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UNIVERSITY OF ALBERTA

THE USE OF BIOLOGICAL ENHANCEMENT TO EXPEDITE LANDFILL STABILIZATION AND BENEFICIAL LAND USE

BY

DEAN KENNETH WALL

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled THE USE OF BIOLOGICAL ENHANCEMENT TO EXPEDITE LANDFILL STABILIZATION AND BENEFICIAL LAND USE submitted by DEAN KENNETH WALL in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in ENVIRONMENTAL ENGINEERING.

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DATED: September 30, 1992

Dedicated to my family...

Who mean more to me than mere words can express.

ABSTRACT

Landfills are frequently considered for urban development but have limited end uses due to large differential settlements and leachate and gas emissions (Rao, et. al., 1977). These processes continue for 20 to 30 years after landfill completion, therefore landfilled areas are left undeveloped because of the long duration of the stabilization process (Stearns, 1987; Aragno, 1988). Current secure vault landfill design does not address this problem because, by inhibiting biodegradation, the time required for stabilization is increased.

The goal of this research was to test the ability of biological enhancement to expedite landfill stabilization and thus beneficial land use. In doing so, the study: 1. Identified the effects of biodegradation on landfill surface settlement; 2. Provided mechanistic explanations and compared models for landfill decomposition and settlement; 3. Tested the ability of enhanced biodegradation to reduce stabilization time and increase landfill end use potential; and 4. Assessed which types of development are socially and technically compatible for use of closed landfill sites.

To determine this, a laboratory experiment and community survey were conducted. For the experimental study, six landfill test cells were constructed to model both settlement and decomposition over extended periods. Three cells were designed to simulate bioreactor landfills, while the other three secure vaults. The land use study was designed to determine the development needs of a typical host community and assess the social and technical compatibility of landfill sites with those needs.

Experimental results demonstrated that secondary settlement was linear with the logarithm of time and decomposition was well represented by a first order model. Comparisons indicated that in the short-term there was no significant increase in the settlement rate due to biodegradation, however,

extrapolation suggested that in the long-term the settlement rate will likely increase as the effects of decomposition become more significant. Future increases in settlement because of water infiltration or decomposition could have detrimental effects on development placed on a landfill. As a proactive approach, enhanced biodegradation addresses this problem by reducing the duration of active decomposition, thus minimizing environmental and, possibly, physical stabilization time.

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1.0 INTRODUCTION

1.1 PROBLEM STATEMENT, THESIS GOALS & OBJECTIVES

Municipal solid waste landfills often occupy large spaces of land on or immediately beyond the urban growth boundary of metropolitan areas (Zeiss and Atwater, 1989). This land frequently cannot be developed because of substantial total and differential post-construction settlement and leachate and gas emissions (Rao, et. al., 1977). These processes continue for 20 to 30 years after landfill completion, therefore landfilled areas are left undeveloped because of the long duration of the stabilization process (Stearns, 1987; Aragno, 1988). Meanwhile, the community around the landfill experiences rapid growth because it is favorably located near transportation routes and offers inexpensive land (Zeiss, 1988).

Current landfill design extends the time period for stabilization by essentially enclosing the waste in a secure vault of top and bottom liner to prevent the infiltration of moisture. Since moisture is the principal element that stimulates biodegradation, the stabilization period of the secure vault design is extended beyond that of the old sanitary landfill (Noble, 1989). An alternative approach is to design and operate the landfill as a controlled anaerobic bioreactor. The design consists of top and bottom liner systems but operationally allows for moisture, microbe and nutrient input to stimulate biological activity. Consequently, leachate and gas are produced when the liner system is new and least likely to fail. By providing favorable conditions for decomposition, landfill stabilization time can be reduced and the land can be returned more quickly to productive use. A landfill is considered stabilized when gas production has ceased, leachate does not constitute a pollution hazard, and maximum settlement has occurred (Leckie, et. al., 1979).

The goal of this research is to test the ability of biological enhancement to expedite landfill stabilization and thus beneficial land use. In doing so, the study must: 1. Identify the effects of biodegradation on landfill surface settlement; 2. Provide mechanistic explanations and compare models for landfill settlement and decomposition processes; 3. Develop test cells to model landfill behavior and obtain experimental data of settlement and biodegradation; 4. Test the effect of enhanced biodegradation on landfill stabilization time; 5. Determine if biological enhancement increases the end use potential of landfill sites; and 6. Assess which types of development are technically and socially compatible for use of closed landfill sites.

1.2 SIGNIFICANCE

Landfilling of municipal solid waste is the most common form of waste disposal in North America (Suflita, et. al., 1992; Wehran, 1983). Landfilling has remained a popular form of waste disposal because of its relatively low cost and the availability of land near urban waste generating centers. Even with recycling and waste-to-energy combustion, landfills will continue to be an integral part of our disposal system (Wingerter and Zykan, 1988; Ham and Noble, 1989; NCRR, 1974; Golueke and McGauhey, 1970).

Landfill design has moved from being based on principles of natural attenuation, towards strategies of containment and storage. Most modern landfill facilities constructed today are designed using the secure vault approach. Unfortunately, secure vault ideologies are based on the prevention problems experienced in the past, and little thought has been given to overall strategies and what exactly the landfill is supposed to accomplish (Ham and

Noble, 1989). This approach is reactive rather than proactive, basing design changes on the reaction to problems rather than sound design principles; conversely, the bioreactor approach considers the landfill as a predictable and controllable system (Ham and Noble, 1989).

As many completed landfills are located very close to large metropolitan areas, their later development and use is in the best interests of the community (Wehran, 1983). However, landfill sites have restricted uses because of their physical and environmental behavior, and hence may not be capable of meeting the community's needs. One potential method to achieve successful integration into the community is to ensure that the developed landfill is compatible with its surrounding land use. Compatibility should be increased by providing more options of the types of development that can be placed on the land.

1.3 THESIS STRUCTURE

This thesis is structured in four sequential parts designed to effectively describe and integrate the required theory, experimental approach, results and analysis, and conclusions of the research. Each chapter deals first with landfill decomposition, then landfill settlement and the effect of decomposition, and finally, land use characteristics. This is a logical progression since decomposition is related to settlement, and both settlement and decomposition are related to final land use.

Chapter 2 describes the theory and significance of landfill biodegradation, settlement, and land use planning changes near existing facilities. To understand the decomposition process and predict its effects on landfill stabilization it is essential to have knowledge of the carbon sources available for decomposition, landfill microbiology, factors influencing the rate of decomposition, and the applicability of available models. To comprehend and predict landfill settlement requires knowledge of the geotechnical properties of landfills, the mechanisms involved, the effect of biodegradation on settlement, and the applicability of available models. Developing an understanding of land use dynamics near waste facilities is achieved by examining landfill siting patterns, the interaction of landfills with urban development, and the compatibility of completed landfills with community land uses. Landfill end use is partially dependent on the physical and environmental attributes of the landfill, which are in turn related to decomposition and settlement. The final goal of chapter 2 is to extract various questions from existing theory and develop a set of hypotheses to be tested experimentally.

Chapter 3 describes the experimental approach used to test the effects of biological enhancement and the contribution of decomposition to settlement. Furthermore, it outlines the rationale used in the community survey and the statistical methods used in hypothesis testing.

Chapter 4 presents and analyzes the results for decomposition, settlement, and land use, and explains the connection between the three. In the assessment of landfill decomposition, carbon balance data and environmental parameters are examined and applied to available models. Landfill settlement analysis involves comparing the visual and statistical fit of various settlement models and estimating the effects of biodegradation on settlement. Next, results of the community survey are presented, outlining the land use needs and landfill development preferences for the two study locations. Finally, all three facets of the study are combined to provide an end use criteria for closed landfill development.

Chapter 5 makes conclusions based upon experimental results, suggests implications for landfill design and operation, and recommends areas for further research.

1.4 SCOPE & LIMITATIONS

The study waste stream consists of shredded municipal solid waste from the City of Edmonton Strathcona transfer station. The addition of business, industrial, or other waste is beyond the present scope of this study. However, as the waste used in this study was randomly sampled and characterized, comparisons to other waste streams and locations can be made. Waste sampling and test cell filling was performed in November of 1991. Therefore, the waste stream will be indicative of early winter patterns, with minimal quantities of yard and garden waste. Settlement tests were performed in landfill test cells specifically designed for this experiment and results may vary under different experimental conditions. The application of results herein requires special consideration of the parameters used in this study.

2.0 THEORY DEVELOPMENT

Existing theories on landfill decomposition, settlement, and land use characteristics are reviewed in this chapter. Emphasis is placed on the interaction between decomposition and settlement, and their subsequent effect on stabilization and landfill final use.

2.1 LANDFILL CHARACTERISTICS

Landfill and refuse characteristics such as particle size and structure, composition, and degradability will have a significant effect on landfill decomposition and settlement processes.

2.1.1 Landfilled Properties of Refuse

The typical composition of municipal refuse is subject to wide variability at certain times of the year, however, paper and paper-related products remain the dominant constituent (Barlaz, et. al., 1990). Due to the heterogeneous nature of refuse, its structure in the landfill consists of a wide range of particle sizes, shapes, and materials compressed together to form a mass. Since the predominant component of refuse is paper, the landfill structure resembles a network of paper pieces compacted together. Due to the non-uniformity of the particles, there is considerable void space in the refuse mass, occupied by both liquid and gas, with the majority of the liquid either being absorbed by the particles or remaining on the particle surface. A conceptual illustration of the refuse particle structure in a landfill is shown below in Figure 2.1.

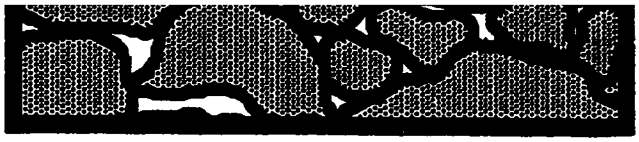
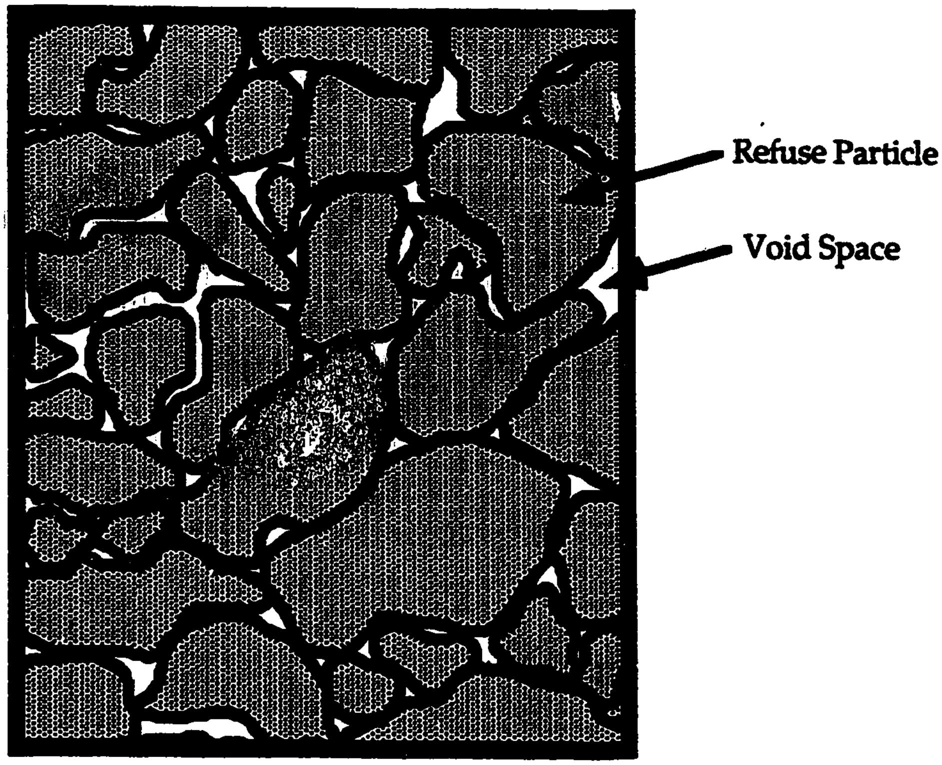


Figure 2.1 - Refuse Particle Structure in a Landfill

Municipal refuse typically contains 40 to 50% cellulose, therefore, a close examination of the microstructure of cellulose may give some insights into the behavior of shredded refuse (Barlaz et. al., 1989). Because the major constituents of fibrous peat are also composed of cellulose, an analogy between the behavior of shredded refuse and fibrous peat can be made (Chen, 1974). Chen suggests that since paper is the principal constituent of solid waste, its pore structure could have a significant influence on the nature of the settlement and decomposition processes. Observations from a photomicrograph of paper indicate two levels of structure: a random agglomerate of fibers containing micropores, interwoven by a network of macropores (Chen, 1974). This seems to indicate three levels of pores: the pores between the paper pieces, the pores between the cellulose fibers, and the pores in the cellular structure of the fiber itself (Chen, 1974).



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2.1.2 Refuse Particle Size

Refuse particle size varies significantly and is strongly dependant upon what processing the garbage receives prior to landfilling. When refuse is fed through a hammermill or shredder, the process converts it into a more homogeneous mass of smaller particle size (Chen, et. al., 1977). Shredded refuse has been observed to require approximately 40%, and sometimes 50%, less landfill space than unshredded refuse (City of Edmonton, 1991; Chen, et. al., 1977). Its general appearance is like that of a homogeneous mass of dirty, shredded paper (Chen, 1974). This observation was also true of the refuse used in this study.

2.1.3 Moisture Distribution and Flow Patterns

Moisture infiltration and distribution in a landfill depends on gravity flow, channelling, and capillary action (Noble and Nair, 1989). It is expected that for shredded refuse, gravity flow and capillary action may be the significant moisture distribution mechanisms, however, for unshredded refuse the effect of channelling may dominate. This effect was observed by Hentrich, et. al. (1979) as shredded refuse in landfill test cells produced a lesser volume of more concentrated leachate than unshredded refuse test cells.

2.1.4 Refuse Composition

There have been many composition studies done on municipal refuse. (see Table 2.1). These studies provide a general description of the variability and make up of the municipal solid waste stream.

Table 2.1 - Municipal Refuse Composition (Adapted From Halvadakis, et. al., 1983 and Emcon Associates, 1980)

Refuse Component	Robinson 1986	Jackson 1976	EMCON 1975	Pfeffer 1974a	Fungaroli 1979	EMCON 1981	Rees 1980b	Golueke 1970	Ham 1971	USEPA 1977	Tchobanoglous 1977	Lewis 1989	Kaiser 1966	Mao 1973
	Composition of Municipal Refuse (percent of wet weight)													
Food Waste	3.9	7.3	10.7	16	15 (b)	7.1	30.6 (b)	12	15.3	14.9	15	7.9	12 (b)	25
Garden Waste	3.5	17.7	10.4	9	xx	1.5	xx	9	13.8	16.3	12	17.9	xx	0
Paper	59.2	39.4	40.6	48	55	55.1	31.2	50	42.4	34.9	44	41	46	50
Textiles	4	6.5	1.7	1	3	1.6	4.1	2	1.6	1.7	5 (c)	8.1 (c)	3	5
Wood	6.4	0.9	1	2	2	8.1	xx	2	1.2	3.8	xx	xx	7	1
Plastic / Rubber	7.3	6.7	4.6	2	3	9.3	5.2	3	1.8	6.4	3	6.5	4	3
Glass / Ceramics	0	7.6	10.9	6	10	5.4	3.8	7	10.1	10.5	8	8.2	10	7
Metal	13	8	9	8	10	10.6	5.3	7	6.7	9.8	9	8.7 (d)	8	4
Ash / Rock	xx	2.6	2.8	8 (a)	2 (a)	1.3 (a)	xx	7 (a)	7.2 (a)	1.7 (a)	4 (a)	1.6 (a)	10 (a)	5 (a)
Fines	2.7	3	8.3	xx	xx	xx	13.5	xx	xx	xx	xx	xx	xx	xx
Miscellaneous	xx	xx	xx	xx	xx	xx	6.3	xx	xx	xx	xx	xx	xx	xx

(xx) accounted for in another category
(a) includes fines
(b) includes garden waste
(c) includes rubber, leather, wood
(d) includes ceramics

2.1.5 Major Organic Carbon Sources

Prior to reviewing the microbial dynamics of the decomposition process it is important to gain insight into the carbon sources that are available for degradation. Chemically, the major biodegradable carbon sources in municipal refuse can be classified as lignocelluloses, polysaccharides, fat containing organic molecules, and proteins (Senior and Balba, 1990). Refuse typically contains 40 to 50% cellulose, 10 to 15% lignin, 12% hemicellulose, and 4% protein on a dry weight basis (Barlaz, et. al., 1990). Barlaz, et. al., also states that the cellulose plus the hemicellulose fraction of refuse accounts for 91% of its methane potential. Lignin, however, is considered to have no methane potential because it is resistant to decomposition under the anaerobic conditions required for methane production. See Table 2.2 for a summary of the composition of municipal refuse by chemical constituent.

Table 2.2 - Chemical Composition of Municipal Refuse

Chemical Constituent	% Dry Weight of Refuse				
	Barlaz 1988	Reese 1972	Pfeffer 1974a	Jones 1983a	Pacey 1989
Carbohydrates			52.8		
Lignocelluloses					
lignin	15.2			7.2	10.2
hemicellulose	11.9			6.7	
cellulose	51.2	58.8 (b)		25.7	39.7
pectin	<3 (a)				
Starch	0.5			2.4	
Soluble Sugars	0.35				
Lipids		5.7	6.2		
Proteins	4.2	2.6		5	

(a) actual value is probably less than 3% but could not be quantified
(b) includes sugars and starch

Lignocelluloses

Lignocelluloses are a broad group which include the three major types of polymers: cellulose, hemicellulose, and lignin. Due to the fact that cellulose is the most abundant bipolymer on earth, it is not surprising that it makes up a significant portion of municipal refuse (Senior and Balba, 1990). Cellulose is a basic constituent of the cell walls of all green plants and some fungi, and comprises 35 to 45% of the dry weight of most woody tissues and wheat straw (Senior and Balba, 1990).

Cellulose is the principal biodegradable fraction of municipal refuse under anaerobic conditions typical of landfills and its decomposition in refuse is well documented (Barlaz, et. al., 1990; Barlaz, et. al., 1989; Bookter and Ham, 1982). The cellulose plus hemicellulose fraction of refuse accounts for 91% of its methane potential (Barlaz, et. al., 1990). Slow decomposition processes and low gas yields in landfills can be partially attributed to the semirecalcitrance of the cellulose polymer (Rees, 1980a), a product of its high molecular weight, pore size distribution, degree of polymerization, unit cell dimension, degree of structural order, insolubility, and low available surface area for cellulase enzyme contact (Senior and Balba, 1990).

Hemicellulose is the second most common bipolymer and is present in the primary cell wall, including the endosperm of certain seeds, and the secondary cell wall. Thick-walled strengthening agents contain up to 35% hemicellulose (Senior and Balba, 1990). The hemicellulose content of hardwoods usually varies from 20 to 40%, softwoods 25 to 35%, and grasses/straw 25 to 50% (Tsao and Chiang, 1983).

Lignin, the last of the lignocelluloses, is the third most abundant bipolymer on earth mineralized by the carbon cycle. It constitutes between 18 and 30% of the dry weight of wood tissues where it is present in the cell walls binding the cellulose fibers together (Senior and Balba, 1990; Emcon Associates, 1980). Due to the structural complexities of specific lignins, generalizations on degradation mechanisms are difficult to make (Reddy, 1984). Recalcitrant under anaerobic conditions, it does not contribute significantly to the amount of usable substrate in refuse (Jones, et. al., 1983b; Young and Frazer, 1987).

Other Carbon Sources

The only remaining carbohydrate of significance is starch, which serves structural and nutrient functions in plants and is present in high concentration in the stem, seeds, and roots (Senior and Balba, 1990). Starch is easily assimilable under anaerobic conditions and is utilized as a substrate in the initial degradation stages of domestic refuse (Jones, et. al., 1983b).

Fats and oils are widely distributed in plant cells and are commonly found in tissues of seeds, where they act as a reserve food supply (Senior and Balba, 1990).

Proteins serve nutrient, enzymatic and structural functions in plants and contain carbon, hydrogen, oxygen, nitrogen, and usually sulfur, although some also contain phosphorus (Senior and Balba, 1990). Although proteins are widely distributed in plant and microbial cells, they do not serve as major substrates in refuse fermentation (Senior and Balba, 1990). Like starch, though, protein is easily assimilable under anaerobic conditions and is also utilized as a substrate in the initial degradation stages of domestic refuse (Jones, et. al., 1983b).

2.2 LANDFILL DECOMPOSITION

Biological decomposition results in a net loss of landfill solids, theoretically this should result in additional settlement and therefore have significance in terms of physical and environmental landfill stabilization. Decomposition in municipal solid waste landfills is a complex and multistage process that is carried out by a mixed population of bacteria. Degradation of refuse organics occurs mainly through anaerobic processes, although some aerobic decomposition occurs near the landfill surface and during the initial stages of biodegradation (Davies and Coleman, 1981). The following section reviews and explains the landfill decomposition process in terms of mechanisms and available models.

2.2.1 Theory of Biological Enhancement

Biological enhancement refers to operating a landfill or landfill simulator in such a fashion that biological degradation processes are encouraged. The objective is to accelerate the decomposition process, thus stabilizing the landfill more rapidly. Because of the complex ecosystem present during the anaerobic decomposition of municipal refuse it is important to consider which bacterial group is being enhanced. If the delicate balance between groups is upset, conditions within the refuse may become unfavorable for further decay.

2.2.2 Microbiology

Anaerobic decomposition of cellulose and hemicellulose in municipal refuse occurs mainly due to three trophic groups of bacteria (Wolfe, 1979; Zehnder, 1982). The first group is referred to as hydrolytic and fermentative microorganisms, the second group is the acetogens, and the third group is the methanogens.

Hydrolysis and Fermentation

Hydrolytic and fermentative microorganisms are responsible for the hydrolysis of polymers such as carbohydrates, fats and proteins (Barlaz, et. al., 1990). Initial products of polymer hydrolysis include soluble sugars, amino acids, long-chain carboxylic acids, and glycerol (Barlaz, et. al., 1990). These products are then converted to short-chain carboxylic acids, carbon dioxide hydrogen, acetate, and alcohols by hydrolytic and fermentative microorganisms (Barlaz, et. al., 1990). This process primarily produces gaseous metabolites such as carbon dioxide and hydrogen, straight and branched chain fatty acids, and compounds such as ethanol, lactate, and succinate (Senior and Balba, 1990). The actual distribution of the individual compounds can vary considerably and is dependent on many interrelated factors such as redox potential, microbial specific growth rate, molecular configuration, and hydrogen concentration (Senior and Balba, 1990).

Acetogenesis

The obligate proton reducing acetogens oxidize the fermentation products of the hydrolytic and fermentative bacteria to acetate, carbon dioxide and hydrogen (Barlaz, et. al., 1990). The conversion of primary substrates such as butyrate, propionate, and ethanol are only thermodynamically favorable at very low hydrogen concentrations (Barlaz, et. al., 1990). Therefore, the acetogens must grow in dual culture with an obligate hydrogen consuming bacterium, which maintains a low partial pressure of hydrogen in the ecosystem (Senior and Balba, 1990). Both methanogens and sulphate reducing bacteria can potentially function to serve this requirement (Barlaz, et. al., 1990).

Methanogenesis

The final step in the anaerobic decomposition process is the production of methane and carbon dioxide through methanogenesis. Methanogenic bacteria can utilize only a limited number of substrates such as formate, methanol, methylamine, hydrogen and carbon dioxide, and acetate (Barlaz, et. al., 1990). In sludge digesters, the acetate route accounts for approximately 70% of the methane generated (Jeris and McCarty, 1965). The consumption of hydrogen ions probably represents the single most important bioregulatory function of methanogenic bacteria in a landfill (Senior and Balba, 1990).

The significance of methanogens in the anaerobic digestion process is summarized by Zeikus (1980). Methanogens are responsible for:

"1) Controlling the pH of their ecosystem by the consumption of acetate.

2) Regulating the flow of electrons by the consumption of hydrogen, creating thermodynamically favorable conditions for the catabolism of alcohols and acids.

3) Excreting organic growth factors, including vitamins and amino acids, that are used by other heterotrophic bacteria in the ecosystem."

