%	9.52	12.20	22%
4	3.01	2.00	-51%	8.27	10.00	17%	10.05	9.50	-6%
5	3.31	2.10	-58%	9.10	9.10	0%	11.05	9.10	-21%
6	2.73	0.50	-446%	7.50	10.00	25%	9.11	9.50	4%
7	3.13	2.50	-25%	8.59	12.50	31%	10.43	13.50	23%
8	2.76	1.70	-63%	7.59	6.00	-26%	9.22	5.50	-68%
9	2.55	13.00	80%	7.00	23.00	70%	8.50	22.50	62%
10	2.73	14.00	80%	7.50	26.50	72%	9.11	29.50	69%

Table I.6 Percent Difference Between Calculated and Observed Settlement for Points A, B, C, D, 2, 3, 4, 5, 6, 7 and 8 for (C + H)/L Ratio of 2.50

Point	Calc	Obs	% Diff	Calc	Obs	% Diff	Calc	Obs	% Diff
	1993			2000			2008		
A	3.83	3.70	-4%	10.52	11.70	10%	12.78	15.20	16%
B	3.90	1.80	-117%	10.71	10.30	-4%	13.01	12.80	-2%
C	3.47	2.50	-39%	9.52	9.70	2%	Filling 2000 - 2008		
D	3.77	2.00	-89%	10.36	10.00	-4%	12.59	14.00	10%
2	2.86	2.50	-15%	7.86	7.50	-5%	9.55	9.30	-3%
3	2.85	2.00	-43%	7.84	9.90	21%	9.52	12.20	22%
4	3.01	2.00	-51%	8.27	10.00	17%	Filling 2000 - 2008		
5	3.31	2.10	-58%	9.10	9.10	0%	Filling 2000 - 2008		
6	2.73	0.50	-446%	7.50	10.00	25%	Filling 2000 - 2008		
7	3.13	2.50	-25%	8.59	12.50	31%	10.43	13.50	23%
8	2.76	1.70	-63%	7.59	6.00	-26%	Filling 2000 - 2008		

Table I.7 Comparison of Differences Between Observed and Calculated Settlement By Year for Each Value of (C + H)/L Ratio Shown

Year	1993		2000		2008	
(C + H)/L	3.11	2.5	3.11	2.5	3.11	2.5
A	20%	-4%	-6%	10%	-2%	16%
B	-67%	-117%	-22%	-4%	-23%	-2%
C	-7%	-39%	-15%	2%		
D	-45%	-89%	-22%	-4%	-9%	10%
2	12%	-15%	-23%	-5%	-24%	-3%
3	-10%	-43%	7%	21%	5%	22%
4	-16%	-51%	3%	17%		
5	-21%	-58%	-17%	0%		
6	-320%	-446%	12%	25%		
7	4%	-25%	19%	31%	6%	23%
8	-25%	-63%	-49%	-26%		

APPENDIX J

STEP BY STEP VALIDATION ANALYSIS USING 40 TO 50 YEAR OLD CONNECTICUT LANDFILL DATA

Graphical method utilizing Figure J.1 and final duration years.