Microbial Dynamics

For simplicity, the anaerobic ecosystem can be represented by the following four step process:

Hydrolysis -» Fermentation -» Acetogenesis -» Methanogenesis

When dealing with soluble substrates, the final step is usually the slowest and therefore rate limiting (McCarty, 1964). Conversely, when insoluble substrates in a landfill environment decompose, hydrolysis may be rate limiting (Chan and Pearson, 1970; Eastman and Ferguson, 1981;

Halvadakis, et. al., 1983; El-Fadel, et. al., 1989; Barlaz, et. al., 1990). These are two important considerations when studying the microbial dynamics of refuse degradation. During the initial stages of decomposition there is a significant amount of readily degradable soluble substrate present. Therefore, the rate of the overall process should be governed by methanogenesis. However, should the activity of the fermentative bacteria exceed that of the acetogens and methanogens, there will be an accumulation of hydrogen and carboxylic acids, which will lower the pH and inhibit methanogenic activity (Barlaz, et. al., 1990). Once the readily degradable soluble substrates are exhausted, the overall process must be governed by hydrolysis (Halvadakis, et. al., 1983). Since the principal carbon sources in landfill are insoluble, the majority of the decomposition process is limited by hydrolysis, however, the methanogens are by far the most sensitive of the microbial species present and can be inhibited by many factors (Halvadakis, et. al., 1983).

Noble and Nair (1989) have approached biological rate limitations using a mechanistic approach that focuses on micro-scale events that must occur during decomposition. They suggest that the possible rate limiting steps for landfill degradation are: external mass transfer, internal mass transfer, enzymatic hydrolysis of cellulose, and methanogenesis. Methanogenesis is the only possibility that does not involve the hydrolysis of refuse solids. Therefore, it is likely that hydrolysis will become a rate limiting step sometime during the decomposition process. With reference to full scale landfills without moisture flow or leachate recirculation, they state that bulk movement or diffusion of material within the landfill is a likely cause of rate limitations.

2.2.3 Progressive Phases of Refuse Decomposition

The progressive decomposition of refuse has been characterized by many researchers by observing changes in landfill leachate and gas production (Farquhar and Rovers, 1973; Rees, 1980b; Ehrig, 1983; Pohland and Harper 1986; Barlaz, et. al., 1990). The best summary of the process to date is provided by Christensen and Kjeldsen (1989). The process is described below in five phases:

1) Aerobic Phase,
2) Anaerobic Non-Methanogenic,
3) Anaerobic Methanogenic Accelerated Unsteady,
4) Anaerobic Methanogenic Steady, and
5) Anaerobic Methanogenic Decelerated Unsteady.

Phase one is a short aerobic phase just following landfilling of the waste where easily degradable organic matter is aerobically decomposed and carbon dioxide is produced. Phase two is characterized by the depletion of oxygen and the onset of anaerobic degradation processes. The activity of the fermentative and acetogenic bacteria results in rapid production of volatile fatty acids, carbon dioxide and some hydrogen. The leachate produced at this point is quite acidic and may contain high concentrations of fatty acids, calcium, iron, heavy metals, and ammonia. Concentrations of nitrogen continue to decrease due to the production of carbon dioxide and hydrogen, and initially high concentrations of sulphate are reduced as the redox potential drops. The third phase begins with the slow growth of methanogenic bacteria. Methane concentrations in the gas begin to increase, while hydrogen, carbon dioxide, sulphate, and volatile fatty acid concentrations decrease. The consumption of fatty acids results in a pH and alkalinity increase, making conditions for methanogenesis more favorable, and resulting in a lower solubility of calcium, iron, manganese, and heavy metals. The fourth phase is identified by the stable production of methane in the landfill gas, roughly 50 to 60% by volume. The continued rate of methane production maintains the low concentrations of volatile fatty acids and hydrogen. The last phase occurs when only the poorly degradable carbon sources are remaining. Methane concentrations will decrease and nitrogen levels will rise due to diffusion from the atmosphere. Aerobic zones and zones with redox potentials too high for methanogenesis will start to appear in upper layers of the landfill. Figure 2.2 illustrates changes in gas and leachate composition in a landfill cell.

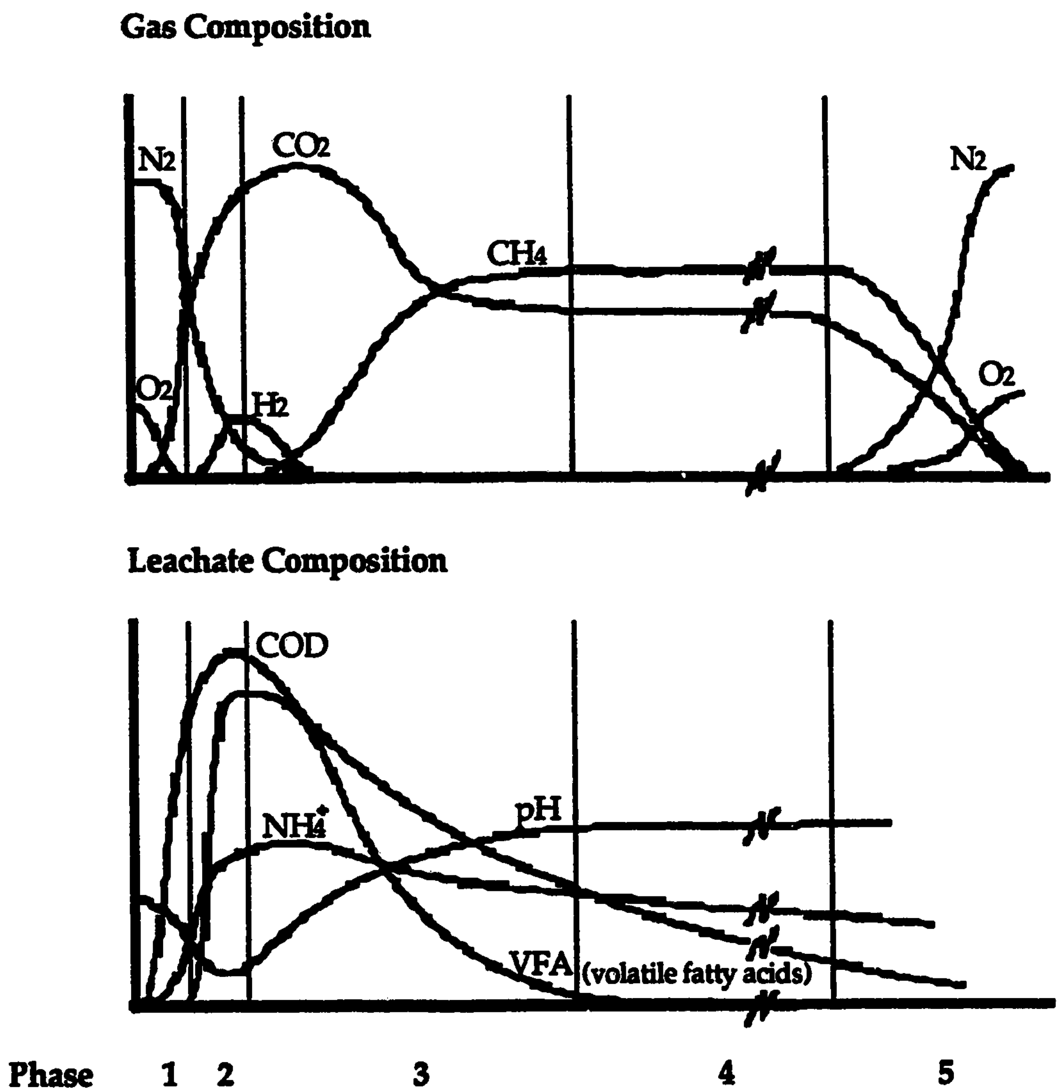

Figure 2.2 - Landfill Gas and Leachate Composition vs Time (Adapted from Christensen and Kjeldsen, 1986; based on Farquhar and Rovers, 1973)

2.2.4 Factors Influencing the Decomposition Process

The decomposition process can be either enhanced or inhibited by a large number of factors which range from the environment to landfill management and waste management. Environmental factors include uncontrollable parameters such as ambient temperature and precipitation. Landfill management factors include operational parameters such as waste placement methods and the addition of seed, moisture and nutrients. Waste management factors deal with waste processing prior to landfill, such as waste separation or shredding. These are summarized in Figure 2.3 and then explained in detail.

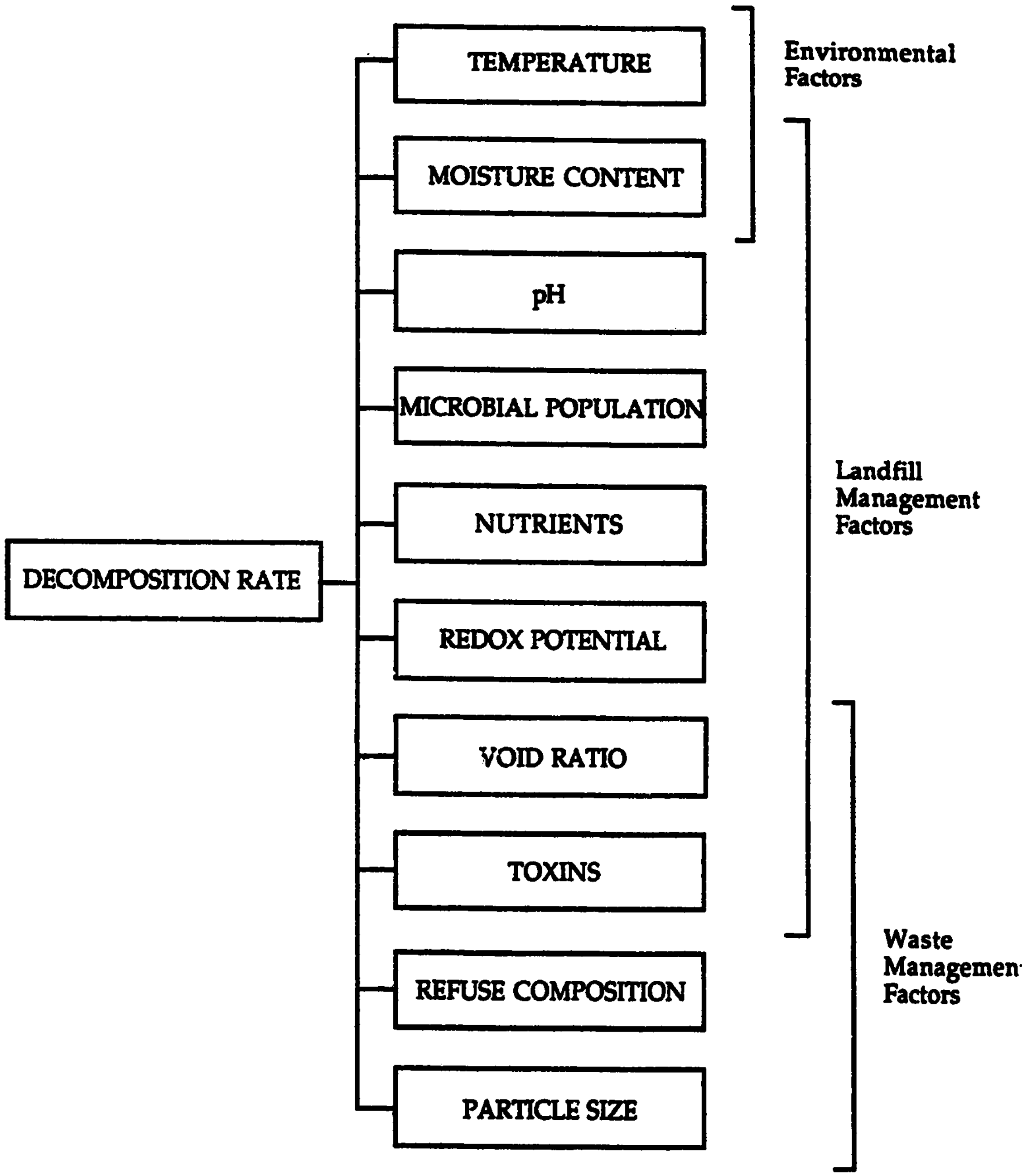

Figure 2.3 - Decomposition Influence Diagram

The first environmental factor is temperature, which is one of the few parameters that cannot be easily controlled in a full size landfill environment. It can, however, be partially controlled by altering the depth of refuse in the landfill. As landfill depth increases, a larger zone of favorable temperature is maintained. The optimum temperature for methane production in the mesophilic range has been identified as 41 to 42 °C (Hartz, et. al., 1982; Pfeffer, 1974b), with the optimum temperature in the thermophilic range being at least 60 °C (Pfeffer, 1974b). Temperatures of refuse samples from the New York Fresh Kills landfill have been observed to vary between 10 and 63 °C (Suflita, et. al., 1992). Ham (1988) states that there is a sharp loss of biological activity below 10 to 15 °C. In this study, constant temperatures of 4 °C have resulted in inhibition of gas and methane production.

Landfill moisture can be either an environmental factor or landfill management factor depending on landfill operation. Moisture is the single most important variable affecting biodegradation rates of municipal solid waste (Noble, 1989). Completely dry refuse cannot decompose because moisture is required for the activity of most microorganisms, including bacteria in the landfill ecosystem (Noble, 1989). Also, it is likely that this activity increases with moisture content (Farquhar and Rovers, 1973; Rees, 1980b). Moisture flow through a landfill may be expected to enhance biological decomposition processes by providing better contact between insoluble substrates, soluble nutrients, and microorganisms (Barlaz, et. al., 1990). The addition of moisture will tend to dilute and remove reaction products and inhibitory substances, and will eliminate air from pore spaces (Rees, 1980b).

Another important landfill management parameter affecting biodegradation is pH. When performing moisture addition or leachate recycle it is important not to upset the balance between the microorganism populations. If polymer hydrolysis and fermentation are stimulated without also stimulating acetogenesis and methanogenesis, there will be an overabundance of reaction by-products, namely, carboxylic acids (Barlaz, et.

al., 1990). Their presence will cause the pH to drop, further inhibiting the methanogens. Methanogenic bacteria are by far the most sensitive in the refuse ecosystem and operate only within a narrow pH range of 6 to 8 (Christensen, 1989). If an excess of fatty acids is produced by the hydrolytic and fermentative bacteria, a buffer material will have to be added to maintain higher pH levels. Most methods of biological enhancement require pH buffering to keep the refuse mass within a range viable for methanogenic bacteria (Pohland and Harper, 1986; Barlaz, et. al., 1987). Various carbonate buffers have commonly been used for these purposes in the past, however, it is necessary to take precautions in order to avoid cation toxicity (Barlaz, 1988).

Obviously, an active microbial population is fundamental to the occurrence of any biological decomposition. As stated earlier, methanogens are the most sensitive and last to develop of the microbial groups. Subsequently, most biological enhancement methods are designed to aid in their development. All of the bacteria required for municipal refuse methanogenesis are present in fresh refuse (Barlaz, et. al., 1987), however, anaerobically digested sewage sludge can be used as a source of methanogenic bacteria, nitrogen, phosphorus, and other nutrients (Barlaz, et. al., 1990).

Municipal solid wastes typically contain sufficient nutrients for bacterial degradation to take place and do not limit the onset of methane production (Pohland and Harper, 1986; Barlaz, et. al., 1990). However, late in the decomposition process there is a depletion of ammonia and phosphate which may become limiting (Pohland, 1974; Barlaz, et. al., 1990).

Methane production requires that the oxidation/reduction potential of the landfill environment is well into the negative range, usually less than negative 200 mV (Farquhar and Rovers, 1973). The redox potential must reflect reducing conditions from -200 mV to -400 mV (Ham, 1988).

Void ratio is a relative measure of landfill void space to solid space and is another means of representing refuse density. In a heterogeneous landfill environment, contact between microorganisms, their substrates, and various growth limiting factors is very important. At higher densities (and void ratios) the opportunity for contact is increased, thus a beneficial effect is expected (Barlaz, et. al., 1990). Conversely, increased density may tend to impede moisture and gas flow through the refuse, thus inhibiting decomposition. To date, studies on the effect of added compaction on refuse degradation are inconclusive (Pohland and Harper, 1986).

The presence of toxins in a landfill can be either a landfill management or waste management factor. As previously discussed, when using leachate recycle as a management option, the toxicity of leachate constituents must be considered. Conditions within the landfill will also have a significant affect on biodegradation. Several potential inhibitors are: oxygen, hydrogen, proton activity, sulphate, substrate concentration, carbon dioxide, salt ions, sulphide, heavy metals, and specific organic compounds (Christensen and Kjeldsen, 1989). The effect of cations on methane generation are shown below in Table 2.3.

Table 2.3 - Effect of Cations on Methane Generation (Adapted from Christensen and Kjeldsen, 1989 and McCarty and McKinney, 1961)

Parameter	Stimulating Effect (mg/l)	Moderate Inhibition (mg/l)	Significant Inhibition (mg/l)
Sodium	100 to 200	3500 to 5500	8000
Potassium	200 to 400	2500 to 4500	12000
Calcium	100 to 200	2500 to 4500	8000
Magnesium	75 to 150	1000 to 1500	3000
Ammonium (total)	50 to 200	1500 to 3000	3000

Refuse composition will determine the type and quantity of the various microbial substrates present in the landfill. Intuitively, the more easily degradable the refuse is, the faster decomposition will proceed. Also, the potential presence of toxic materials in the municipal waste stream could be a factor in the inhibition of biodegradation.

Finally, particle size likely has a significant effect on decomposition. A reduced particle size may be expected to enhance biological degradation by increasing the surface area available for microbial attack and improving the ability to retain moisture (DeWalle, et. al., 1978; Fungaroli and Steiner, 1979). However, none of the results of past studies are clearly conclusive on this question (Pohland and Harper, 1986).

2.2.5 Degree of Refuse Decomposition

Knowledge of the extent of refuse decomposition can help provide estimates of stabilization times for existing landfills. If the relative amounts of substrate decomposed and remaining are known, then the state of the decomposition process can be identified Refuse methane potential is commonly used for the estimation of cumulative landfill gas production (Barlaz, et. al., 1990).

Theoretical approaches for the calculation of methane potential involve using balanced stoichiometric equations. In some cases additional factors such as biodegradability are incorporated into the equation. Equation 1 shown below has been derived by Mao and Pohland (1973).

$$C_aH_bO_cN_dS_e + [a - (b/4) - (c/2) + 3(d/4) + (e/2)]\,H_2O \rightarrow [(a/2) + (b/8) - (c/4) - 3(d/8) - (e/4)]\,CH_4 + [(a/2) - (b/8) + (c/4) + 3(d/8) + (e/4)]\,CO_2 + dNH_3 + eH_2S \quad (1)$$

By using an equation such as this, theoretical predictions of methane and carbon dioxide volumes can be made on the basis of refuse composition. Table 2.4 indicates some of chemical formulas for refuse and its constituents.

Table 2.4 - Municipal Solid Waste Chemical Formulas (Adapted from Pohland and Harper, 1986)

Waste Component	Chemical Formula
Municipal Solid Waste	$C_{99}H_{149}O_{59}N$
Paper, Garden Wastes, Wood	$C_{203}H_{334}O_{138}N$
Food Wastes	$C_{16}H_{27}O_8N$
Cellulose	$C_6H_{10}O_5$

Barlaz, Ham and Schaefer (1990) have proposed a mass balance approach to determining methane potential. Calculations are based on actual chemical analyses of refuse samples, and quantities of substrates for methanogenic bacteria are then stoichiometrically converted to equivalent methane potential. In fresh refuse, cellulose and hemicellulose make up 91.1% of the methane potential with the remaining 8.4% and 0.5% from organic nitrogen and sugars respectively (Barlaz, et. al., 1989). At virtually any state in the decomposition process cellulose, hemicellulose, and carboxylic acids comprise at least 90% of the methane potential (Barlaz, et. al., 1990). Methods have been devised to measure these parameters in refuse samples (Barlaz, et. al., 1989). Based upon equation 1 the methane potential of carbohydrates ($C_nH_{2n}O_n$) at standard temperature and pressure is 373 L/kg (Barlaz, et. al., 1989). Methane potential from carboxylic acids can be calculated by examining the reactions involved in their conversion to acetate and hydrogen and their subsequent conversion to methane. (McInerney and Bryant, 1981). The basic steps are outlined below (McInerney and Bryant, 1981) with their equivalent methane potential (as calculated by Barlaz, et. al., 1989).

valerate --> propionate & acetate	720.8 L CH_4 / kg valerate
butyrate & propionate --> acetate & H_2	643.7 L CH_4 / kg butyrate
H_2 & CO_2 --> CH_4	537.0 L CH_4 / kg propionate
acetate --> CH_4 & CO_2	373.0 L CH_4 / kg acetate

It is important to understand that the methods described above provide only a theoretical estimate of methane potential, and because of incomplete bacterial mineralization the actual methane potential will be less than calculated values (Barlaz, et. al., 1990). However, chemical analyses and mass balances have proven useful for assessing the degree of refuse decomposition and the maximum remaining methane potential (Barlaz, et. al., 1990).

2.2.6 Decomposition Modelling

In this study, the purpose of modelling decomposition is to evaluate the amount of refuse solids lost over time due to biological decay. It is hypothesized that this reduction in solids directly relates to an increase in the magnitude and rate of secondary settlement. Therefore the decomposition step of concern is the conversion of refuse organic solids to liquid. Once in liquid form, the intermediate decomposition products are free to drain out of the landfill mass as void space is reduced. Detailed studies on the degradation process indicate that the polymer hydrolysis step is responsible for this solubilization (Barlaz, et. al., 1990). As the most abundant source of degradable carbon is cellulose and hemicellulose, its biological decomposition is of importance. Many researchers have assumed that cellulose hydrolysis is governed by first order kinetics (Chen, 1974; McGowan, et. al., 1988; El-Fadel, et. al., 1989; Young, 1989).

Mathematical modelling of the landfill decomposition process is a very difficult task, mainly because of its complexity. The degradation process is a multistep mechanism with several different groups of bacteria working together to maintain the process. Many other factors also come into play such as nutrient limitations and the presence of inhibitory compounds. The nature of the landfill structure tends to confound matters further. As the refuse mass is heterogeneous and there is no mixing, decomposition processes are slow to get established, and reaction products tend to buildup and inhibit subsequent processes. Also, poor surface area contact and mass transfer limitations start to play a key role in the rate of decomposition (Noble, et. al., 1989). Because of these reasons and the undefined nature of the landfill environment, results from anaerobic digester studies cannot be directly applied to organic decomposition in sanitary landfills (Leckie, et., al., 1979).

Biodegradation model paramaters such as substrate concentration and microbial population are difficult to experimentally monitor in a landfill test cell. In order to measure these parameters in a landfill environment the use of surrogate indicators or destructive testing methods must be considered. Using surrogate parameters involves finding suitable decomposition indicators in the landfill gas or leachate that is produced. The problem with this, besides the obvious fact that it is only a surrogate, is that the complex processes within the landfill cannot be measured by the few potential parameters that are available. However, models that can represent the process in simple usable terms are still quite valuable to engineers. Some commonly used parameters of measure are: methane concentration and gas production rate, leachate biochemical oxygen demand (BOD), total organic carbon (TOC), chemical oxygen demand (COD), and the concentration of carboxylic acids.

Destructive testing involves the operation of several replicate experimental cells, and when a parameter needs to be evaluated one or more of the cells is sacrificed and analyzed to provide actual parameter measurements. This approach is based on the assumption that each cell is representative of the group. The use of destructive testing for modelling purposes dramatically increases the number of test cells that are required to maintain statistical validity. With the modelling of time series data such as biodegradation, each time increment would require that at least one test cell be opened and destroyed. In addition, the heterogeneous nature of refuse makes the validity of using different cells to represent the continual decomposition process somewhat questionable. Much variability has been observed in both the time required for the onset of methane production and methane production rates in replicate experimental reactors (Barlaz, 1988). However, Barlaz (1988) has effectively utilized destructive testing methods to evaluate the extent of biological decomposition and estimate methane potential in laboratory reactors and full-size landfills.

Few articles in the literature evaluate decomposition models in actual landfill (or lysimeter) situations; most models are based on digester studies with various solid substrates. The most common approach used for actual landfill modelling is to describe the entire decomposition process as a single first order reaction. Degradation half lives are assumed for the various refuse components and converted into first order rate coefficients.

First Order Model

This model treats bacteria as "catalysts" and represents an overall mass transfer kinetic model for the reaction (Mata-Alvarez and Cecchi, 1990). Even though it is not a sophisticated model, it provides a single kinetic constant that is useful when dealing with complex processes (Pfeffer, 1974b). The basic equation is shown below:

$$\frac{dS}{dt} = -kS \qquad (2)$$

S = biodegradable substrate concentration at time t [M/V]
t = time
k = first order degradation rate constant [T^{-1}]

Various parameters have been used to represent substrate concentration; methane production or methane potential as described previously in this chapter are probably the most common approaches. In digester studies, model parameters can actually be measured due to complete mix conditions and the ability to remove refuse samples for analysis.

Various half lives for organic components of refuse have been estimated and calculated. A summary of these values are shown in Table 2.5 as first order rate constants ($t_{1/2} = \ln 2/K$).

Table 2.5 - First Order Rate Constants for Municipal Refuse

Rate Constant K (1/yr)	Source	Basis	Conditions
0.0365	Farquhar, 1973	Lysimeter Data	Overall Degradation Rate
0.6931	Ham, 1979	Estimated	Food Waste
0.0462	Ham, 1979	Estimated	Paper, Wood, Grass, Brush & Leaves
0.693	Hoeks, 1983	Estimated	Readily Degradable
0.139	Hoeks, 1983	Estimated	Moderately Degradable
0.046	Hoeks, 1983	Estimated	Slowly Degradable
1.386 to 0.462	Ham, 1988	Estimated	Rapidly Decomposable
0.139 to 0.028	Ham, 1988	Estimated	Moderately Decomposable
0.091	Piccholutto, 1987	Landfill Data	Overall Degradation Rate
2.92	McGowan, 1988	Computer Model	Overall Degradation Rate
0.083	Leuschner, 1989	Lysimeter Data	Cell With Infiltration Only
0.286	Leuschner, 1989	Lysimeter Data	Enhanced Reactor (pre-methanogenesis)
1.183	Leuschner, 1989	Lysimeter Data	Enhanced Reactor (methanogenesis)
0.427	Leuschner, 1989	Lysimeter Data	Enhanced Reactor (post-methanogensis)
0.071 ± 0.016	Suflita, 1992	Landfill Data	Cellulose Biotransformation

Modified First Order Model

Singh, et. al. (1983) developed a model based on the first order model which accounts for the remaining substrate being progressively less biodegradable.

$$\frac{dS}{dt} = \frac{-kS}{1+t} \quad (3)$$

S = biodegradable substrate concentration at time t [M/V]
t = time
k = modified first order degradation rate constant

The model was proven to be applicable to the anaerobic digestion of cattle waste, where S was expressed as COD or volatile solids (VS) concentration (Singh, et. al., 1983).

Monod Model

When substrate limiting conditions are applied to the classical Monod equation, a pseudo-first order equation as shown below is produced (Emcon Associates, 1980; Mata-Alvarez and Cecchi, 1990).

$$\frac{dS}{dt} = \frac{-kSX}{K_s + S} \tag{4}$$

S = biodegradable substrate concentration at time t [M/V]
t = time
k = maximum rate of substrate utilization per unit mass of microorganism (occurring at high substrate concentrations) $[T^{-1}]$
X = concentration of microorganisms [M/V]
K_s = substrate concentration at which the rate is one half the maximum rate of substrate utilization [M/V]

In the equation, the rate of substrate utilization is related to both the concentration of microorganisms and the concentration of soluble substrate surrounding the organisms. In the two extreme cases, when S is very large ($S>>K_s$), and when S is very small ($S<<K_s$), equation 5 can be approximated by the following functions (Emcon Associates, 1980):

$$\frac{dS}{dt} = -kX \qquad (S>>K_s) \tag{5}$$

$$\frac{dS}{dt} = -\frac{kXS}{K_s} \qquad (S<<K_s) \tag{6}$$

Equation 6 is zero order with respect to substrate concentration, while equation 7 is first order with respect to substrate concentration. This model has been rigorously applied to the anaerobic digestion of soluble substrates

(Mata-Alvarez and Cecchi, 1990). In applying the model to solid substrates (municipal sewage sludge), Lawrence (1971) assumed that methanogenesis was the limiting step. In the case of refuse decomposition in landfills, rate limiting steps may change over time with polymer hydrolysis often being rate limiting (Chan and Pearson, 1970; Eastman and Ferguson, 1981; Halvadakis, et. al., 1983; El-Fadel, et. al., 1989; Barlaz, et. al., 1990).

<u>Diffusional Model</u>

The combination of the Monod model with mass transfer limitation equations produces the following overall rate equation (Suidan, et. al., 1987):

$$\frac{dS}{dt} = - k\, S^{0.5} \tag{7}$$

k = apparent kinetic constant $[(M/V)^{0.5}]$

<u>Numerical Models</u>

As the biological processes in refuse decomposition have become better understood, more sophisticated modelling techniques have been developed. Several authors have developed numerical models that solve systems of differential equations to simulate the degradation process. El-Fadel, et. al. (1989) used a model developed by Halvadakis (1983) to simulate the multistep biodegradation process, consisting of a series of reactions based on Monod microbial growth equations and the microbial product formation model, with the hydrolysis of refuse solids represented by a first order expression. McGowan, et. al. (1988) has also developed a numerical model involving three steps: hydrolysis, acidogenesis, and methanogenesis. He also models hydrolysis using first order kinetics, with subsequent reactions following Monod expressions. Young (1989) similarly proposed a three stage numerical model for decomposition. He breaks the decomposition process into primary decomposition (hydrolysis), secondary decomposition (acidogenesis), and methanogenesis. Hydrolysis and acidogenesis are modelled using first order kinetics while methanogenesis is represented by a Monod equation. One of the major problems in landfill modelling is the lack of numerical data on reaction rates (Young, 1989; El-Fadel, et. al., 1989).

2.2.7 Section Review

The previous section reviewed the microbiology and stages of landfill decomposition, reviewed factors influencing its rate, and discussed the applicability of various decomposition models to landfills. It is suggested that decomposition of refuse solids causes a loss of organic matter by which landfill settlement results. In the next section, this connection is further investigated as the geotechnical properties and settlement mechanisms of landfills are reviewed.

2.3 GEOTECHNICAL CONSIDERATIONS OF LANDFILLS

Sanitary landfills present unique problems for geotechnical engineers to contend with. Landfill materials are heterogeneous, and their geotechnical properties may change with time due to biological decomposition. It is necessary for design engineers to be able to quantify geotechnical properties such as deformability, compressibility, permeability, and strength, and understand how they may change with time (Landva, et. al., 1984). Some of the major geotechnical problems that limit the future types of development are: low bearing capacity, large surface settlement, significant differential settlement, and the long duration of settlement processes. Settlement is the most critical problem associated with developing landfill sites for commercial, industrial, or residential uses (Sowers, 1973; Kurzeme and Walker, 1985; Charles and Burland, 1982; Charles, et. al., 1986; Morris and Woods, 1990). Low bearing capacity is due mainly to the inherently low strength of the components of municipal refuse and poor compaction during landfilling procedures. Subsequently, most landfill improvement techniques increase the density of fills (Charles and Burland, 1982). Low refuse density is the result of poor compaction procedures. This stems from difficulties in compacting the garbage at the time of placement and can be greatly improved with the proper selection and use of equipment.

2.3.1 Geotechnical Properties of Landfills

Density

Refuse density is one of the main factors governing the geotechnical performance of a landfill site. If higher densities can be achieved, reductions in settlement and increases in bearing capacity can be expected (Charles and Burland, 1982). Density is dependent on refuse composition, moisture content, and the compactive effort that is applied. Unit weights of refuse in Canadian landfills have been observed to vary from 7 to 14 kN/m^3 (714 to 1428 kg/m^3) with an average of about 11 kN/m^3 (1122 kg/m^3) (Landva and Clark, 1990). Some typical unit weights are shown in Table 2.6.

Table 2.6 - Unit Weights of Refuse in Sanitary Landfills (Adapted from Oweis and Khera, 1986 and Sharma, et. al., 1990)

Source	Placement Conditions	Total Unit Weight (Kg/m3)
Bromwell (1978)	poor compaction	320
	good compaction	641
	best compaction	881
Schumaker (1972)	poor compaction	296
	moderate compaction	474 to 593
Sowers (1973)	as delivered	120 to 296
	various degrees of compaction	481 to 961
NSWMA (1985)	Municipal Refuse landfill	705 to 769
	after degradation & settlement	1009 to 1121
Landva, et. al., (1984)	various Canadian landfills	913 to 1346

Moisture Content

As with soils, refuse moisture content has a significant effect on the density and compactability of the refuse. Typical optimum moisture contents for compacting pulverised municipal refuse range from 50 to 70% (Harris, 1979). However, municipal refuse is usually delivered at moisture contents dryer than these values, typically around 22% by wet weight basis (Barlaz, et. al., 1990). This results in poorer levels of compaction compared to what is achievable at higher moisture contents.

Permeability

Permeability (or hydraulic conductivity) of refuse controls the rate of water and leachate flow through the landfill. In fine grained soils permeability is an important factor in primary consolidation. The primary settlement rate is governed by the release of pore water pressure as water flows out of the soil mass. Thus, permeability is an important consideration when ground modification methods are used to reduce the magnitude of post-construction settlement (Charles, et. al., 1986). In a series of field tests, Landva and Clark (1990) found the range of permeabilities of various Canadian landfills to be $1x10^{-3}$ to $4x10^{-2}$ m/s. These values correspond to those associated with clean sand and gravel. The high permeability of refuse suggests that perhaps consolidation mechanisms are not applicable to landfill settlement. Some typical permeabilities for various unit weights are shown in Table 2.7.

Table 2.7 - Permeability Test Data on Compacted Waste Material (Adapted from Oweis and Khera, 1986)

Unit Weight		Coefficient of Permeability, K	
(pcf)	(Kg/m3)	(cm/sec)	(ft/day)
35.8	573.4	1.2 x 10^-2	42.6
49	784.9	4.8 x 10^-3	13.6
52.2	836.1	3.5 x 10^-3	10
71	1137.3	7.1 x 10^-4	2

Strength Parameters

In order to correctly assess the slope stability and bearing capacity of landfills, knowledge of the strength parameters is required. Landva and Clark (1990) performed direct shear tests on refuse from Canadian landfills. They found the friction angle to vary between 24° and 41°, with cohesion parameters between zero and 23 kPa. From the results of their testing they concluded that the shear strength of refuse is highly variable and that the lowest strength would have to be used for analyses. Cancelli, et. al. (1987) suggests that the following parameters be used for routine design: friction angle of 25° to 26° and intercept cohesion limited to a maximum of 30 kPa.

Recently, Singh and Murphy (1990) performed a comprehensive review of the strength properties of refuse. They stated that because of the scatter and scarcity of the data, it is difficult to draw any definitive conclusions on the shear strength of refuse. They also suggest that stability analysis of landfills may be related more to its settlement and bearing capacity than to its slope failure. Figure 2.4 is a summary plot of their findings and shows an envelope of recommended strength parameters.

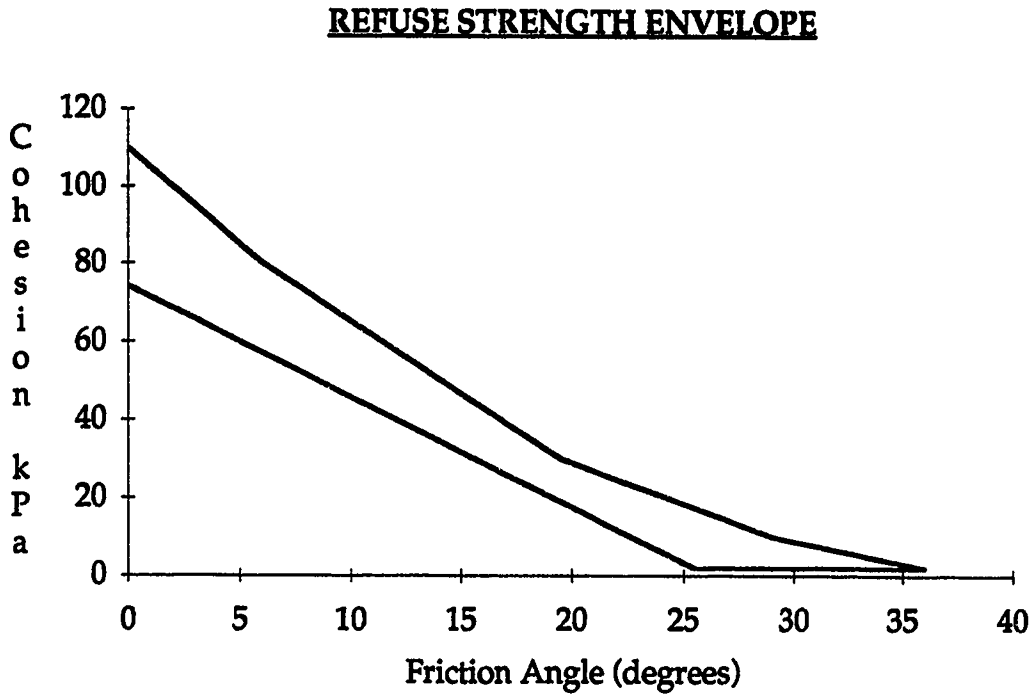

Figure 2.4 - Recommended Refuse Strength Parameters (Adapted from Singh and Murphy, 1990)

Bearing Capacity

The allowable bearing pressure of foundations placed upon refuse material is usually governed by settlement (Oweis and Khera, 1986; Harris, 1979). Harris also suggested that loads causing a bearing pressure less than 100 kN/m^2 can be supported on a landfill, however, the corresponding settlement may be unacceptable. Sargunan, et. al. (1986) recommends that values not greater than 25 to 40 kPa be used. It should be noted that there is considerable variation in the literature with respect to the strength of refuse and design values should be selected carefully. A consistent view is, however, that settlement is usually the governing factor when landfill sites are used for development (Sowers, 1973; Morris and Woods, 1990).

2.3.2 Landfill Settlement Stages

Settlement is defined as the change in refuse height over a specified time period and is probably the most commonly used means to represent height changes in a landfill. Estimates of the total settlement of a sanitary landfill range from 25% to 50% of the initial landfill depth (Stearns, 1987). There are essentially three stages of settlement: initial compression, primary compression, and secondary compression. Initial compression takes place almost immediately when a load is applied to the landfill surface. Primary settlement usually occurs during the first month after load application (Sowers, 1973). Secondary compression, however, can take place over a 30 to 50 year period, or even longer (Stearns, 1987). This time-dependant settlement is attributed to creep mechanisms and decomposition of organic matter present in the refuse (Sowers, 1973; Kurzeme and Walker, 1985). Because of its relatively short duration, the magnitude of primary settlement is the principal concern rather than the shape of the settlement vs time curve. Conversely, secondary compression occurs over long periods of time, therefore modelling is essential for predicting long-term performance of building foundations and developments. For this reason, secondary settlement is the major concern with landfill re-development.

Initial Compression

Initial compression is the settlement that occurs directly when an external load is applied to a landfill. Initial compression is generally associated with the immediate compaction of void space and particles due to a superimposed load (Tuma and Abdel-Hady, 1973). This type of settlement is analogous to the elastic compression that occurs in soils and is virtually instantaneous.

Primary Compression

In a completed landfill, primary settlement takes place usually within one month after load application and is due to compaction associated with the removal of gas and liquid from refuse void spaces (Gordon, et. al., 1986; Morris and Woods, 1990; Edil, et. al., 1990; Dodt, et. al., 1987; Sowers, 1973).

Secondary Compression

Taylor (1942) was one of the first to identify secondary compression effects which he termed "plastic structural resistance to compression." Barden (1965) attributed secondary creep effects to the gradual readjustment of the soil skeleton. Furthermore, he said the rate of secondary compression is strongly influenced by the viscous effects of the adsorbed double layer. The cause of secondary compression is subject to much controversy and a general agreement to its cause has never been reached (Rao, 1974).

Settlement due to secondary compression can account for a major portion of the total landfill settlement and can take place over many years (Rao, 1974). Secondary compression is generally the result of creep of the refuse skeleton and biological decay (Sowers, 1973; Gordon, et. al., 1986). Coduto and Huitric (1990) suggest that secondary compression due to creep and other compaction mechanisms can account for up to 25% of the refuse thickness. Furthermore, they state that settlement resulting from biological decomposition is probably between 18 and 24% of the refuse thickness. Figure 2.5 illustrates the primary and secondary stages of landfill settlement.

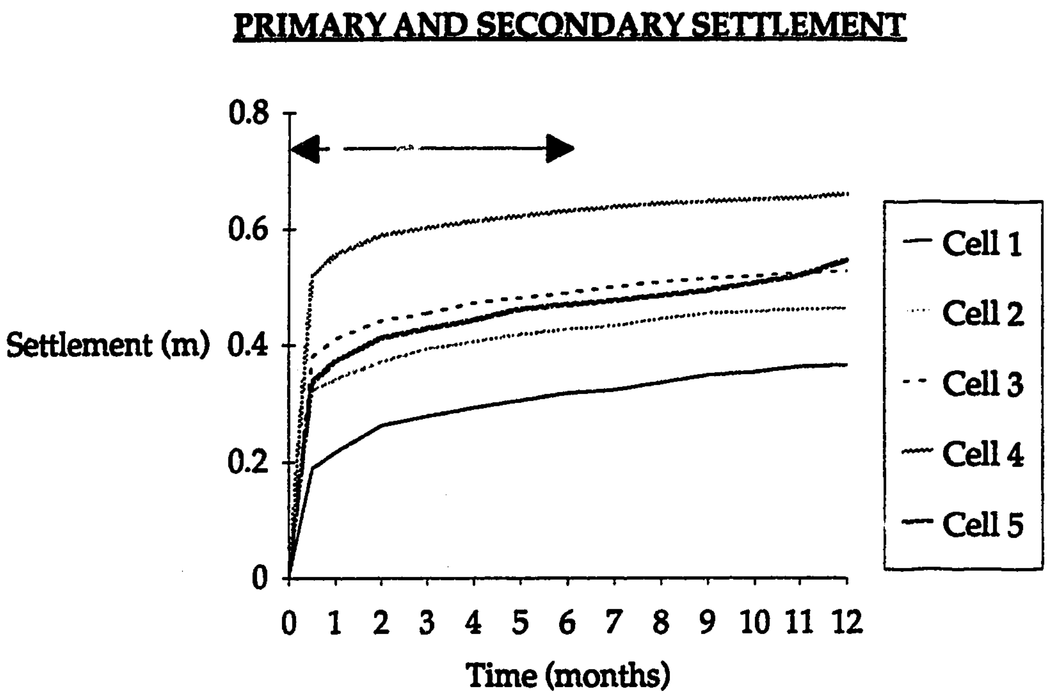

Figure 2.5 - Landfill Settlement vs Time (Adapted From Merz and Stone, 1962)

2.3.3 Landfill Settlement Mechanisms

Settlement mechanisms in refuse landfills are very complex and are not as well understood as in coarse or fine grained soils (Edil, et. al., 1990). Sowers (1973) was the first discuss the settlement mechanisms in a landfill environment, proposing five mechanisms: mechanical deformation and reorientation of materials, movement of fine particles into larger void spaces, physico-chemical change, bio-chemical decay, and interaction between mechanisms. The mechanisms involved in refuse settlement are best described using a category system derived by Coduto and Huitric (1990). Landfill settlement can be categorized by three mechanisms:

- Consolidation
- Compaction
- Shrinkage

Consolidation

Consolidation refers to the squeezing of water from the pore spaces of a saturated material under an applied load (Terzaghi, 1943). Consolidation is often suggested to be the settlement mechanism of primary compression in landfills (Sowers, 1973; Gordon, et. al., 1986). However, there are significant indications that mechanisms of this nature may not be responsible for primary settlement in municipal solid waste landfills. First, refuse in municipal landfills is seldom saturated as secure vault principles prohibit the entry of water to the fill. Secondly, no mechanistic differences were observed in this study (see chapter 4) between landfill test cells operating at field capacity, and cells operating with only inherent moisture. Thirdly, the permeability of refuse has been characterized as the same order of magnitude as sand and gravel, therefore no pore water pressure should develop as liquid can readily escape from the landfill mass. During secondary compression, however, the micropore structure of cellulose may be responsible for some secondary consolidation effects (Chen, 1974).

Compaction

Compaction is defined as the movement of solids into a more dense configuration due to void space and particle compression and changes in the rigidity of refuse solids (Coduto and Huitric, 1990). It is likely that compaction in some form or another accounts for the majority of settlement that occurs in a municipal landfill.

Shrinkage

Shrinkage is defined as the loss of solids due to biological and chemical decomposition processes occurring in the landfill. As previously discussed, biodegradation of organic matter can occur in a municipal landfill provided conditions are favorable for microbial growth. Since the onset of decomposition requires time for microbial populations to become established, any settlement caused by the loss of solids will be observed during the secondary compression stage.

2.3.4 Effect of Biodegradation on Settlement

As discussed earlier, biodegradation in landfills is a lengthy, multistage process in which solid organic particles are solubilized and ultimately converted to methane and carbon dioxide. It is hypothesized that this reduction in solids directly relates to an increase in magnitude and rate of secondary settlement. Therefore, the decompostion step of concern is the conversion of refuse organic solids to liquid. Once in liquid form, the intermediate decomposition products are free to drain out of the landfill mass as void space is reduced. Detailed studies on the degradation process indicate that the polymer hydrolysis step is responsible for this solubilization (Barlaz, et. al., 1990). Substrate for hydrolysis is predominantly cellulose and hemicellulose (Barlaz, et. al., 1990). Common practice by many researchers is to assume that cellulose hydrolysis occurs by first order kinetics (Chen, 1974; McGowan, et. al., 1988; El-Fadel, et. al., 1989; Young, 1989).

This is quite different from the usual geotechnical situation where the mass of solids is assumed to be constant for the duration of the settlement process. Since biodegradation occurs mainly during the secondary compression stage, it is suggested by several researchers that it increases the rate of secondary compression (Sowers, 1973; Leckie, et. al., 1979; Kurzeme and Walker, 1985; Oweis and Khera, 1986; Yen and Scanlon, 1975; Charles and Burland, 1982). Thus, if the biological processes are enhanced, the time required for stabilization will be reduced. Leckie, et. al. (1979) confirmed these findings when they investigated the effects of leachate recycle on a refuse test cell. In their analysis of landfill settlement rate data, Yen and Scanlon (1975) found that settlement rates were higher in landfills where conditions were favorable to decomposition than in landfills where conditions were unfavorable. However, consolidation tests done by Landva, et. al. (1984) show no significant difference between secondary compression rates in older and more recent fills. Also, in tests performed by Rao, et. al. (1977) it was found that the effects of biological decomposition did not significantly influence the rate of secondary compression. The authors suggest that this may have been due to the relatively short duration of the consolidation tests. Chen (1974) developed a numerical settlement model which incorporated a first order expression to account for biodegradation. He found the model to be insensitive to changes in the degradation rate constant between 0.012 and 0.788 years^{-1}. The upper value is quite high and is very close to 0.693 yrs^{-1} which Hoeks (1983) associated with the rapid decomposition of food waste. Farquhar and Rovers (1973) suggest an overall decomposition rate constant for landfills of 0.0365 yrs^{-1}. Recently, Suflita, et. al. (1992) recorded cellulose biotransformations of 0.071 ± 0.016 yrs^{-1} in the New York Fresh Kills landfill.

To determine the contribution of decomposition to settlement it is necessary to have an understanding of the amount of solid carbon that decomposes. If refuse is comprised of 40 to 50% cellulose and 12% hemicellulose (Barlaz, et. al., 1990), and this fraction represents roughly 90% of its methane potential (Barlaz, et. al., 1990), then the cellulose concentrations of 9 to 30% which have been measured in decomposing landfills (Bookter and Ham, 1982), indicate that approximately 25 to 40% of municipal refuse is available for decomposition. Clearly, if this amount of solid material was removed from a landfill, considerable settlement would occur.

2.3.5 Settlement Models

The prediction and modelling of settlement processes in landfills is predominantly emperical and usually based on measured laboratory and field parameters (Rao, 1974). There is a lack of one workable theory that accounts for all factors influencing the settlement of refuse landfills (Rao, 1974), and most of the assumptions used in classical consolidation theory are not valid for the settlement of municipal refuse in a landfill environment (Chen, 1974). Classical assumptions are violated because landfills are usually not saturated, have large void spaces and particles, experience large deformations and creep, have compressible solids and pore fluid, undergo solids loss due to biodegradation, and have changing material properties over time (Chen, 1974).