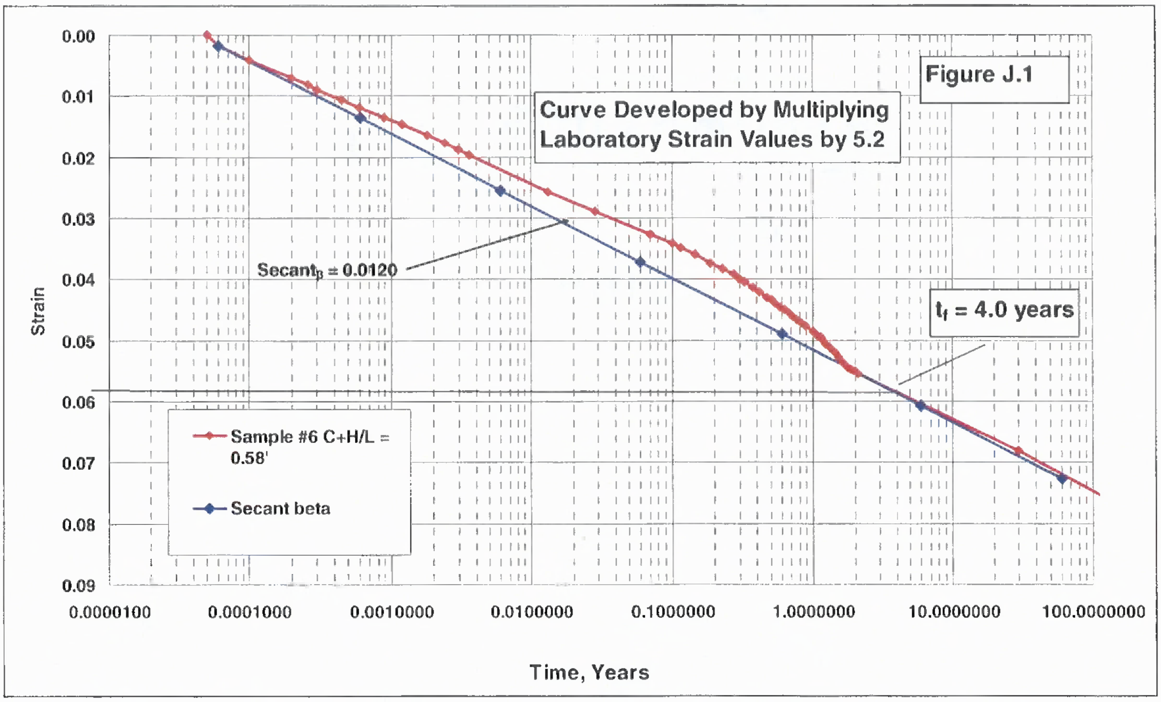

Figure J.1 Extended settlement curve for (C + H)/L Ratio of 0.58

Table J.1 Calculated Versus Observed Settlement Using Figure J.1

SP #	Thickness (m)	Obs. Settlement	Duration years	Strain From Figure J.1	Calc. settlements (m)	Calc./Obs %	% Difference
84-2	10.06	0.65	4	0.057	0.5734	88%	-12%
84-3	10.06	0.58	4	0.057	0.5734	99%	-1%
84-4	11.58	0.6	4.1	0.058	0.6716	112%	12%
84-5	5.49	0.33	4.1	0.058	0.3184	96%	-4%
84-6	10.06	0.61	3.9	0.056	0.5634	92%	-8%
84-7	11.58	0.52	3.3	0.055	0.6369	122%	22%

The following step by step analysis can be utilized to calculate the settlement using the formulae discussed in Chapter 5. One value is calculated for demonstration purposes and the remaining values can be calculated in a similar manner.

The following example was described by Edil, Ranguette and Wuellner (1990) and is for a landfill in Connecticut that is 40 to 50 years old. The landfill was excavated, re-deposited and compacted in an alternate location.

A (C + H)/L ratio value of 0.58 was selected as representative of a northeastern U.S. municipal solid waste of this age. The results of an analysis comparing the laboratory gas remaining value at a (C + H)/L value of 0.58 was utilized to determine the time, in years, when the same value of the gas remaining would occur in the field. A theoretical evaluation of time versus gas remaining, using the descriptive modifier exponents discussed by Findikakis et al (1979) was utilized. The values of the readily, moderately and slowly descriptive modifier exponents were selected based upon the best fit curve shown in Figure J.2 for half life values of 0.5, 3.5 and 25 years, respectively`. The time, in years was determined by choosing the value of the gas remaining, as discussed above, and selecting the time associated with that value from the results of the curve of gas remaining versus years shown on Figure J.3. The values for C'_α and Secant_β were selected by using Figures J.4 and J.5, respectively. Because biodegradation is re-initiated by re-deposition, a t_1 value equal to 0.00005 days (approximately 30 minutes) was selected as defining the beginning of secondary compression (C'_α) following re-deposition. Settlement values after 3.3 to 4.1 years are desired. The landfill thickness (H_0), varies from 5.49 to 11.48 meters.