Initial Compression

The initial compression phase is very seldom modelled in landfills except in the case of foundation design. No references could be found that included detailed calculations of settlement due to initial compression. However, the following model is one used for foundation design purposes for all partially saturated fine-grained soils and coarse grained soils with large permeabilities (Bowles, 1988). Since landfills have a relatively large permeability and experience a visible immediate compression when loaded, equation 9 was applied.

$$S = \frac{\Delta q \, H_0}{E_s} \tag{8}$$

S = settlement due to initial compression
Δq = stress increase in stratum (kN/m^2)
H_0 = initial height of refuse
E_s = modulus of elasticity (kN/m^2)

Terzaghi Theory

The primary consolidation process as it applies to landfills is most common modelled using Terzaghi theory. Many researchers have utilized this approach: Sowers (1973), Landva, et. al. (1984), Rao, et. al. (1977), Gordon, et. al. (1986), Morris and Woods (1990), Kurzeme and Walker (1985), Moore and Pedler (1977), Oweis and Khera (1986). Terzaghi (1943) derived his original equation to describe the deformation caused by consolidation mechanisms. He defined consolidation as the volume loss due to the decrease in water content of a saturated soil without the replacement of air and water. As discussed above, it is probable that primary compression in landfills is attributed more to compaction mechanisms than consolidation. However, the parameters used in Terzaghi's equation are well documented for landfills (see Table 2.10). The notation selected below is derived from Mesri and Godlewski (1977) as used in Holtz and Kovacks (1981).

$$S = \frac{H_i C_c}{(1 + e_0)} \log [(p_0 + \Delta p)/p_0] \tag{9}$$

S = settlement due to primary consolidation
H_i = height of refuse after initial compression
C_c = primary compression index
e_0 = void ratio after initial compression
p_0 = existing overburden pressure at mid level of layer
Δp = increment of overburden pressure at mid level of layer

where:

$$C_c = \Delta e/\Delta \log p \tag{10}$$

C_c = slope of the void ratio vs log effective stress curve

$$C_{ce} = C_c/(1+e_o) \tag{11}$$

$$C_{ce} = \Delta strain/\Delta \log p \tag{12}$$

C_{ce} = modified compression index
C_{ce} = slope of the strain vs log effective stress curve

$$e_o = \frac{W_o p_s}{S p_w} \tag{13}$$

W_o = refuse initial water content
p_s = density of refuse solids
S = degree of saturation
p_w = density of water

Sowers (1973) suggests that the primary compression index (C_c) increases linearly with the initial void ratio (e_o) and organic content. He provides the following range for estimating C_c (0.15 corresponds to low organic content while 0.55 corresponds to high).

$$C_c = [0.15 \text{ to } 0.55]\, e_o \tag{14}$$

Extension of Terzaghi Theory

Compression that takes place at essentially zero pore pressure is not accounted for by the classical theory, therefore a model to describe this was developed. Buisman (1936) was one of the first to model secondary compression and suggested that effects were linear with the logarithm of time. Sowers (1973) was the first to present a model for the secondary compression of refuse in sanitary landfills. The equations he presents are a modification of Buisman's theory for secondary compression of soils. The theory assumes that the secondary portion of the settlement curve is linear with respect to the logarithm of time. This behavior has been confirmed by many researchers and field data: Sowers (1973), Landva, et. al. (1984), Rao, et. al. (1977), Gordon, et. al. (1986), Morris and Woods (1990), Kurzeme and Walker (1985), Moore and Pedler (1977), Oweis and Khera (1986). The notation selected below is derived from Mesri and Godlewski (1977) as used in Holtz and Kovacks (1981).

$$S = \frac{H_p C_a}{(1 + e_p)} \log [t/t_p] \tag{15}$$

S = settlement due to secondary compression
H_p = height of refuse after primary consolidation
C_a = secondary compression index
e_p = void ratio after primary consolidation
t = time (days)
t_p = time for primary consolidation to occur (usually 30 days)

where:

$$C_a = \Delta e / \Delta \log t \tag{16}$$

C_a = slope of the void ratio vs log time curve

$$C_{ae} = C_a/(1+e_p) = \Delta \text{strain}/\Delta \log t \tag{17}$$

C_{ae} = slope of the strain vs log time curve

C_{ae} is otherwise known as the secondary compression ratio or rate of secondary compression.

$$e_p = \frac{W_p \rho_s}{S \rho_w} = \frac{V_v}{V_s} \tag{18}$$

W_p = refuse water content after primary consolidation
ρ_s = density of refuse solids
S = degree of saturation
ρ_w = density of water
V_v = volume of voids
V_s = volume of solids

Sowers (1973) suggests that the secondary compression index (C_a) increases linearly with the initial void ratio (e_p) and favorable decomposition conditions. He provides the following range for estimating C_a (0.03 corresponds to unfavorable conditions while 0.09 corresponds to favorable conditions).

$$C_a = [0.03 \text{ to } 0.09]\, e_p \tag{19}$$

Some typical values for refuse compressibility are shown in Table 2.8 below.

Table 2.8 - Refuse Compressibility Parameters (Adapted from Oweis and Khera, 1986)

Reference	Cce	Cae
Rao, et. al., 1977	0.16 to 0.235	0.012 to 0.046
Converse, 1975	0.25 to 0.3	0.07
Zoino, 1974	0.15 to 0.33	0.013 to 0.03
Sowers, 1973 (for eo=3)	0.1 to 0.41	0.02 to 0.07
Oweis and Khera, 1986	0.08 to 0.217	
Landva, et. al., 1984	0.2 to 0.5	0.0005 to 0.029

In attempts to provide a single equation combining the primary and secondary settlement of refuse, Edil, et. al. (1990) apply models previously used to describe the secondary compression of materials. The two models that they investigated were: the Gibson and Lo rheological model, and the power creep law.

<u>**Rheological Model**</u>

Gibson and Lo (1961) derived a rheological model that combines the effects of primary and secondary compression into one convenient equation. Rheological models have been successfully used to describe one dimensional consolidation of clays and peats (Rao, 1974) Edil and Mochtar (1981) found the model works well on peats and consequently applied it to the settlement of landfills with reasonable results. They make the presumption that peat is similar to refuse in that both have relatively large void spaces that compress quickly during initial and primary settlement, and that the largest settlement is due to the slow and continuous process of secondary compression.

In the model primary compression is represented by the stress transfer from the pore water to the soil skeleton. As time proceeds, stress is transferred completely to the soil skeleton, resulting in secondary compression. Therefore, the model allows for primary and secondary compression to occur simultaneously. Barden (1968) suggested that the progressively decreasing strain rate with time was due to increases in structural viscosity. This is the result of interference from adsorbed double layers as particles become closer and closer to one another. However in criticizing the model, Barden (1965) states that it is too simple to give an accurate representation of the consolidation process.

The equation is derived for the case of an instantaneous loading and large values of time. Due to the mathematical nature of the model, the graph of settlement versus the logarithm of time will not be linear in the secondary compression range. This is a significant shortfall, as observations of numerous time-settlement plots of landfills indicate that secondary compression is frequently linear with the logarithm of time.

$$S = H_0 \Delta p \, [a + b\,(1 - \exp(-Lt))] \tag{20}$$

S = amount of primary and secondary settlement
H_0 = initial refuse height
Δp = compressive stress
a = primary compressibility parameter $[kPa]^{-1}$
b = secondary compressibility parameter $[kPa]^{-1}$
L = rate of secondary compression, lambda/b $[day]^{-1}$
t = time since load application

Power Creep Law

The Power Creep Law has been used extensively to represent the transient creep behavior of many materials and is one of the simplest equations describing time dependent deformation under constant stress (Edil, et. al., 1990). Edil, et. al. (1990) were the first to apply the Power Creep model to landfill settlement. They found that the amount of primary and secondary settlement could be satisfactorily modelled using the basic creep equation. Furthermore, they concluded that the Power Creep Law provided a better representation of landfill settlement than the Gibson and Lo model.

$$S = H_0 \Delta p \, m \, (t/t_r)^n \tag{21}$$

S = amount of primary and secondary settlement
H_0 = initial refuse height
Δp = compressive stress
m = reference compressibility
t = time since load application
t_r = reference time to make time dimensionless (usually 1 day)

2.3.6 Section Review

The previous section provided a description of the geotechnical characteristics and behavior of municipal solid waste landfills. A theoretical connection was made between biological decomposition and landfill settlement. More specifically, cellulose hydrolysis was establised as the decomposition step that affects settlement. The section following this will address the interaction between the landfill and the community, and the role settlement and biodegradation play in landfill re-development.

2.4 LANDFILL / COMMUNITY INTERACTION

In this section, patterns of landfill location will be compared to patterns of urban development. It is hypothesized, that because of landfill site selection criteria, landfills will frequently come into contact with the neighboring community. This interaction would require that closed landfill sites be developed into productive land for community use.

2.4.1 Patterns of Landfill Facility Location

Landfill site selection is a process that weighs different technical, environmental, economic, social, and political criteria (Robinson, 1986; Wilson, 1981). Some specific considerations are the availability and cost of land, accessibility and distance from the waste generating center, site soil conditions and hydrogeology, and distance from residential areas (Tchobanoglous, et. al., 1977; Robinson, 1986). More recently, issues such as public opinion have come into play in the landfill siting process (Bagchi, 1990). Use of these site selection criteria often result in landfills that are located outside the urban boundary, on marginal, inexpensive land, but close to major roads or highways (Zeiss, 1988).

2.4.2 Patterns of Land Use Change

Since the rural host community is in close proximity to the urban fringe, it is frequently overgrown by urban development (Zeiss, 1988). Any landfills located within the rural area will become encompassed by new development. For example, in the City of Edmonton, municipal solid waste landfills have followed this pattern, playing leap-frog with the urban growth boundary (see Figure 2.6). The pattern has also been established by Zeiss (1988) in the greater Vancouver (B.C.) metropolitan area.

As a result of this urban development, open or agricultural land next to the landfill may be converted into commercial, industrial or residential land uses (Schmalensee, et. al., 1975; Zeiss, 1988). This causes the character of the rural-agricultural community to eventually shift to a more suburban middle class community (Zeiss, 1988).

Over time, the new land use zoning and development of the host community strongly begins to contrast with the undeveloped landfill area. This existing land area has restricted uses due to its physical behavior and environmental characteristics, hence it may not be capable of meeting the community's needs. Theoretically, landfill biological enhancement may improve these characteristics by reducing the stabilization period, thus resulting in greater use potential for the land.

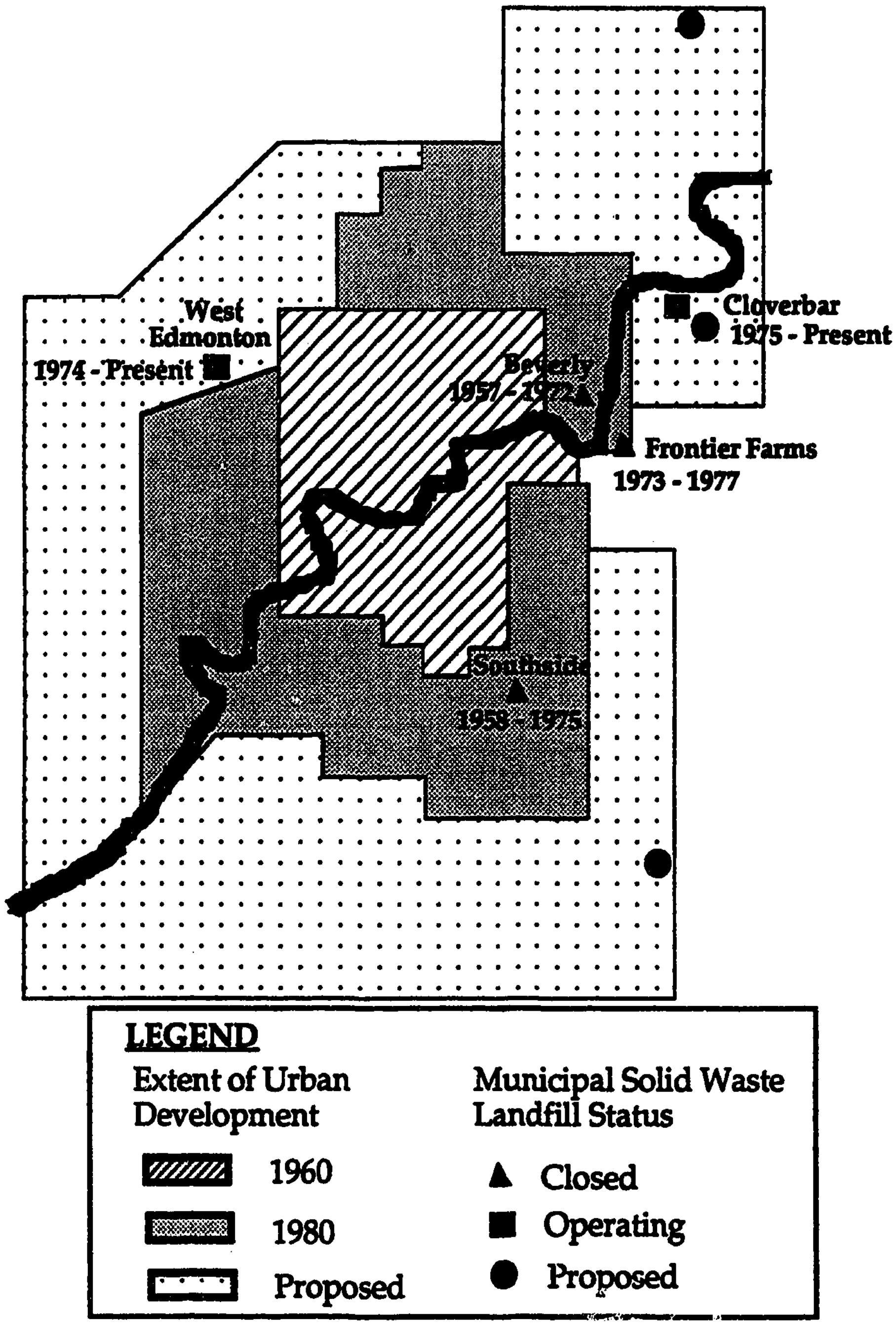

Figure 2.6 - Landfill Siting & Closure Dates Relative to Urban Development

2.4.3 Landfill End Usage

There have been many types of development placed upon refuse landfills, each with varying degrees of success or failure. The most popular use of completed landfill sites has traditionally been for recreational use (NCRR, 1974). This is understandable since this type of development is more likely to tolerate subsequent settlement and gas production. Wehran (1983) suggests that the type of buildings that are most likely to be built on these sites include equestrian centers, indoor swimming and sports facilities, golf course clubhouses, ski lodges, office and conference centers, restaurants, industrial and commercial facilities, research facilities, greenhouses, and residential housing. The following articles present case studies of development of roads, container storage facilities, parking lots, shopping centers, and schools respectively (Sheurs and Khera, 1980; Hinkle, 1990; York, et. al., 1977; Mabry, 1977; Walker and Kurzeme, 1984).

2.4.4 Expanded Use Potential Theory

To more effectively utilize closed landfill facilities and re-integrate them back into the community the physical and environmental stabilization of these sites must be addressed. Post closure ground improvement techniques designed to aid in physical stabilization are quite costly and settlements remain relatively large. This tends to limit the range of potential end uses of the sites to non-structural development. In addition to this, methane production calls for the installation of gas barriers and intercept systems, further increasing complexity and cost. If environmental and physical stabilization can be dealt with in a quicker, more effective fashion, then a greater range of potential end uses is expected.

2.4.5 Section Review

In this section landfill siting criteria and patterns of urban land use change were reviewed. Landfill siting and urban growth patterns in the City of Edmonton were found to be typical of established patterns. This confirmed the hypothesis that landfills are frequently overgrown by their host communities, thus creating the need for their re-development. In turn, this established the connection between landfill end use, settlement, and biodegradation.

2.5 SUMMARY AND HYPOTHESES

In this chapter the basic theories of landfill decomposition, settlement, and landfill/community interaction were reviewed. Landfill decomposition was found to occur mainly by three groups of bacteria: 1. Hydrolytic and fermentative microorganisms; 2. Acetogens; and 3. Methanogens. Also, factors affecting the rate of decomposition were identified in terms of environmental, landfill management, and waste management. Various decomposition models were reviewed and their applicability to landfill conditions evaluated. Following decomposition was a review of the geotechnical properties of landfills. Settlement was identified as the major factor which limits landfill end use, and was observed to occur in three stages: 1. Initial compression; 2. Primary compression; and 3. Secondary compression. A connection was made between secondary settlement and solids loss due to cellulose hydrolysis. Settlement models were then presented to describe the various stages of compression. Finally, landfill siting criteria were compared to urban development patterns. This helped to establish that landfills are frequently encompassed by urban development, but, cannot be readily developed because of large surface settlements and methane gas production.

Based on what has been seen in the literature, several hypotheses can be extracted regarding landfill biodegradation, settlement, and future land use. The evaluation of these and underlying hypotheses will direct the experimental portion of this study. Expected results are: 1. Biological enhancement will increase the rate of secondary compression, thus initially increasing settlement but reducing subsequent settlement; 2. Refuse settlement occurs in three identifiable stages (initial compression, primary compression, and secondary compression); 3. Initial compression occurs immediately upon load application; 4. Primary compression occurs within the first 30 days after load application; 5. Secondary compression is linear with the logarithm of time and continues for long periods; and 6. Biological enhancement will reduce physical and environmental stabilization times, thus increasing landfill end use potential.

3.0 APPROACH

This study uses both a laboratory experiment and a community survey to evaluate the hypotheses generated in chapter 2 and understand the connection between landfill decomposition, settlement, and re-development. The experimental program consists of operating six simulated landfills for an extended period. The cells are uniquely designed to monitor both biodegradation and consolidation throughout the project duration. The land use study is designed to determine development needs of a typical community and assess the social and technical compatibility of landfill sites with those needs.

3.1 EXPERIMENTAL DESIGN

The primary objective of the experimental portion of this study is to test the ability of enhanced biodegradation to expedite landfill settlement and stabilization. The experiment is designed to specifically test the contribution of biological enhancement to refuse settlement. From the decomposition and settlement data, existing models will be evaluated and methods proposed that will accurately describe the processes.

3.1.1 Methodology

Landfill test cells were operated in a way to simulate secure vault landfills and bioreactor landfills. Three replicate test cells were used in order to provide an estimate of the experimental error. Secure vault cells are operated to inhibit biodegradation, while bioreactor cells are operated to encourage biodegradation. By comparison, the contribution of biological enhancement to settlement can be isolated. This will allow existing settlement models to be tested against both the actively decomposing cells and inhibited cells.

By exercising controlled operation in the laboratory setting the decomposition process within the test cells can be more closely regulated. Although this method does not exactly duplicate actual field conditions, additional variation due to changing climatic conditions would make interpretation of the results more difficult and their application to other locations somewhat limited.

3.1.2 Statistical Tests

Hypothesis testing was performed using a one-sided paired t-test to compare means of inhibited test cell data to means of enhanced test cell data. A 95% confidence interval was used for significance testing unless otherwise noted.

3.1.3 Test Cell Design

The test cells were designed with cost effectiveness and simplicity in mind. The cells were unique in that each cell was designed to perform as a lysimeter and a consolidometer. To accomplish this, both environmental and geotechnical parameters had to be accounted for. This often resulted in trade-offs being made in one area for gains in the other. A visual representation of the landfill test cell can be seen in Figure 3.1.

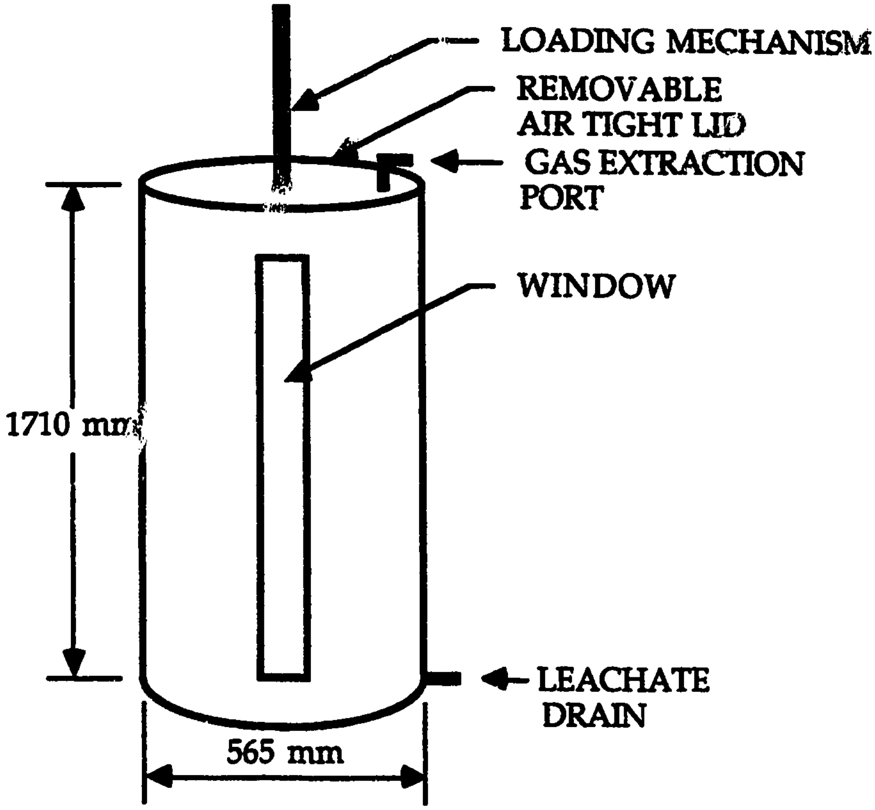

Figure 3.1 - Landfill Test Cell

Cell Diameter

As a general rule of thumb in geotechnical engineering, the diameter of the test cell should be approximately 10 times the largest particle size in order to reduce the influence of a single particle on the behavior of the material as a whole (Robertson, 1992). The container should also allow for even distribution of refuse composition throughout the cross-section, and be large enough to simulate actual field conditions and eliminate the significance of wall effects. Logistical problems with having a larger diameter include difficulties in finding construction material, and difficulties in moving and storing cells. During transportation from the waste transfer station to the lab several doors must be passed through and cells must be manually handled. Increases in diameter required increased mass to achieve the same overburden pressure. As a result, placing the cells into the lab and applying the loading on the cells became more difficult.

A diameter of 0.565 m and an overburden mass of 200 kg was finally chosen. This corresponded to an overburden pressure of approximately 10 kN/m^2. This is roughly equivalent to having a 2 to 3 m layer of additional refuse overlying each test cell. The diameter selected was the largest that was practically achievable given laboratory conditions, the availability of materials, and the amount of overburden pressure required for this cross-sectional area.

Cell Height

The height of the refuse has an influence on the incremental settlement that occurs within the refuse layer. Obviously, the larger the height of refuse, the larger the settlement that occurs. It is important that a significant amount of settlement occurs to ensure that any sources of error are made insignificant by comparison. The selected height should also be that indicative of a typical lift of garbage in an actual landfill cell. Design constraints were door and laboratory heights, and test cell maneuverability.

Unfortunately, these constraints set the maximum possible height of the test cells to be 1.71 m. This was achieved by welding two specially manufactured steel oil drums together. This height, although less than ideal, is fairly representative of typical landfilling procedures and incremental settlements should be readily distinguishable.

Gas Tight Seal

Given that the decomposition process in landfills is mainly anaerobic, and that a carbon balance was to be assessed, the test cells had to be sealed from the atmosphere. This was accomplished by using silicone caulking on joints and greased rubber seals around exposed moving parts. An illustration of the cell carbon balance is shown in Figure 3.2.

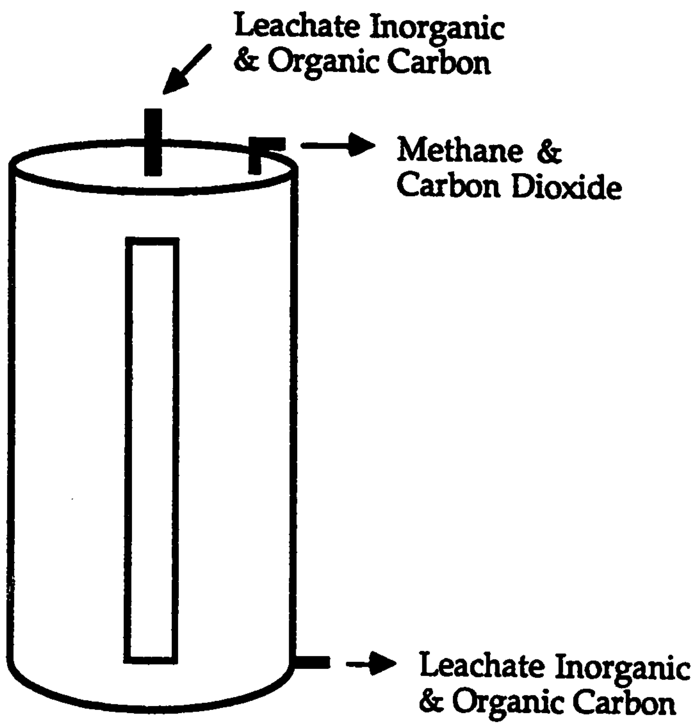

Figure 3.2 - Cell Carbon Balance

<u>Gas Collection System</u>

As decomposition processes produce large amounts of methane and carbon dioxide gas, collection for analysis was necessary. Tedlar gas sample bags were connected to sample ports on the test cells, when bags became full they were replaced with empty bags. Sample bags were then analyzed for gas quantity and composition.

<u>Leachate Collection and Recirculation System</u>

The collection of leachate was facilitated by a sloped concrete base in the bottom of the test cells. The ramp drained to a valve fitting that is threaded into the side of the cell. A thin layer of gravel was used to prevent the spout from becoming clogged.

The leachate recirculation system is complicated by the presence of the loading mechanism and the requirement of a gas tight seal. Leachate is recirculated through a pipe that protrudes from the top of the test cell. The pipe acts both as a guide for the weight assembly and a pathway for leachate addition. The pipe is connected to the top of a perforated sprinkler plate that allows the leachate to pond and then distribute evenly over the refuse surface.

Load Mechanism and Overburden Pressure

The design principal of the load mechanism had simplicity as its priority, the fewer moving parts the better. Also, the mechanism had to be able to handle large surface settlements and operate in conditions of low overhead clearance. For these reasons, an internally contained dead load was selected. However, the use of freely floating weights raised concerns that the load may shift, resulting in an uneven load distribution. The final design was a dead load system that was slightly smaller in diameter than the test cell and was held in place by a vertical guide assembly at the top of the test cell.

The overburden pressure was chosen to be representative of that which occurs in the middle layer of typical sanitary landfills. Additional constraints were related to manageability of the weight, total loading on the lab floor, costs of material and strength of test cell walls. The selected mass of the dead load was 192 kg, corresponding to an overburden pressure of 8.2 kPa, roughly equivalent to 1.5 m of compacted refuse (600 kg/m^3).

Settlement Gauge

There were several significant constraints in the test cell design regarding the geotechnical requirements of oedeometric test equipment. The first and foremost was the ability to monitor settlement of the refuse material over time. This measurement had to be representative of the average surface settlement in the test cell and should be relatively easy to read and record. The method also had to account for the test being of long duration, occurring in a sealed container.

<u>Inner Cell Surface</u>

Due to the long test duration, the inner surface of the test cell had to be resistant to both biological and chemical action. Since the cells were constructed of 20 gauge steel, a corrosion resistant coating was required. For manufacturer convenience, a Vorax spray used in the lining of aviation fuel drums was selected. To stop the loading assembly weights from catching on the test cell wall and to minimize frictional wall effects, three strips of high density polyethylene were used as guide rails.

<u>Internal Observation Window</u>

It was deemed important to be able to observe the settlement and decomposition process as it occurs over time. For this reason a lexan window was installed along the entire height of the test cell. Periodic observations were made regarding the changing characteristics of the refuse material. This also allowed for continual visual assurance that the test cell was functioning properly.

3.2 EXPERIMENTAL METHODS

Experimental methods required in the study included scheduled test cell monitoring, controlled operation and test cell conditions, and preliminary refuse characterization.

3.2.1 Monitoring

The height of refuse was monitored over time in all reactors. Readings were taken very frequently at first when large changes occurred and less frequently as the process slowed. Settlement was calculated from corresponding changes in refuse height.

Leachate analysis was performed weekly during the leachate recirculation process. Analysis included volume determination, pH, total organic carbon (TOC), and biochemical oxygen demand. Determinations were performed in accordance to Standard Methods (APHA, et. al., 1989).

Gas production and composition was monitored periodically as the Tedlar gas sample bags became full. Gas quantities were determined using a GCA/Precision Scientific Wet Test Meter. Composition analysis was performed with an ADC LFG10 landfill gas analyzer (The Analytical Development Company Limited). The LFG10 uses an infrared detector to determine concentrations of methane and carbon dioxide in the gas. Supplementary analyses for oxygen and carbon dioxide were performed using an Orsat gas absorption apparatus.

3.2.2 Operation

Test cells 1 to 3 were operated under enhanced conditions while cells 4 to 6 were operated under inhibited conditions. Inhibited test cells received no additional moisture and therefore produced no leachate that could be recycled. Leachate was recycled in the enhanced test cells on a weekly basis for the first 79 days of the study. During this time, volumes in excess of 4 litres were discarded and volumes less than 4 litres were made up with distilled water. Since no methane was produced from the test cells during this period, concerns were raised regarding potential leachate toxicity. For this reason, volumes of recycled leachate were reduced to 1 litre and 3 litres of distilled water was added. It was thought that this would help dilute and wash out any toxic materials present in the reactors. On day 107 methane production commenced in reactor 3. To avoid disruption of the methanogenic bacteria, leachate recirculation and water addition was discontinued for the remainder of the study. During this period methane concentrations steadily increased to a value of 25% at day 220. Leachate recirculation allowed for the simultaneous addition of buffer solution and microbial seed.

Since methanogenic bacteria are very sensitive to extremes in pH, buffer solution was added to maintain it close to neutrality (7). Buffer was added on a weekly basis to neutralize the leachate that was to be recycled. For the first 65 days Na_2CO_3 (200 g/L) was added, then for the next 14 days K_2CO_3 (200 g/L) was added. The type of buffer was changed due to concerns of potentially reaching cation concentrations that could be toxic to the anaerobic bacteria (Barlaz, 1988).

Microbial seed in the form of anaerobically digested sewage sludge was added to the enhanced reactors. Two hundred millilitres of sludge was added to each reactor during weekly leachate recirculation from day 51 to day 100.

3.2.3 Conditions

Inhibited cells (4 to 6) were kept at a constant temperature of 4 ^{o}C to minimize any biological activity and still allow pore water movement in the refuse. Enhanced cells (1 to 3) were maintained at a temperature of 25 ^{o}C to encourage biological activity. This temperature, although less than the optimum temperature for methanogenic bacteria, was seen as more representative of actual landfills. Due to existing laboratory conditions temperatures higher than 25 ^{o}C were not achievable. In addition to this, actual landfill operating temperatures cannot be practically sustained at temperatures higher than 25 ^{o}C in most Canadian climates.

Inhibited cells were maintained at their original moisture content, and no additional water was added throughout the experiment. Enhanced cells were brought to field capacity by the sequential addition of distilled water until leachate was produced. Water was added every 30 minutes in 5 litre amounts and distributed evenly over the compacted refuse surface. This procedure was continued over a 5 hour period, after which tests cells were left overnight.

Refuse in all tests cells was compacted using a manual ramming device designed specifically for that purpose. Achieved refuse densities ranged from 204 kg/m^3 to 276 kg/m^3.

3.2.4 Preliminary Tests

A series of preliminary tests were performed to determine field capacity, channelling and moisture distribution characteristics of the refuse in the test cells. These tests included filling two of the test cells with refuse and performing infiltration tests on them. Distilled water with a dye additive was poured over the waste surface in sequential 5 litre applications. This was continued until the production of leachate in the bottom of the cell was observed. Then the refuse was removed in layers, noting patterns in moisture distribution and travel. These tests helped to determine the appropriate infiltration rate and establish a rationale for predicting moisture distribution patterns.

3.2.5 On-Site Filling Operation

All test cells were filled on site at the City of Edmonton Strathcona Transfer Station. Filling was performed from the back of a randomly chosen semi-trailer with one layer of refuse in it (one pass with the conveyor). Containers were filled using complete cross-sections of the trailer with intermittent compaction. Taking entire cross-sections was done to avoid influences due to ballistic separation of the waste stream as it falls from the conveyor in a perpendicular path to the trailer. Two random samples of refuse were also obtained at this time for the determination of composition, particle size distribution, moisture content, and volatile solids content.

3.3 COMMUNITY SURVEY

The community survey was designed to determine land development needs of a typical of a host community and evaluate residents' opinons on landfill end use. This information could then be used to assess the land use compatibility between completed landfills and typical community development. This will determine if the available land use options for closed landfills can satisfy the land use needs of the host community. Two null hypotheses were tested: 1. Residents do not have the need for additional development; and 2. Residents do not want landfills used for development other than recreation.

Two neighborhoods in the City of Edmonton were selected; the old Beverly landfill site, and the old Southside landfill site. The Beverly site is in the northern part of Edmonton and is now Rundle Park and golf course. The Southside location is in south Edmonton and is now the Millwoods golf course. All single family households along the periphery of each golf course were asked to participate in the survey. Interested residents were then sent a copy of the land development questionnaire to complete. These communities are of particular importance because they have first hand experience with closed landfills that have been re-integrated into the community. A copy of the community survey can be found in Appendix D of this document.

4.0 RESULTS AND ANALYSIS

4.1 SUBSIDIARY TESTING

Tests were performed at the start of this experiment to determine refuse characteristics and moisture movement patterns in the test cells.

4.1.1 Refuse Characterization

During the November 1991 filling operation of the test cells, two random samples of refuse were obtained for classification. Sample characterization included waste composition, particle size, moisture content, and volatile solids content.

Waste composition data can be seen in Table 4.1. For the first sample the characteristic particle size was 3.5 cm with a slope of 1.30, using the Rosin-Rammler method. Sample 2 had a characteristic particle size of 4.9 cm and a slope of 0.65. The particle size distribution for both samples can be observed in Figure 4.1. Moisture content of the raw waste was 53.6 % by dry weight basis. Volatile solids content for the refuse was 686.4 mg/g dry refuse. Where appropriate, Standard Methods (APHA, et. al., 1989) was consulted for analytical procedures.

4.1.2 Preliminary Tests

A series of preliminary tests were performed to determine moisture distribution and movement patterns within the landfill test cells. Visual inspection of dye tracer patterns and moisture distribution identified that there was fairly even distribution throughout the cell. The effect of channelling was not observed to be a significant factor in the distribution of test cell moisture.

Table 4.1 - Sampled Refuse Composition

Refuse Component	Refuse Composition (percent of wet weight) Sample 1 (November 1991)	Sample 2 (November 1991)
Food Waste	21.6	19.6
Garden Waste	0	0
Paper	42.1	43
Textiles	0.9	9.9
Wood	0.1	0.1
Plastic	8.1	9.1
Glass	1.9	0.6
Metal	4.4	2.6
Diapers	1.5	0
Fines	19.4	15.1

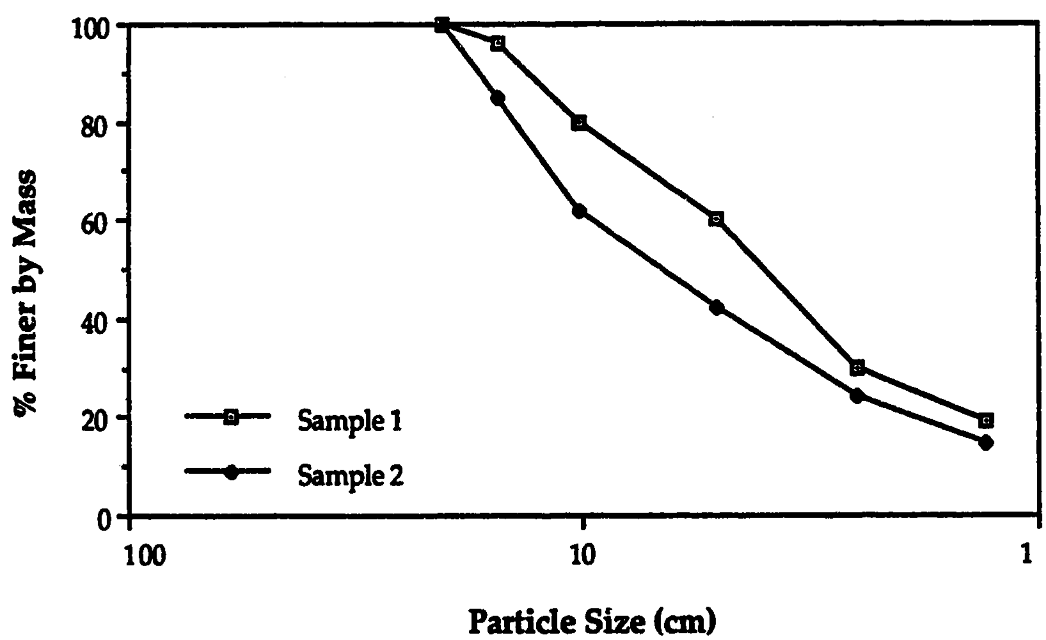

Figure 4.1 - Sampled Refuse Particle Size Distribution

4.2 DECOMPOSITION

The purpose of monitoring test cell decomposition data was to: 1. examine the mechanisms of decomposition occurring in the test cells and compare with expected behavior; 2. determine the magnitude and rate of mass loss due to biodegradation; 3. model this mass loss over time; and 4. test the hypothesis that biological enhancement reduces environmental stabilization time.

4.2.1 Mass Balances

Judging from methane production and carbon balance data, decomposition has proceeded at a very slow rate. In the enhanced bioreactors, two of the cells have not produced any landfill gas while the third cell is producing methane at steadily increasing rates. As expected, there has been no leachate or gas production in the inhibited test cells. Levels of organic carbon and pH in the leachate indicate that hydrolysis and fermentation are occurring in all reactors, however methanogenic bacteria have only been established in reactor 3. Mass balance data and cumulative carbon loss over time are shown in Table 4.2 and Figure 4.2, respectively.

Table 4.2 - Reactor Carbon Balance

Landfill Component	Mass of Carbon Degraded (g)		
	Cell 1	Cell 2	Cell 3
Leachate TOC reduction	600.5	617.3	457.1
Methane production	0.0	0.0	35.2
Carbon dioxide production	0.0	0.0	187.5
TOTAL CARBON LOST	600.5	617.3	679.8

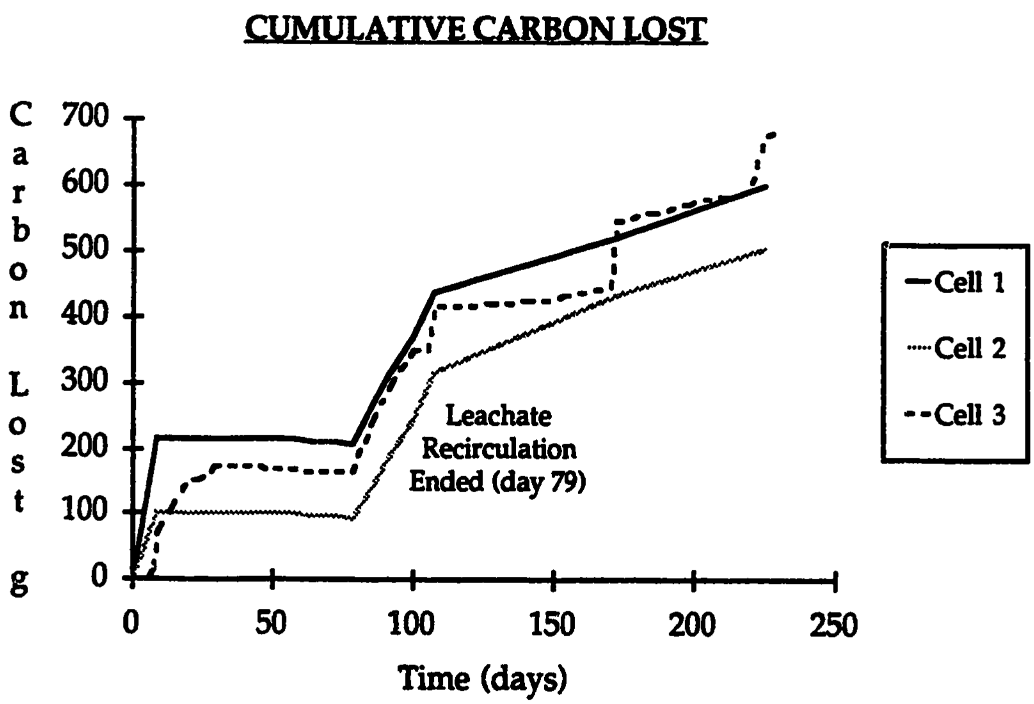

Figure 4.2 - Cumulative Carbon Lost

As explained in chapter 3, leachate was recycled for the first 79 days, after which a portion of leachate was discarded and distilled water was added. Moisture addition was discontinued on day 107 with quantities of leachate being discarded on days 107, 172 and 225. This irregular recycle and monitoring pattern resulted in a carbon loss curve that looks somewhat like a staircase (see Figure 4.2). Periods of significant carbon loss are associated with discarding quantities of leachate that are produced. Conversely, periods of little change are associated with leachate recycle conditions (day 9 to 79) and periods of only gas production (day 107 to 172 and day 172 to 225; cell 3 only). Mass balance data can be found in Appendix A.

4.2.2 Leachate Characteristics

Initial values of total organic carbon (TOC) in the three reactors ranged from 20 000 to 30 000 mg/L. The ratio of BOD_5 to TOC was found to be 1.84. This organic content is quite high when compared to literature values. One possibility is that the composition of the refuse used in this study is slightly different than that in other studies. However, a more likely explanation is that less channelling and better distribution of moisture occurred in the test cells, thus resulting in a leachate that has contacted more waste. This moisture distribution pattern was observed in a series of preliminary tests performed in this study.

As expected, leachate recycle resulted in a decrease in organic content indicative of biological decomposition and self treatment. The effects of leachate recycle on total organic carbon content can be seen in Figure 4.3.

Initial values for pH were as low as 4, however, when buffered to pH 7 and re-introduced the pH stabilized around 6. These values are below suggested optimum values for methanogenic bacteria and may have been a factor in the inhibition of methane formation in reactors 1 and 2. Leachate pH trends are illustrated in Figure 4.4.

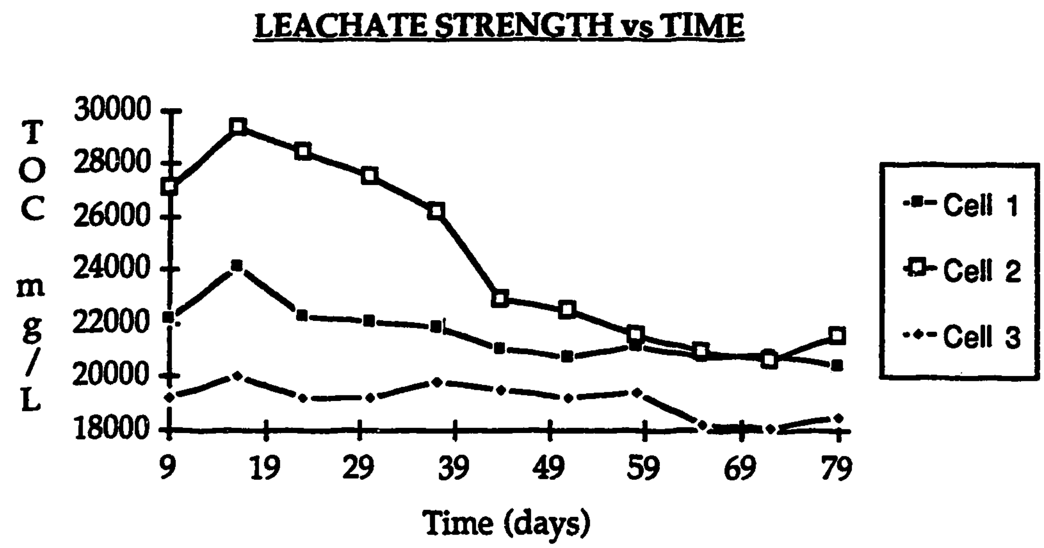

Figure 4.3 - Effects of Leachate Recycle

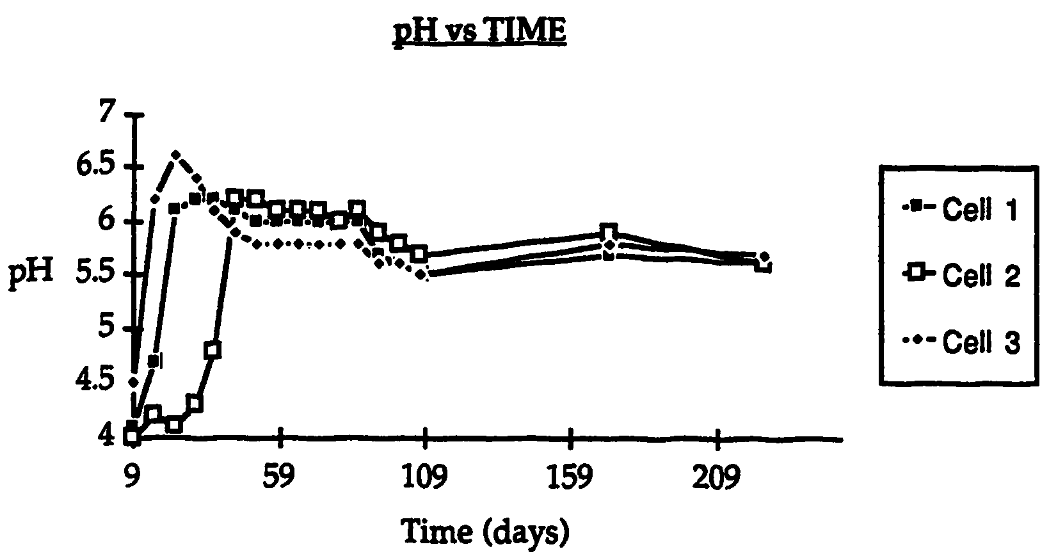

Figure 4.4 - pH Variation with Time

4.2.3 Gas Production

Gas production was observed only in reactor 3, occurring in two separate phases: an initial aerobic phase and a subsequent anaerobic phase. When gas production started, oxygen was consumed and large amounts of carbon dioxide were produced. This was indicative of the occurrence of aerobic decomposition. After one month, aerobic activity ceased and was followed by a lag period of approximately two months before gas production resumed. Immediately with the production of gas came measurable percentages of methane and higher proportions of carbon dioxide, thus indicating anaerobic bacterial growth. To date, concentrations of both methane and carbon dioxide have been steadily increasing and are associated with an increase of methanogenic bacteria (see Figure 4.5). Also demonstrating an increasing trend are methane and total gas production rates (see Figures 4.6 to 4.8).

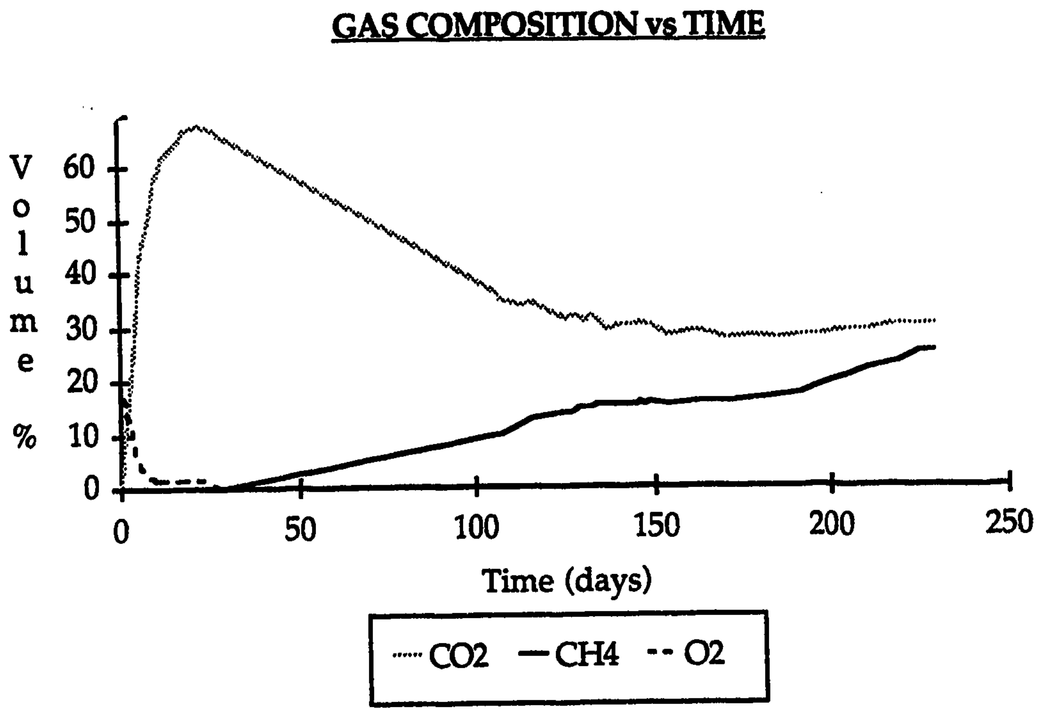

Figure 4.5 - Gas Composition (Cell 3)

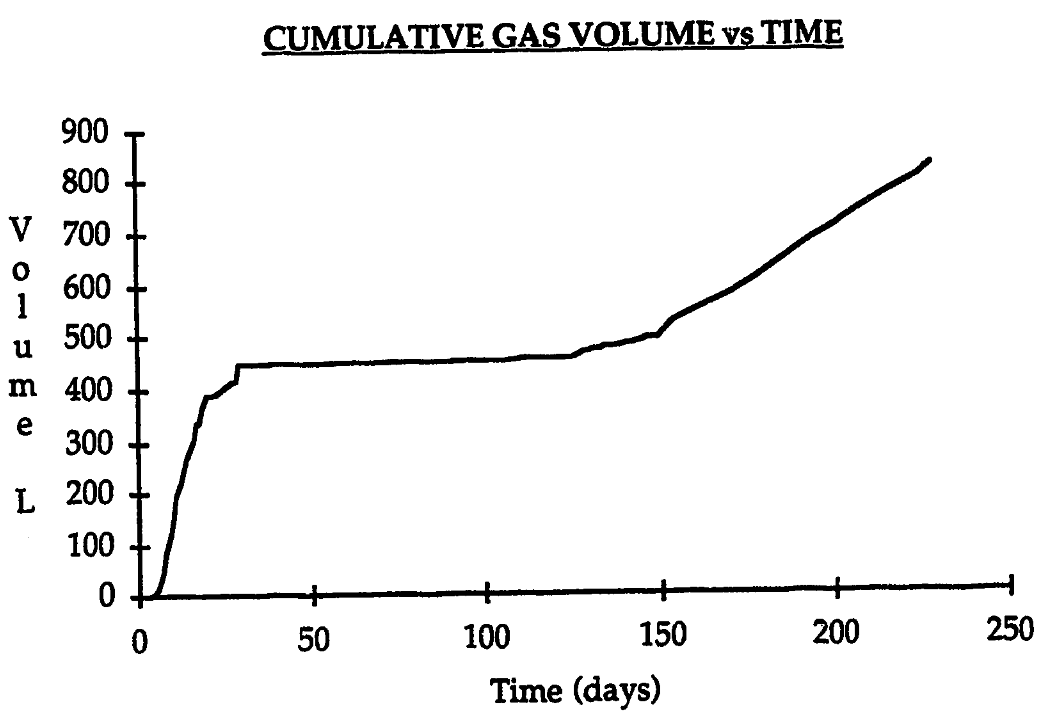

Figure 4.6 - Cumulative Gas Produced (Cell 3)