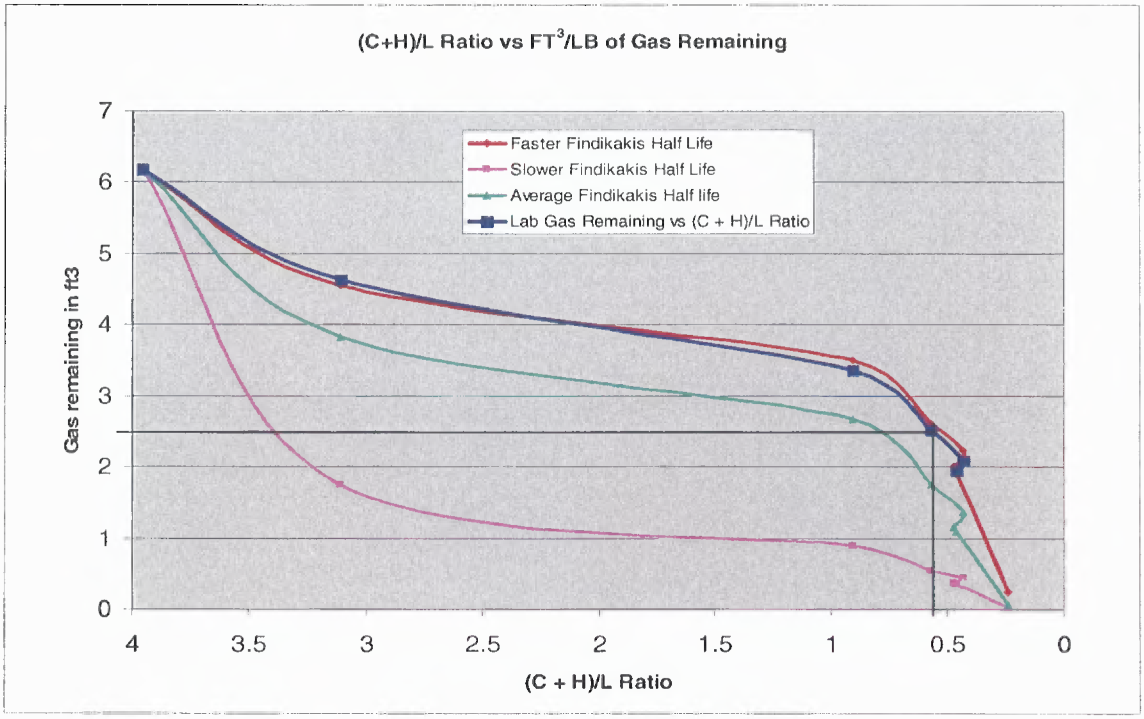

Figure J.2 Comparison of (C + H)/L Ratio versus gas remaining using Findikakis (1979)

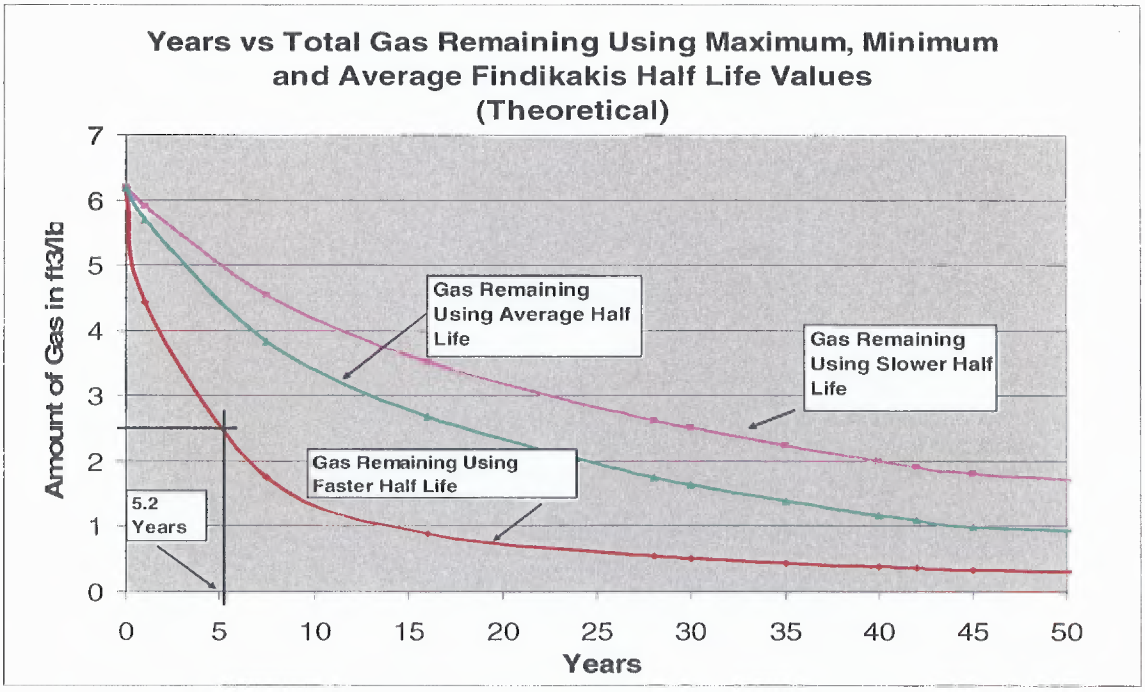

Figure J.3 Determination of field time using gas remaining and Findikakis (1979).

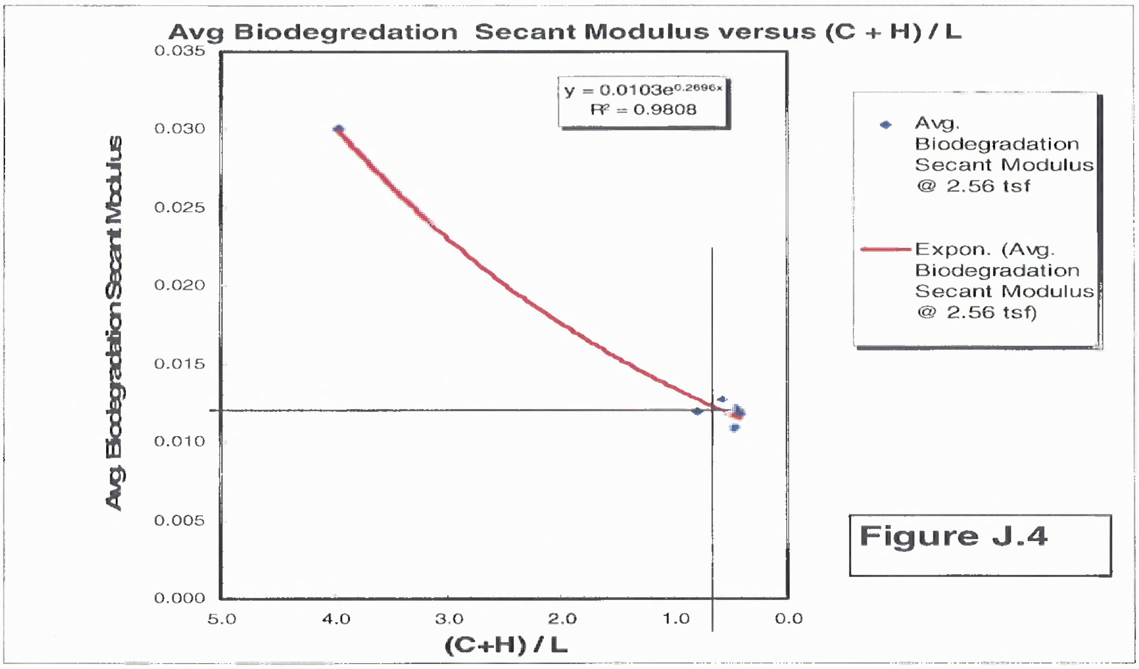

Figure J.4 Average Biodegradation Secant Modulus versus (C + H)/L Ratio.