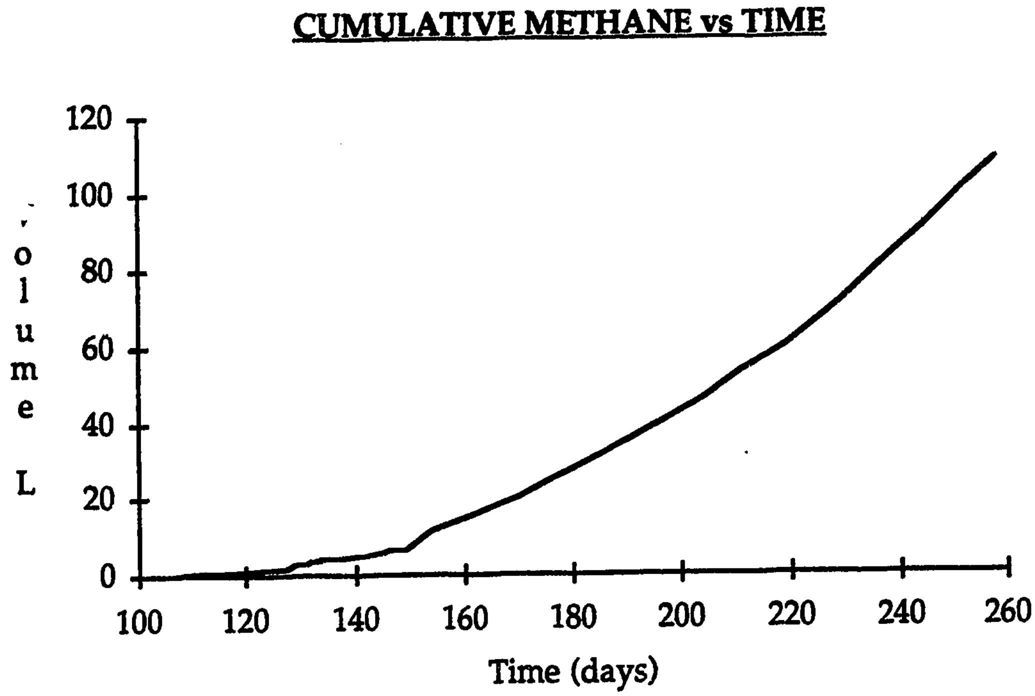

Figure 4.7 - Cumulative Methane Produced (Cell 3)

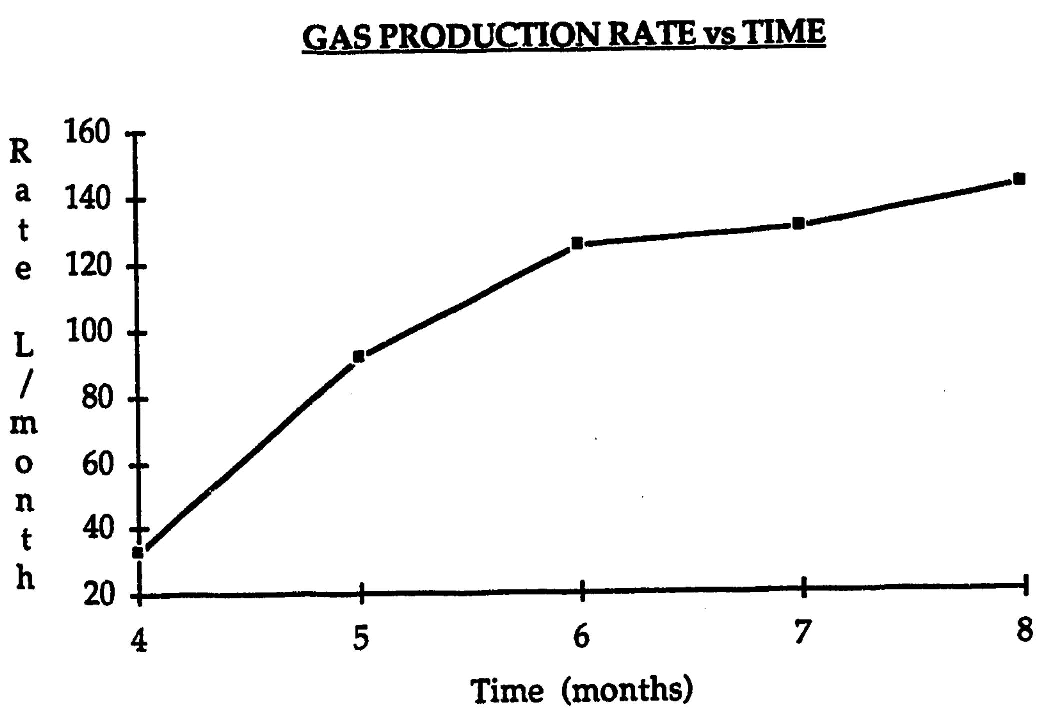

Figure 4.8 - Reactor Gas Production Rate (Cell 3)

Methane concentration and gas generation rate in reactor 3 was quite low, thus indicating that the decomposition process was in its early stages. By the categories described in Chapter 2, reactor 3 was in the "anaerobic methanogenic accelerated unsteady" phase of refuse decomposition, while reactors 1 and 2 were in the "anaerobic non-methanogenic" phase. Methanogenic bacteria were inhibited in reactors 1 and 2, therefore microbial development was most likely limited to hydrolytic bacteria. Refuse decomposition was expected to occur at a faster rate than what was observed. Biological inhibition may likely have resulted from oxygen intrusion, hydrogen accumulation, or low pH.

4.2.4 Substrate Quantities

If the decomposition process is to be modelled, knowledge of the amount of substrate present is essential. Values for organic carbon are derived by taking the Volatile Solids content and dividing by a factor of 1.8 (Golueke, 1972). This accounts for losses of inorganic and other material that occurs at high temperatures (550 ^oC). Values of the amount of substrate present are illustrated in Table 4.3.

Table 4.3 - Reactor Substrate Quantities

Substrate Indicator	Mass (kg)		
	Cell 1	Cell 2	Cell 3
Refuse Solids	67.3	68.6	62.2
Total Volatile Solids (TVS)	46.2	47.1	42.7
Organic Carbon, Co (initial)	*25.7	*26.2	*23.7
Organic Carbon, Cf (degradation to date)	25.1	25.7	23.0

* TVS adjusted by a factor of 1.8 (Golueke, 1972)

4.2.5 Decomposition Modelling

Since cellulose hydrolysis is the decomposition step affecting settlement, and hydrolysis is commonly modelled by first order kinetics, back calculations were performed to determine first order rate constants. Carbon mass balance data from reactors one, two, and three was used. Table 4.4 displays the model parameters and the percent of refuse degraded.

Table 4.4 - First Order Rate Constants (Mass Balance)

Model Parameter	Cell 1	Cell 2	Cell 3
Initial Substrate Mass, Co (kg)	25.7	26.2	23.7
Final Substrate Mass, Cf (kg)	25.1	25.7	23.0
Time, t (days)	225	225	229
Percent of Total Refuse Degraded	0.9	0.7	1.1
First Order Rate Constant, k (1/yr)	0.0383	0.0312	0.0478

Experimental mass loss data for reactor 3 was compared to first order model predictions. Although the shape of the experimental data is irregular, it seems to follow a general trend of first order decay. This would tend to confirm literature findings that cellulose hydrolysis can be represented by first order kinetics. It is important to note that first order decomposition coefficients are quite low, therefore, the characteristic decreasing rate curve is not visible over this small degree of change and appears linear. Results are presented in Figure 4.9.

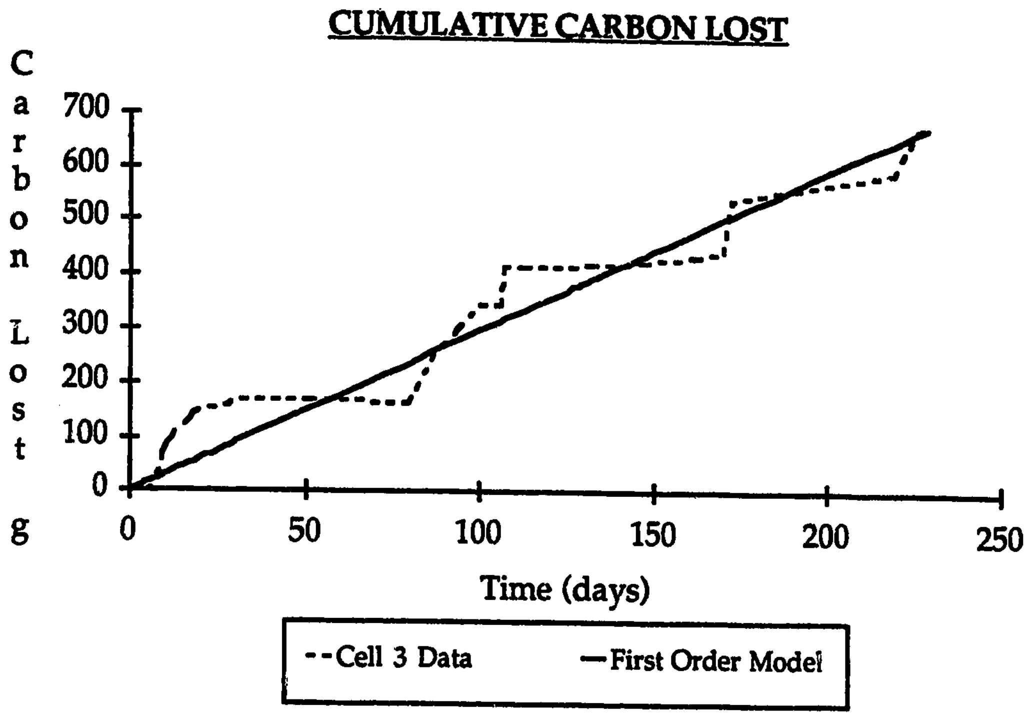

Figure 4.9 - Experimental Results Compared to First Order Model (Cell 3)

These values are based on the actual mass of carbon entering and leaving the reactor and represent the measured decomposition rate. Since these values are low, it is worthwhile to determine a potential maximum rate. To arrive at an estimate the recirculation of leachate was ignored as an input of carbon for mass balance calculations. Calculations indicated that minimal carbon loss occurred during periods of leachate recycle and high carbon losses during periods of distilled water addition and leachate discarding. This is because quantities of leachate generated by distilled water addition have similar organic concentrations of recirculated leachate but are discarded, thus resulting in a significant mass lost. During test cell operation it was observed that when either distilled water or leachate was added to the reactors, the total organic content of the subsequent leachate produced was approximately the same. Leckie et. al. (1979) also observed this: during periods of high infiltration leachate organic strength remained fairly constant. This suggests that reaction end products of hydrolysis and fermentation may be building up within the refuse matrix. Table 4.5 shows predicted maximum rate constants for hydrolysis.

Table 4.5 - First Order Rate Constants (Estimated Maximum)

Model Parameter	Cell 1	Cell 2	Cell 3
Initial Substrate Mass, Co (kg)	25.7	26.2	23.7
Final Substrate Mass, Cf (kg)	24.3	24.9	22.3
Time, t (days)	225	225	229
Percent of Total Refuse Degraded	2.1	1.9	2.3
First Order Rate Constant, k (1/yr)	0.0909	0.0826	0.0970

Using the range of values for the first order rate constant plots of substrate concentration vs time for the three bioreactors were constructed. Figures 4.10 to 4.12 show reactor substrate mass over time for each reactor.

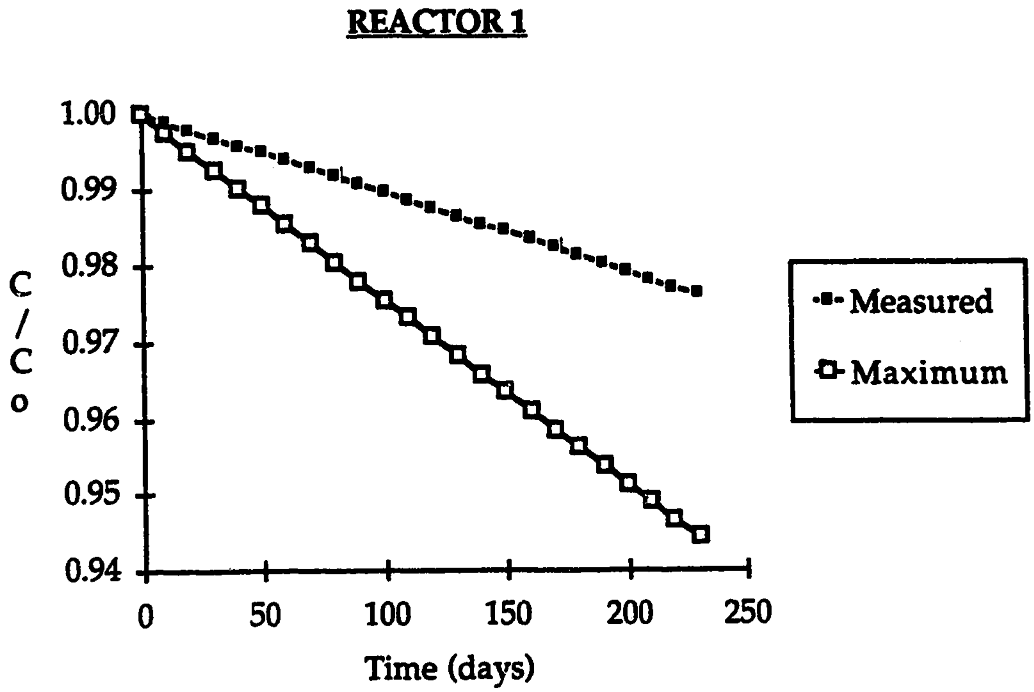

Figure 4.10 - C/C_0 vs Time (Reactor 1)

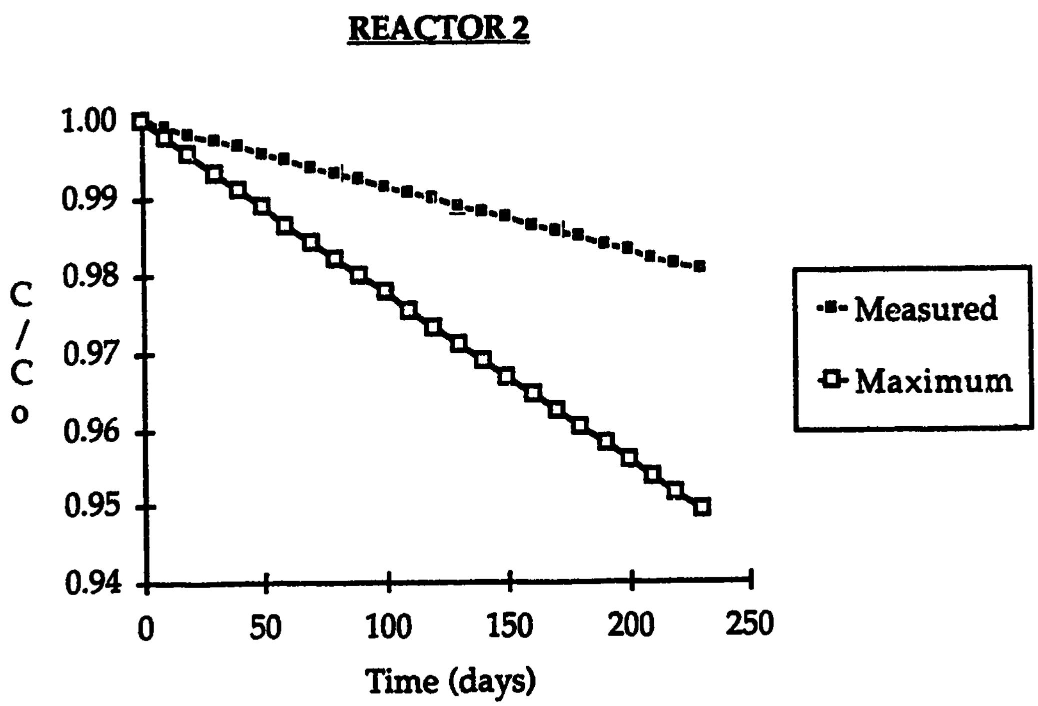

Figure 4.11 - C/C_0 vs Time (Reactor 2)

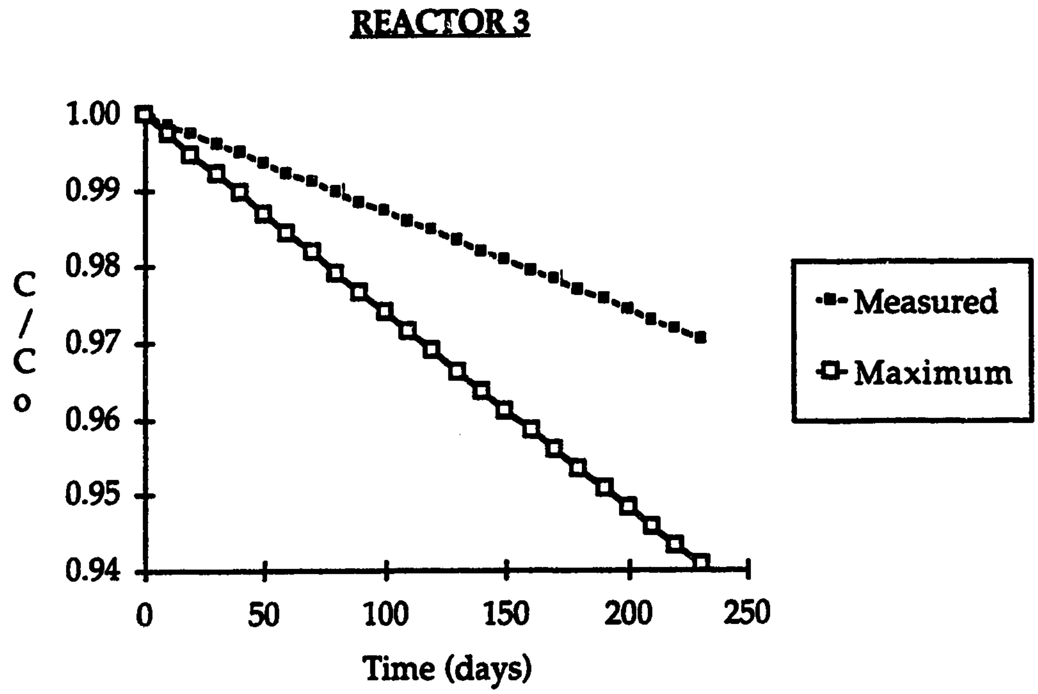

Figure 4.12 - C/C_0 vs Time (Reactor 3)

Because of the small magnitude of the rate constants, the first order decomposition curves appear linear. The average measured value for the rate constant was 0.0391 yrs^{-1} while the estimated maximum was 0.0902 yrs^{-1}. These values are at the bottom of the range of typical values given in Table 2.5, and are indicative of slowly to moderately degradable carbon sources. Recent measurements on the New York Fresh Kills landfill by Sulflita, et. al. (1992) indicate that the rate constant for cellulose biotransformation is 0.071 ± 0.016 yrs^{-1}. This indicates that decomposition is proceeding quite slowly in the test cells and is similar to rates in existing landfills. This is also confirmed by the slow rate of methane production in reactor 3. Judging from methane quantities produced and estimated values for methane potential, the test cells are in the introductory stages of biodegradation and will continue decomposing for quite some time. Barlaz, et. al. (1989) suggests that the methane yield for municipal refuse is between 90 and 170 L CH_4/kg dry refuse. Using the average of 130 litres CH_4/kg for the mass of refuse in test cell 3, a total of 8082 litres of methane should be produced. To date only 71.4 litres of methane has been produced, approximately 1% of the total methane potential.

4.3 SETTLEMENT

The purpose of analyzing test cell settlement data is to: 1. Identify settlement mechanisms and changes over time; 2. Determine the effect of biodegradation on settlement; 3. Model landfill settlement over time; and 4. Test the hypothesis that biological enhancement reduces physical stabilization time. All graphs in this section use the same line convention for each test cell. Cells one, two, three are biologically enhanced (active) while cells four, five, and six are biologically inhibited (inert). Enhanced test cells are designed to simulate bioreactor landfills while inhibited test cells simulate secure vault landfills.

4.3.1 Refuse Height

The reduction in refuse height over time resembled the classic time settlement curve described in Chapter 2. This indicated that refuse settlement in the test cells occurred by the same mechanisms observed in full-size landfills. The plot exemplified the three stages of settlement: initial compression, primary compression, and secondary compression. Figure 4.13 shows the settlement of refuse over time for all six landfill cells. Numerical settlement data for all reactors can be found in Appendix B.

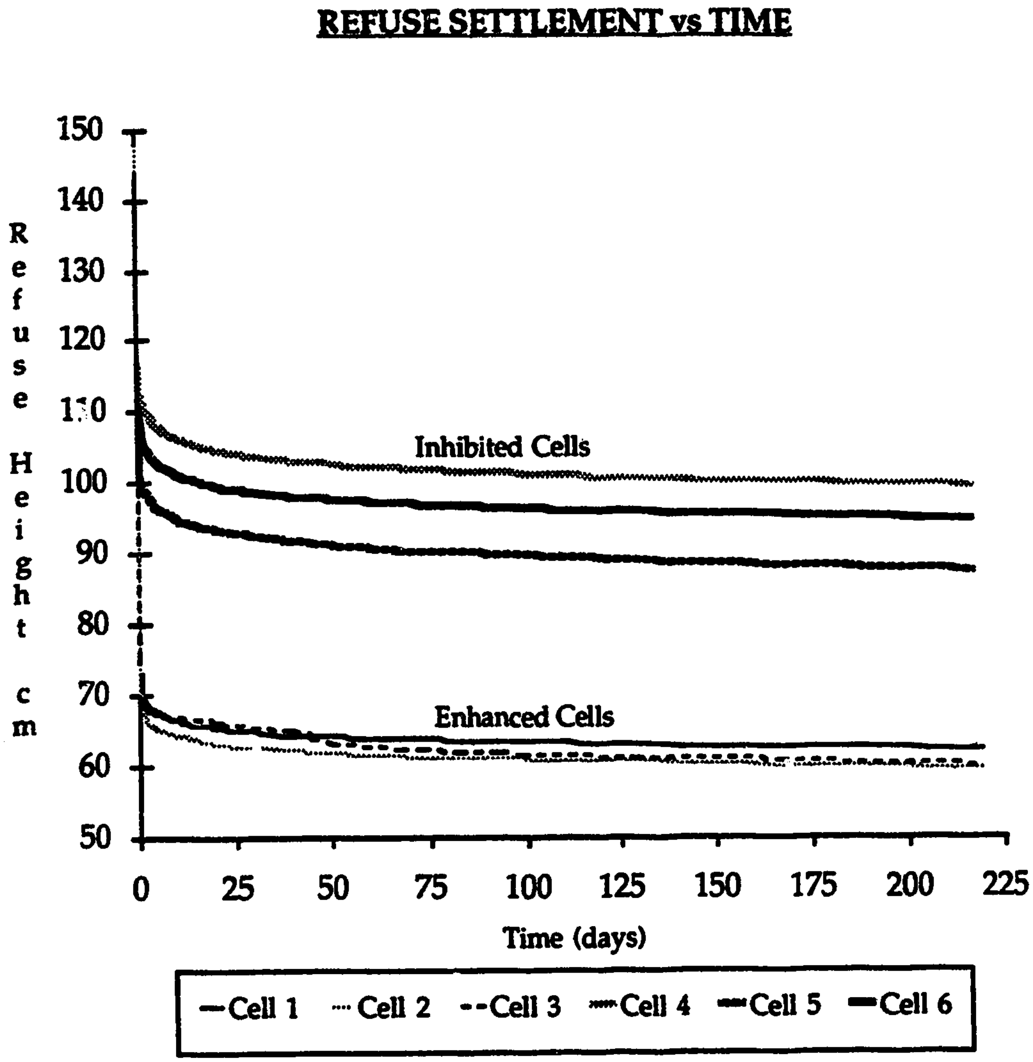

Figure 4.13 -Refuse Height vs Time

Immediately after load application there was an initial settlement of approximately 20% of the initial refuse height. This was followed by a primary stage of settlement w' ı occurred at a rapidly decreasing rate for a period of approximately 30 days and resulted in a further height reduction of 15% (based on the height after initial settlement). This was followed by a secondary stage of long duration settlement which occurred at a much slower rate and resulted in an additional compression of 3% over the next 220 days.