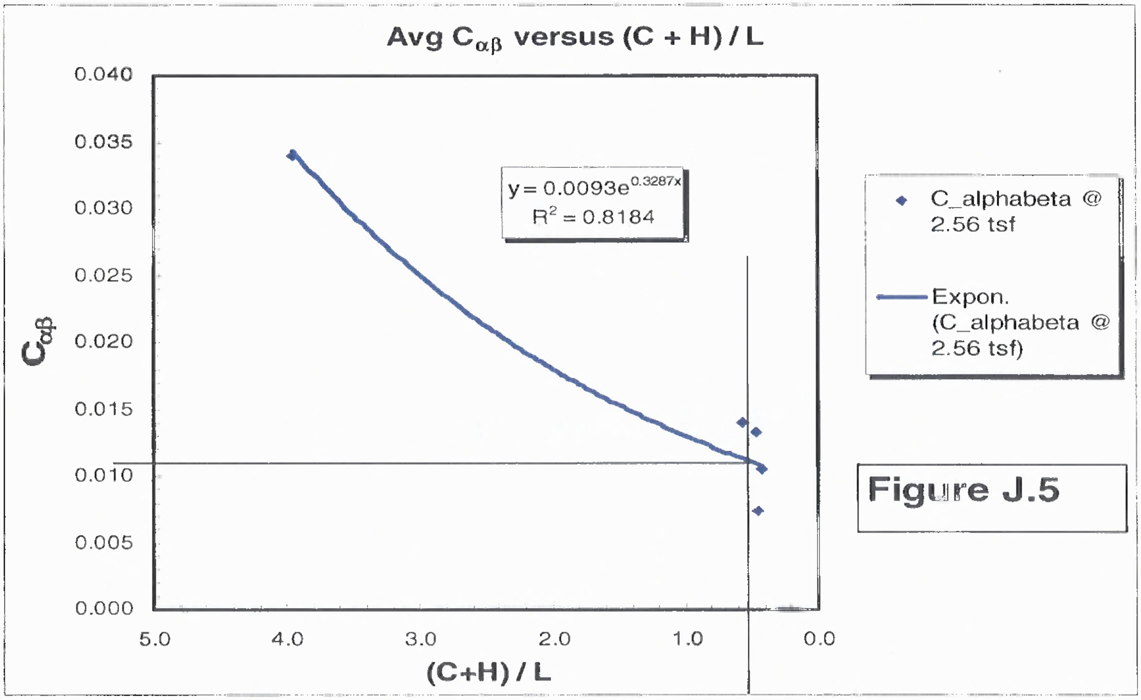

Figure J.5 Average Tertiary Settlement $C_{\alpha\beta}$ values versus (C + H)/L Ratio

Table J.2 Step by Step Analysis of Settlement Calculation for Validation Problem

<table>
<tr><td colspan="2">Step 1: Assign value of $(C + H)/L$ ratio for waste. Since waste is 40 to 50 years old $(C + H)/L$ ratio < 0.58.</td></tr>
<tr><td colspan="2">Step 2: Waste is re-deposited and compacted and left to biodegrade from 3.3 to 4.1 years.</td></tr>
<tr><td colspan="2">Step 3: It is observed from the curve in Figure J.1 that t_f is greater than t_3 (start of tertiary compression)</td></tr>
<tr><td colspan="2">Step 4: Secant Modulus of Biodegradation Settlement $\rho Secant_\beta = H_o * Secant_\beta * Log\ (t_3/t_1)$ and Tertiary Biodegradation Settlement $\rho_{\alpha\beta} = H_o * C_{\alpha\beta} * Log\ (t_f/t_3)$ may be used.</td></tr>
<tr><td colspan="2">Step 6: Total settlement at t_f equals: $\rho Secant_\beta + \rho_{\alpha\beta}$</td></tr>
<tr><td colspan="2">Step 7: Use $Secant_\beta = 0.0120$ (see Figure J.4)</td></tr>
<tr><td colspan="2">Step 8: Use $C_{\alpha\beta} = 0.0110$ (see Figure J.5)</td></tr>
<tr><td colspan="2">Step 9: Calculate settlement at different values of t_f, in this example t_f equals 4.1 years</td></tr>
<tr><td></td><td>$H_o * Secant_\beta * Log\ (t_3/t_1) + H_o * C_{\alpha\beta} * Log(t_f/t_3)$</td></tr>
<tr><td colspan="2">for $t_1 = 0.00005$ years, $t_3 = 3.0$ years and $t_f = 4.0$ years</td></tr>
<tr><td></td><td>$\rho = 10.06 * 0.0120 * Log(3.0/0.00005) + 10.06 * 0.0110 * Log\ (4.0/3.0) =$ 0.59 meters</td></tr>
<tr><td colspan="2">Step 10: Compute settlement values for remaining t_f values in a similar manner.</td></tr>
</table>

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