Differences between enhanced and inhibited test cell settlement occurred because enhanced cells were brought to field capacity by the addition of water prior to the load application. This resulted in an additional settlement of 30%, thus causing enhanced cells to start with a lower initial refuse height.

4.3.2 Strain

Strain is defined as the change in refuse height over the initial height ($\Delta H/H_0$) which is equivalent to the settlement divided by the initial height. Since strain is an incremental measure, curve differences due to varying initial heights are eliminated. However, since it differs from settlement only by a constant, it still exhibits the same trends. Figure 4.14 indicates that enhanced test cells (1 to 3) experience larger values of strain and, hence, greater settlement than inhibited cells (4 to 6).

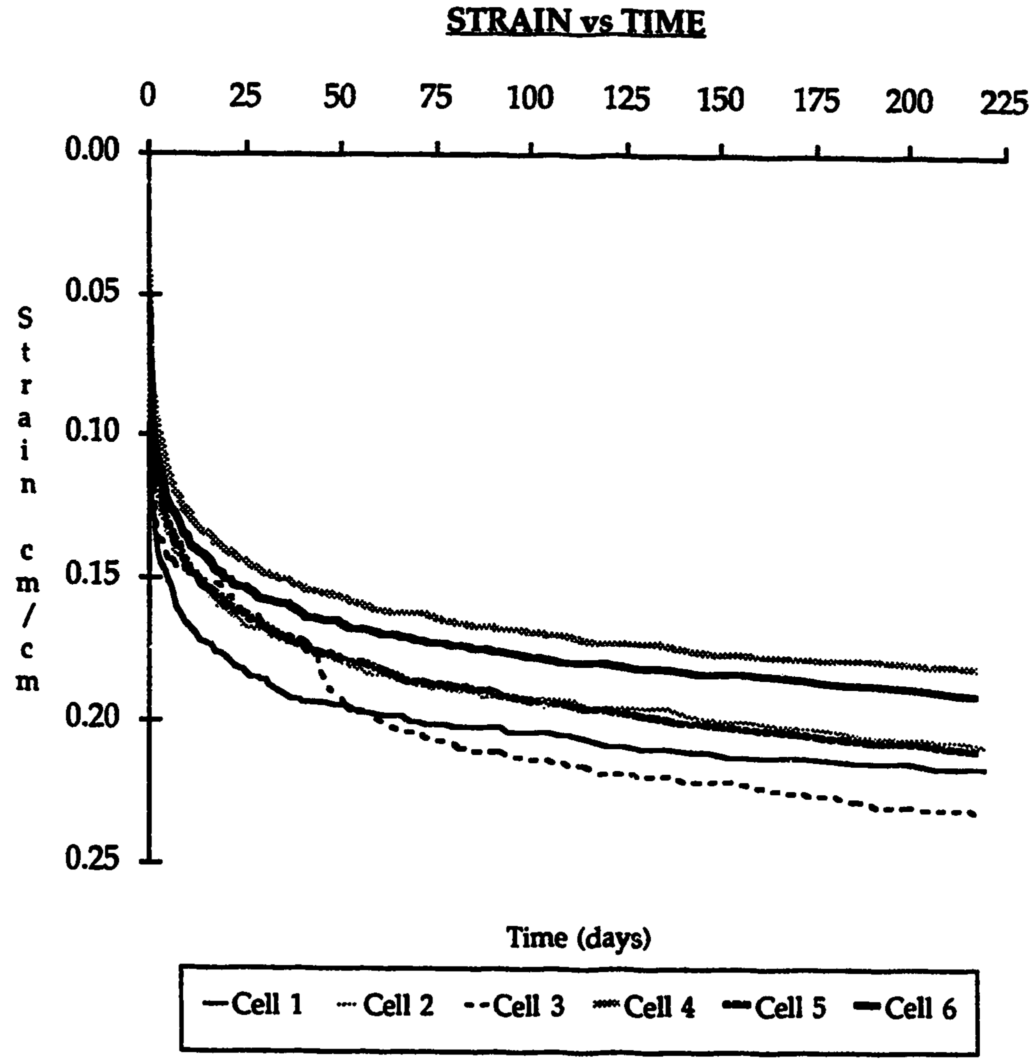

Figure 4.14 - Refuse Strain vs Time

4.3.3 Void Ratio

Void ratio is another method of representing compression in a refuse landfill. It is defined as the volume of voids divided by the volume of solids (V_V/V_S). Void ratio (e) is directly related to settlement and can be calculated by the equation, $S = H_0 \Delta e / (1+e_0)$. The relationship of void ratio and time can be seen in Figure 4.15.

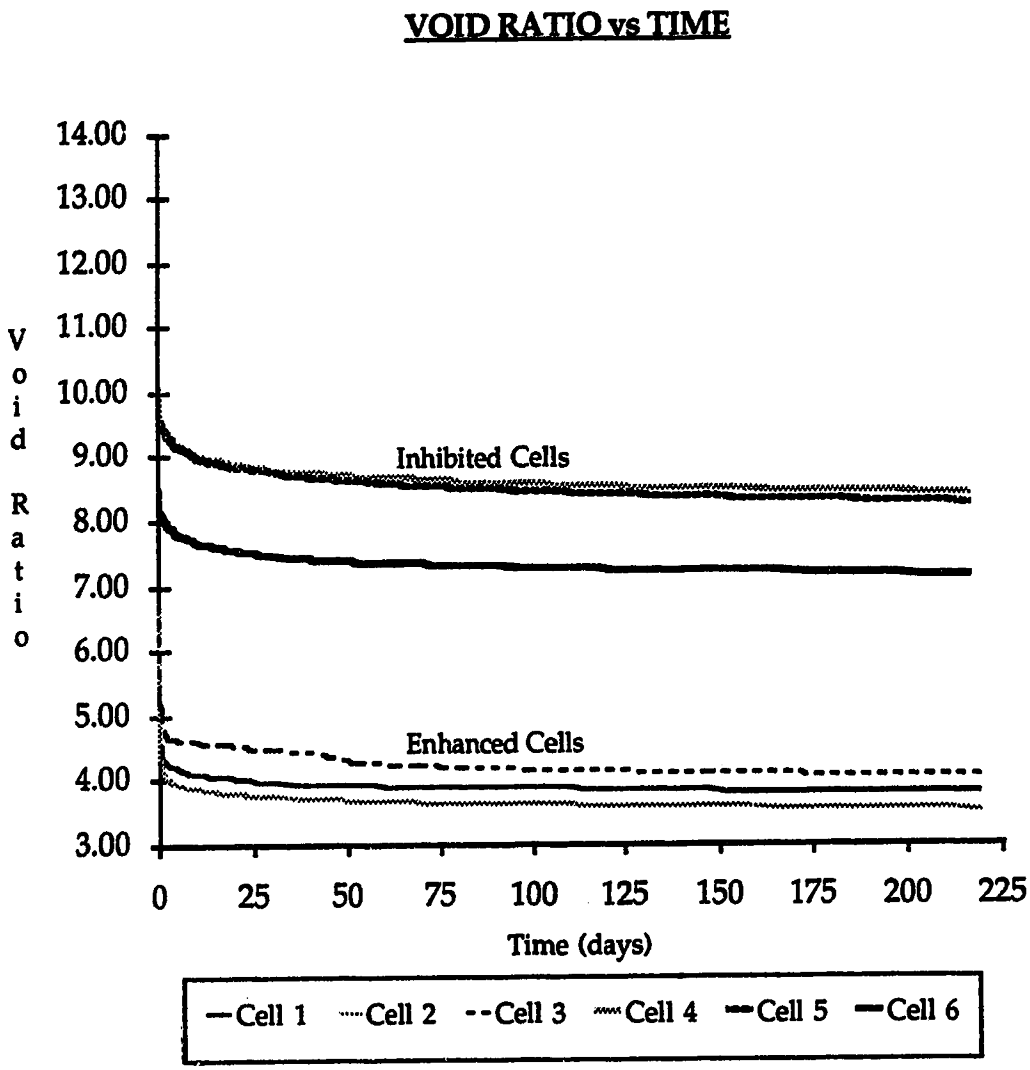

Figure 4.15 - Refuse Void Ratio vs Time

Since void ratio is simply another way to represent settlement the shape of the void ratio-time curve is similar to the settlement-time curve. Enhanced test cells (1 to 3) have a lower initial void ratio than inhibited test cells (4 to 6). This is attributed to the compacting effect water had on the refuse. Initial values for the void ratio were calculated using an assumed specific gravity of 2 for average refuse solids, this is consistent with Moore and Pedler (1977) and within the range of 1.7 to 2.5 suggested by Sowers (1973). A summary of test cell parameters is provided in Table 4.6.

Table 4.6 - Test Cell and Refuse Characteristics

Characteristic	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Initial Refuse Height, Ho (m)	1.435	1.473	1.461	1.473	1.423	1.435
Field Capacity Refuse Height, Ho	1.003	1.016	1.016	-	-	-
Immediate Compressed Height, Hi	0.796	0.753	0.783	1.216	1.109	1.17
Primary Compressed Height, Hp	0.647	0.625	0.634	1.036	0.925	0.986
End of Study Refuse Height, Hf	0.624	0.596	0.601	0.995	0.875	0.946
Cell Diameter (m)	0.5751	0.5751	0.5751	0.5751	0.5751	0.5751
Average Applied Stress (kN/m2)	10	10	10	10	10	10
Total Mass of Refuse (kg)	103.3	105.4	95.5	84.7	75.5	93.1
Assumed Solids Density (kg/m3)	2000	2000	2000	2000	2000	2000
Initial Moisture Content (% dry wt.)	53.6	53.6	53.6	53.6	53.6	53.6
Field Capacity Moisture Content	127.9	125.4	138.4	-	-	-
End of Study Moisture Content (%)	116.1	127.7	141.0	53.6	53.6	53.6
Mass of Refuse Solids (kg)	67.3	68.6	62.2	55.1	49.2	60.6
Initial Refuse Wet Density (kg/m3)	277.1	275.5	251.6	221.4	204.3	249.8
Refuse Wet Density at Field Capacity	396.5	399.4	361.9	-	-	-
Immediate Compressed Wet Density	499.6	538.9	469.5	268.1	262.1	306.3
Primary Compressed Wet Density	614.6	649.2	579.9	314.7	314.2	363.5
End of Study Wet Density	637.3	680.8	611.7	327.7	332.2	378.9
Initial Void Ratio	10.1	10.2	11.2	12.9	14.0	11.3
Void Ratio at Field Capacity	6.7	6.7	7.5	-	-	-
Immediate Compressed Void Ratio	5.1	4.7	5.5	10.5	10.7	9.0
Primary Consolidated Void Ratio	4.0	3.7	4.3	8.8	8.8	7.5
End of Study Void Ratio	3.8	3.5	4.0	8.4	8.2	7.1

4.3.4 Linearity

As discussed in Chapter 2, many researchers have observed that secondary settlement (time ≥ 30 days) is linear with the logarithm of time. To test the results from this study, plots of strain and void ratio were plotted against the logarithm of time. As expected, all cells exhibited linearity of with the logarithm time. Figure 4.16 shows strain vs log time and Figure 4.17 void ratio vs log time.

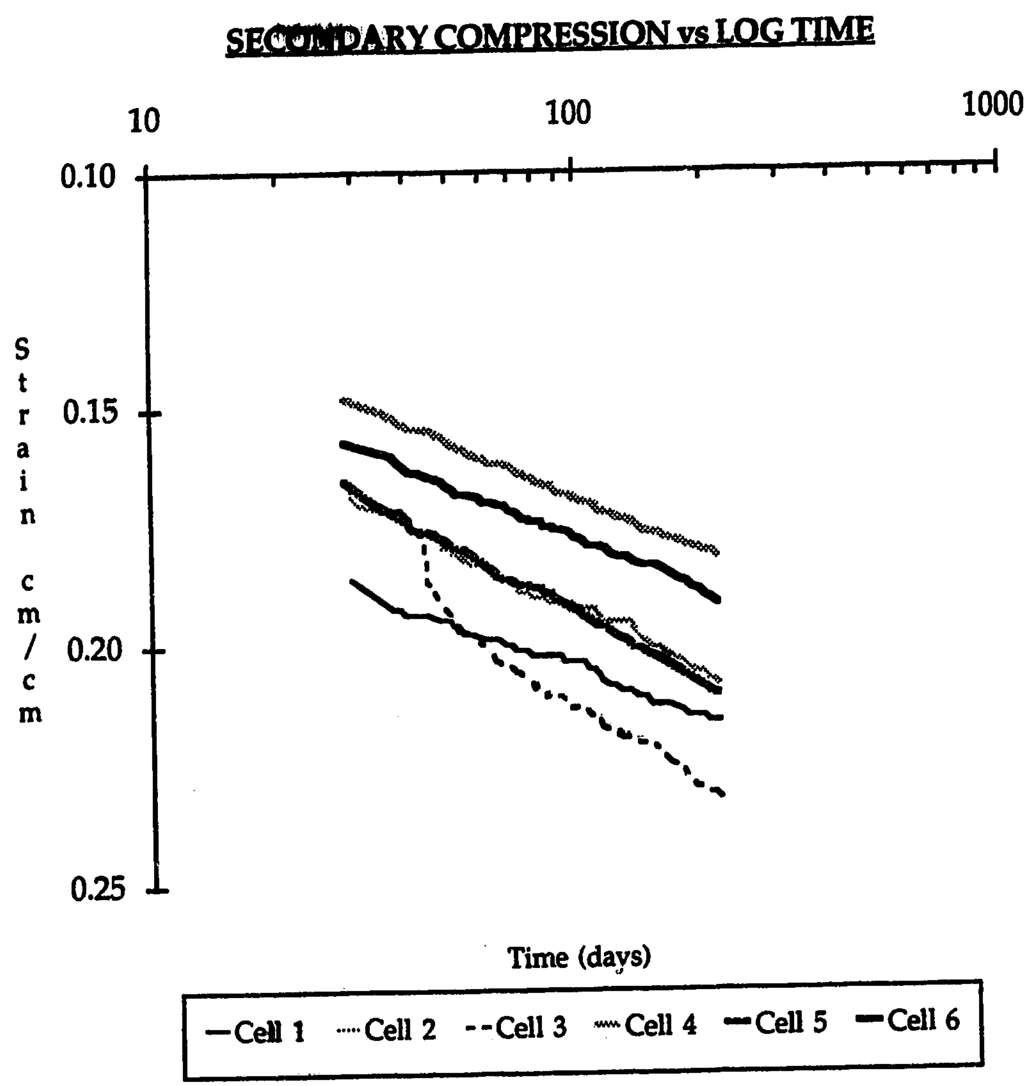

Figure 4.16 - Secondary Strain vs Logarithm of Time

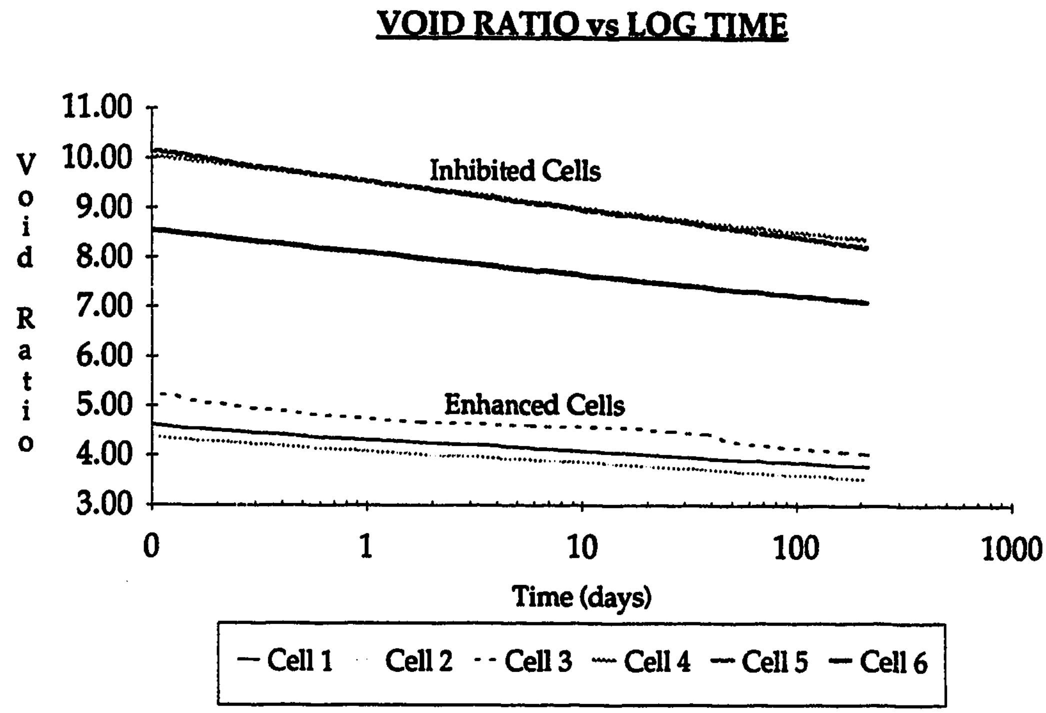

Figure 4.17 - Void Ratio vs Logarithm of Time

4.3.5 Effect of Water Addition

Enhanced landfill cells 1, 2, and 3 were initially brought to field capacity with water and kept continually "irrigated" while inhibited cells 4, 5, and 6 received no water. Addition of water to refuse field capacity resulted in an immediate settlement of 30% prior to load application and visibly increased the amount of strain that subsequently occurred. Differences in strain can be observed in Figure 4.14 while effects on compression are shown in Table 4.7.

Table 4.7 - Compression Due to Settlement Mechanisms (expressed as a percentage of each respective initial height)

Mechanism	% Compression					
	Enhanced			Inhibited		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Addition of Water to Field Capacity	30.1	31.0	30.5	-	-	-
Initial Compression	20.6	25.9	22.9	17.4	22.1	18.5
Primary Compression	18.7	17.0	19.0	14.8	16.6	15.7
Secondary Compression (to date)	3.6	4.6	5.2	4.0	5.4	4.1

4.3.6 Strain Rate

By analyzing data from numerous landfills, Yen and Scanlon (1975) proposed a linear relationship between the settlement rate (or strain rate) and the logarithm of time. Judging from the poor correlation coefficients and scatter in the graphs that they produced, a linear settlement rate with the logarithm of time is probably not accurate. However, it is still worthwhile to compare their observation with the data of this study. Figures 4.18 and 4.19 show strain rate vs time and the logarithm of time respectively.

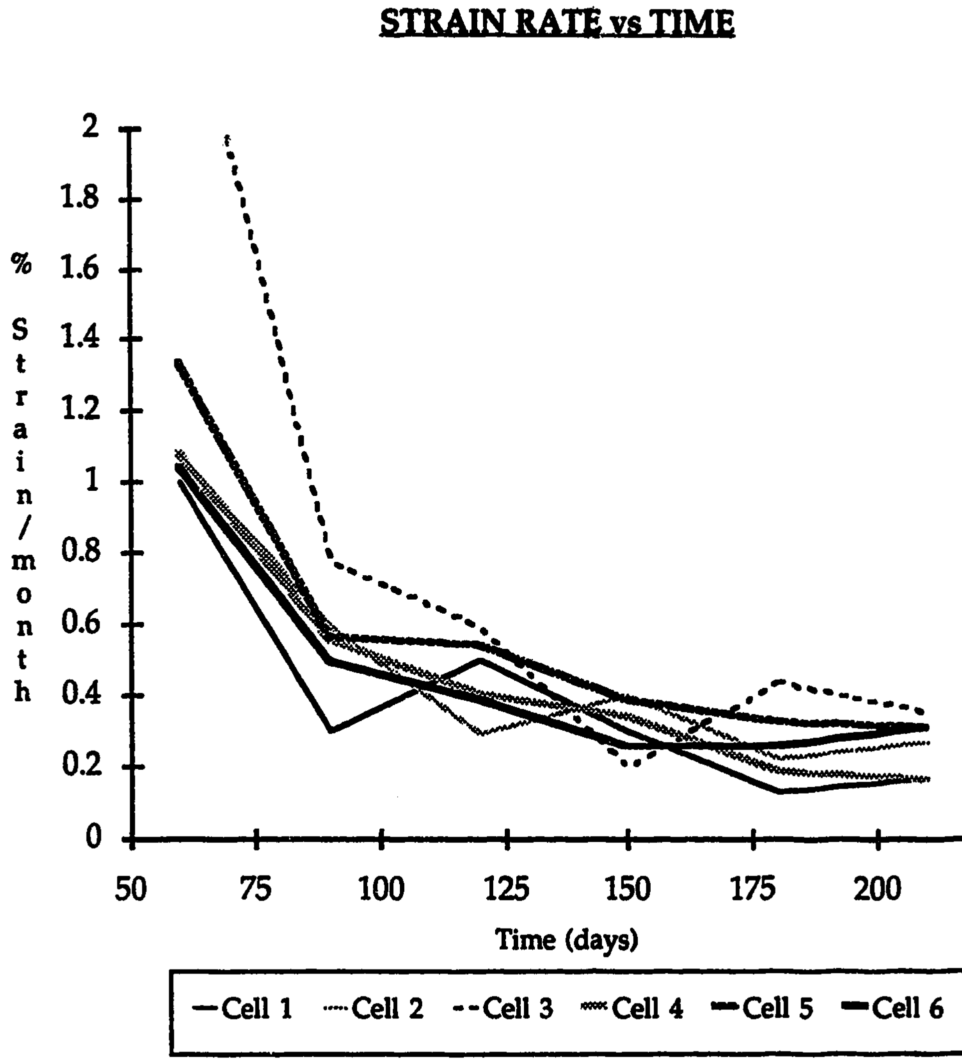

Figure 4.18 - Strain Rate vs Time

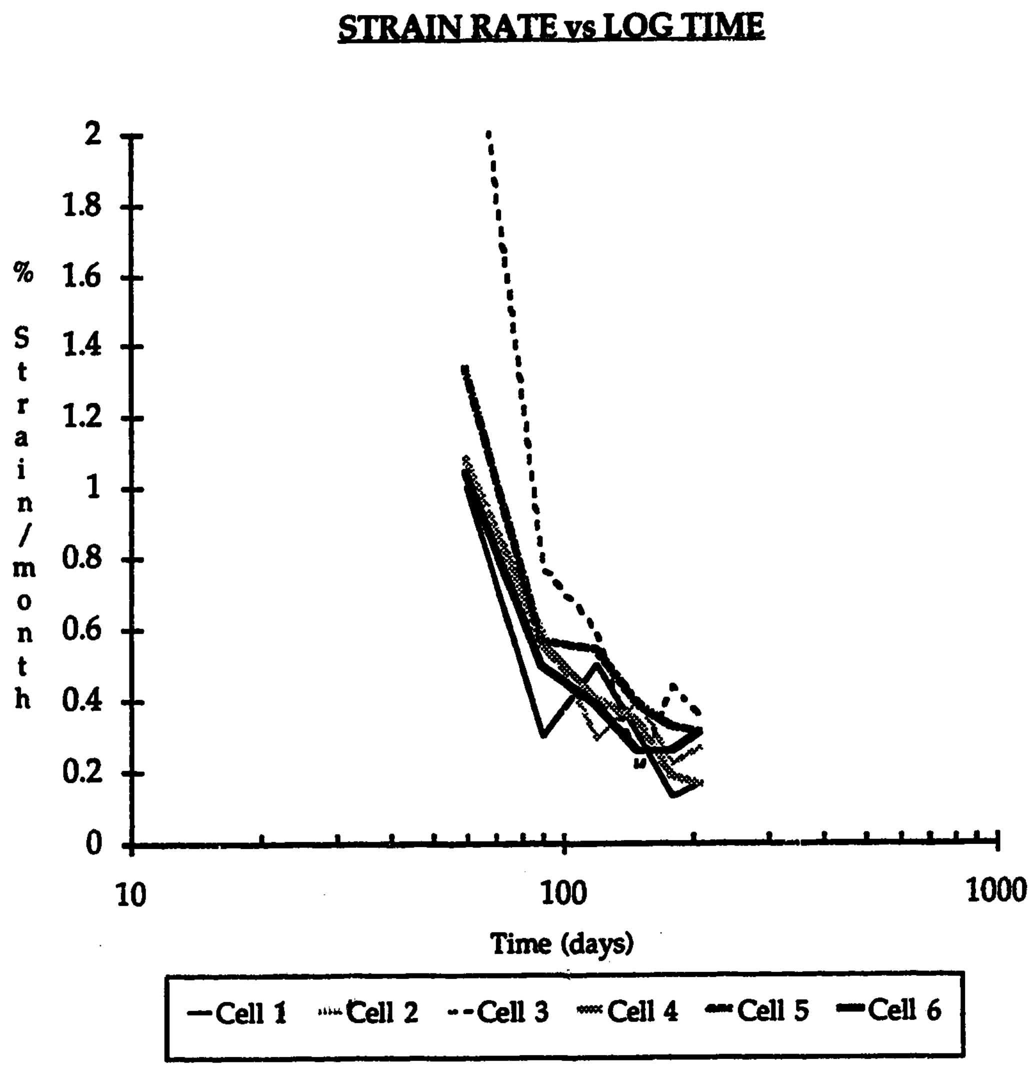

Figure 4.19 - Strain Rate vs Logarithm of Time

In the time frame of this study, it is quite obvious that strain rate is not linear with the logarithm of time. Over longer periods of duration it may appear to be linear because of smaller incremental settlements and subsequent settlement rates.

4.3.7 Settlement Modelling

Initial Compression

Initial compression calculations were performed using equation 5 previously described in Chapter 2. The usual method of calculation would be to assume or measure a modulus of elasticity for the refuse, then calculate the expected settlement. In this case, since the amount of settlement is known, the modulus of elasticity was determined to facilitate comparisons to expected values. Parameters for the elastic settlement equation are shown in Table 4.8.

Table 4.8 - Immediate Settlement Parameters

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Density (kg/m^3)	277.1	275.5	251.6	221.4	204.3	249.8
H_o (m)	1.003	1.016	1.016	1.473	1.423	1.435
Δq (kN/m^2)	10	10	10	10	10	10
S_{actual} (m)	0.207	0.263	0.233	0.257	0.314	0.265
E_s (kN/m^2)	48.5	38.6	43.6	57.3	45.3	54.1

The calculated modulus of elasticity values are quite low when compared to values obtained by Moore and Pedler (1977) using plate load tests in the field. Their values ranged from 50 to 700 kPa depending on the density of the refuse that they tested. The lower experimental values in this study were expected due to the low initial densities achieved in the test cells. The effect of saturation with water (cells 1, 2, and 3) appears to reduce the modulus of elasticity of the refuse, thereby increasing settlement. This effect is similar to having a lower initial density as seen with cell 5. Bowles (1988) states that the modulus of elasticity (E_s) is heavily dependent on density and water content. The modulus increases with higher densities and decreases with higher moisture contents. Therefore low densities and high moisture contents serve to decrease the refuse modulus of elasticity and increase immediate settlement.

Terzaghi Theory

Calculated parameters for primary settlement processes are listed in Table 4.9. Values for the primary compression index are then compared to values observed by Sowers (1973) in Figure 4.20.

Table 4.9 - Primary Settlement Parameters

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
H_i (m)	0.796	0.753	0.783	1.216	1.109	1.170
Δp (kN/m^2)	8.2	8.2	8.2	8.2	8.2	8.2
p_o (kN/m^2)	1.8	1.8	1.8	1.8	1.8	1.8
S_{actual} (m)	0.149	0.128	0.149	0.180	0.184	0.184
C_{ce}	0.25	0.23	0.26	0.20	0.22	0.21

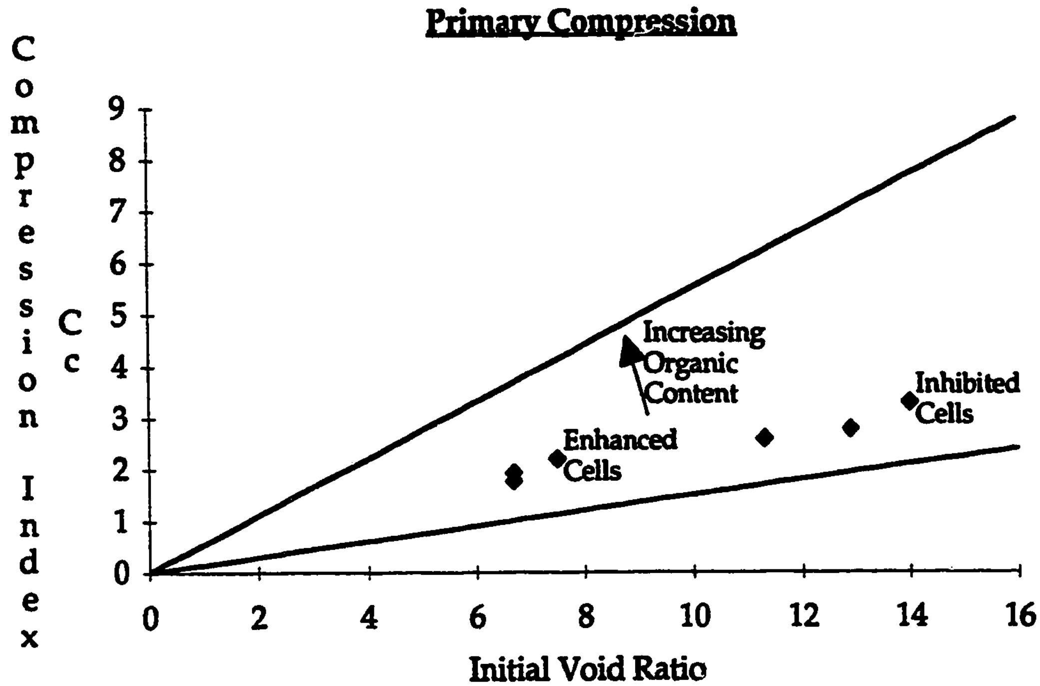

Figure 4.20 - Primary Compression Index vs Initial Void Ratio (Adapted From Sowers, 1973)

Values obtained for the modified compression index (C_{ce}) are well within the range of values obtained by other researchers (see Table 2.8). Also, calculated values for the compression index (C_c) fall within the envelope suggested by Sowers (1973). Using this plot indicates that the landfill test cells are equivalent to an actual landfill that has lower than average organic content. All cells exhibited relatively similar indices, however a trend may exist for higher values of C_{ce} and settlement with the addition of water. High initial void ratios and low densities result in higher values for the modified compression index and larger subsequent settlements (Sowers, 1973). Sowers also makes the observation that organic content is proportional to the compression index, thus higher organic contents such as those found in landfills, result in higher compression indices and greater settlement.

Extension of Terzaghi Theory

Secondary settlement results from the experimental study were analyzed to calculate parameters for the model proposed by Sowers (1973). In addition to this, non-linear regression analysis was performed to determine the fit of the model to the landfill cell settlement. Regression analysis was performed on a Macintosh personal computer system using the software package Systat version 5.1. Secondary settlement parameters are shown in Table 4.10. Figure 4.21 shows the actual and predicted strain vs time for the Sowers model (Cell one). Similar figures (B.1 to B.5) for the remaining cells can be found in Appendix B.

Table 4.10 - Secondary Settlement Parameters

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
H_p (m)	0.647	0.625	0.634	1.036	0.925	0.986
t_p (days)	30	30	30	30	30	30
t (days)	219	219	219	217	217	217
S_{actual} (m)	0.023	0.029	0.033	0.041	0.050	0.040
C_{ae} (best fit)	0.033	0.043	0.056	0.039	0.049	0.037
R^2 (model)	0.989	0.988	0.991	0.996	0.996	0.996

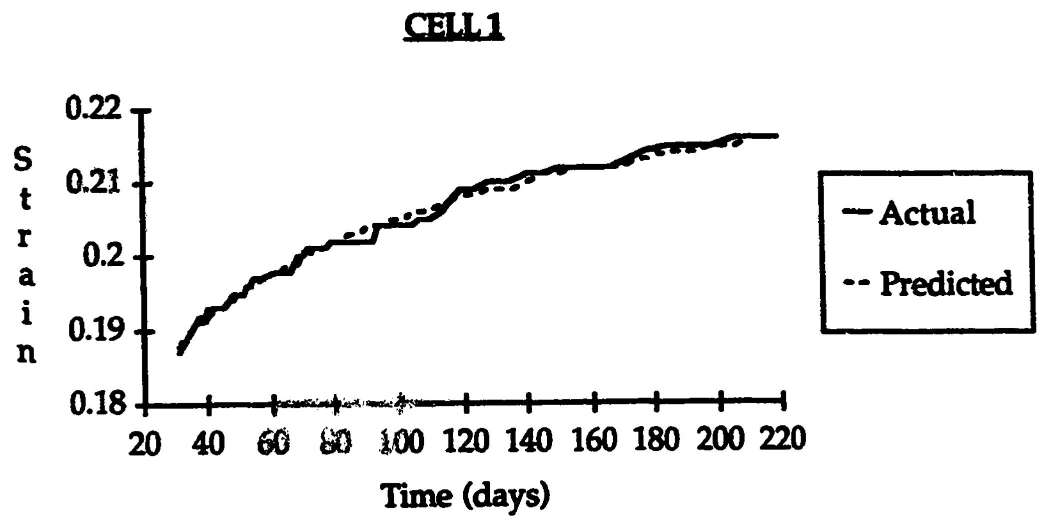

Figure 4.21 - Strain vs Time (Sowers Model) - Cell 1

Values calculated in this study for the secondary compression ratio (C_{ae}) appear to be on the higher end of the range but are still within observed limits as listed in Table 2.8. Judging from the high correlation coefficient (see Table 4.10) and good visual fit, the linear logarithm time model used by Sowers seems to describe the secondary settlement data collected in this experiment very well. Calculated values of the secondary compression index (C_a) are compared to values obtained by Sowers (1973) in Figure 4.22. Results indicate that the landfill test cells in this study are equivalent to landfills with varying degrees of decomposition conditions. Results from Figure 4.22 seem to be indicative of actual decomposition conditions in the reactors. Enhanced reactors are generally in the favorable range while inhibited cells are in the unfavorable range. Reactor 3, the most biologically active test cell, is on the upper limit for favorable decomposition conditions.

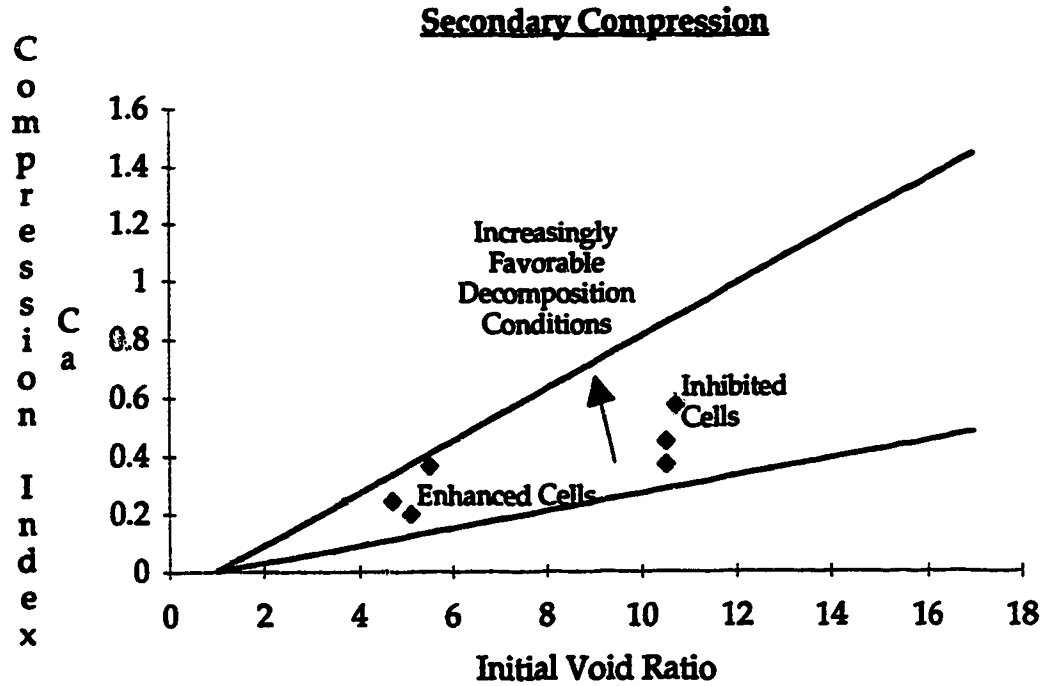

Figure 4.22 - Secondary Compression Index vs Initial Void Ratio (Adapted From Sowers, 1973)

Sowers (1973) concludes that the secondary compression index (C_a) is proportional to initial void ratio and favorable decomposition conditions. Sowers suggested that increased rates of degradation due to favorable biological conditions result in higher values for the secondary compression index and therefore higher settlement rates. Results from this study do not support such a conclusion at this time (see section 4.3.8 Hypothesis Testing). Results from Chen (1974) also suggest that decomposition is not a significant factor in landfill settlement.

Although the model provides a good fit of the data, it has been derived semi-emperically to explain the frequent linearity of settlement with the logarithm of time. The lack of theoretical rationale and the fact that settlement may not always be linear with the logarithm of time, suggests that a more theoretically based approach is needed to understand the settlement process.

Rheological Model

To evaluate the Gibson and Lo model, results for total settlement were tested for statistical fit. Parameter estimates for the model are shown in Table 4.11 while actual and predicted settlement results for cell one can be seen in Figure 4.23. Other test cell figures (B.6 to B.10) can be found in Appendix B.

Table 4.11 - Gibson & Lo Model Parameters

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
H_0 (m)	1.003	1.016	1.016	1.473	1.423	1.435
Δp (kN/m^2)	8.2	8.2	8.2	8.2	8.2	8.2
a $(kN/m^2)^{-1}$	0.010	0.008	0.011	0.005	0.006	0.006
b $(kN/m^2)^{-1}$	0.014	0.014	0.016	0.015	0.017	0.015
L (day^{-1})	0.180	0.119	0.039	0.129	0.123	0.140
R^2 (model)	0.871	0.884	0.853	0.927	0.916	0.927

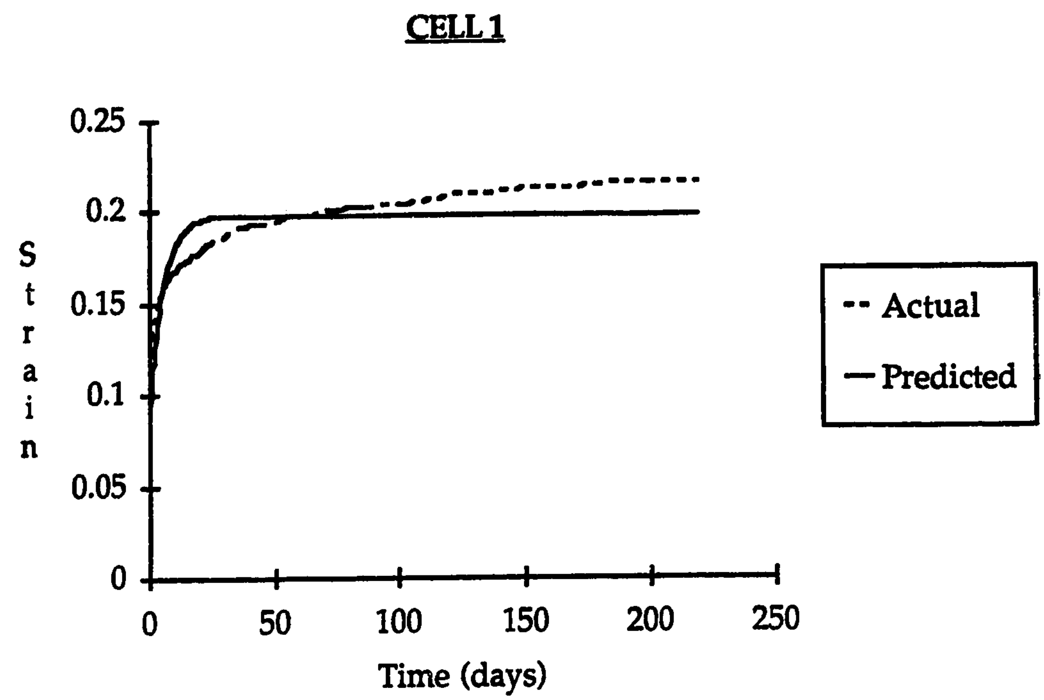

Figure 4.23 - Strain vs Time (Gibson and Lo Model) - Cell 1

Judging from the regression coefficients, one would be inclined to say the model fits the data reasonably well. However, when examining the plot of actual and predicted settlement values, it becomes obvious that the model does not fit either the primary or secondary stages of settlement to any great degree. More importantly, the model underestimates and poorly represents the long term settlement in the secondary compression range. As time increases, so do differences between the actual and predicted values. This results in larger discrepancies as time increments increase.

<u>Power Creep Law</u>

Regression analysis was performed to determine the fit of the Power Creep model and its parameters using the total settlement data from this study. Table 4.12 indicates the model parameters and regression coefficients while Figure 4.24 shows the actual and predicted model values for cell one. Additional Figures (B.11 to B.15) can be found in Appendix B.

Table 4.12 - Power Creep Model Parameters

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
H_0 (m)	1.003	1.016	1.016	1.473	1.423	1.435
Δp (kN/m^2)	8.2	8.2	8.2	8.2	8.2	8.2
m	0.015	0.013	0.012	0.010	0.011	0.011
n	0.113	0.138	0.159	0.163	0.161	0.154
t_r (days)	1	1	1	1	1	1
R^2 (model)	0.964	0.969	0.965	0.961	0.968	0.962

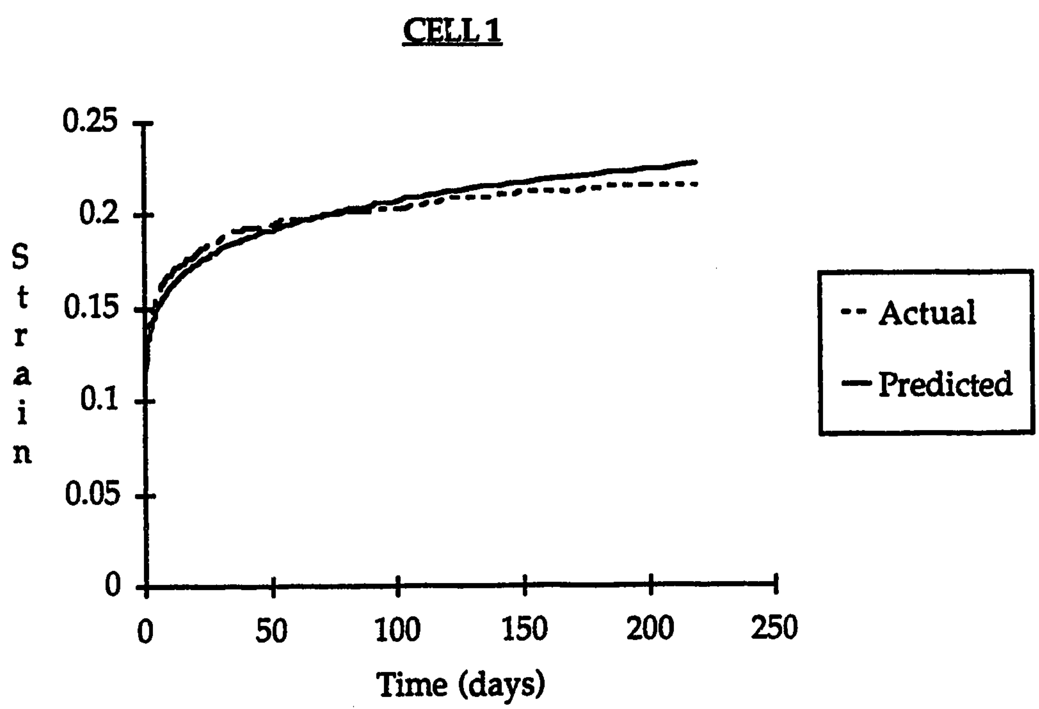

Figure 4.24 - Strain vs Time (Power Creep Model) - Cell 1

The Power Creep model seems to provide a good representation of the settlement data from this study. However, it seems to consistently underestimate primary settlement and overestimate secondary settlement. From a foundation design perspective this is not a serious problem since it appears to always err on the conservative side. Judging from the consistent differences in the actual and predicted strain curves it is obvious that the model is not fundamentally representing the actual processes involved.

Emperical Model

A purely emperical model was developed to describe the time settlement data obtained in this experiment. Various curve fitting procedures were analyzed to linearize the data. It was found that primary settlement was essentially linear with respect to the logarithm of square root time and occurred in the first month after load application. Secondary settlement was seen to be linear with the logarithm of time and continues for a significant period of time. The model was based upon these two observations and some principles of Terzaghi theory. Although it is highly emperical and offers little predictability at this time, it provides a better fit of the entire settlement data in this experiment than any of the other models studied. It is presented mainly to stimulate thought on ways to better represent the time dependent primary settlement process as it occurs in landfills. The two part equation of the model is described below.

$$S = H_i C_{pe} \log \left[\frac{(p_o + \Delta p)}{p_o} (t/t_1)^{1/2}\right], 1 \le t \le t_p \; + \; H_p C_{ae} \log (t/t_p), t \ge t_p \qquad (22)$$

S = refuse settlement (m)
H_i = height of refuse after initial compression (m)
H_p = height of refuse after primary compression (m)

C_{pe} = primary compression coefficient
C_{ae} = rate of secondary compression (as previously described)
p_o = existing overburden pressure at mid level of layer (kN/m^2)
Δp = increment of overburden pressure at mid level of layer
t = time (days)
t_1 = reference time to make time dimensionless (1 day)
t_p = time required for primary compression (usually 30 days)

The fit of the model to actual data for landfill test cell 1 is shown in Figure 4.25 using the following parameter estimates: $C_{pe} = 0.127$, $C_{ae} = 0.033$, $t_p = 30$ days.

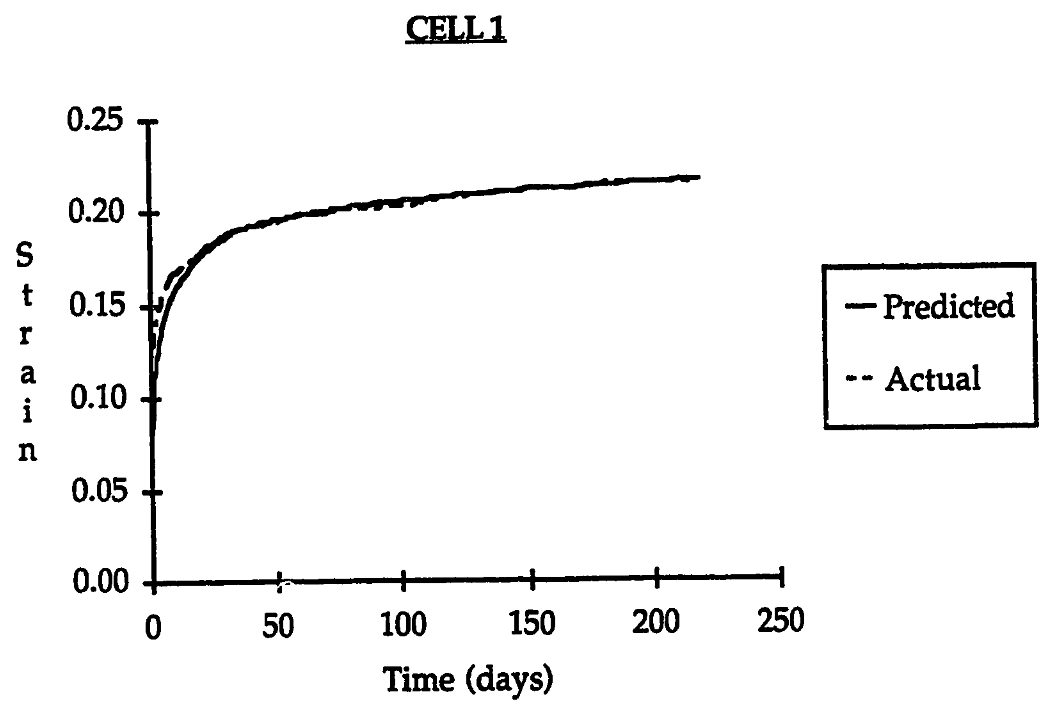

Figure 4.25 - Strain vs Time (Emperical Model) - Cell 1

Model Summary

Of the settlement models studied, the extension of Terzaghi theory as used by Sowers (1973) seems to provide the best representation of secondary settlement. Another advantage is the relative abundance of typical parameter values for laboratory and full scale landfills. Also, the coefficients used in the model can be estimated using field testing procedures at specific sites. Its principal shortfall is that it requires separate prediction of the magnitude and duration of primary settlement. This can be calculated reasonably well using Terzaghi theory and assuming a primary settlement duration of one month. When considering placing development on a landfill site that involves applied loads, one would most likely preload the area prior to construction, thus circumventing the need to predict primary settlement.

The Gibson and Lo rheological model proved to be the least favorable of the models that were evaluated. Results generated from the expression lead to consistent overestimations of primary settlement and underestimations of secondary settlement. This is unacceptable from an engineering design perspectives as variations are not on the conservative side. The model indicates that ultimate settlement is reached very quickly without the development of secondary compression as demonstrated in this study. The limited past application of this model makes prediction of its coefficients quite subjective. Edil, et. al. (1990) provide a series of figures that aid in parameter estimation, however, they caution against using similar parameter estimates between sites of similar composition and location if there are differences in refuse thickness and applied stress.

The Power Creep Law provided a very good description of the entire settlement process. Contrary to the Gibson and Lo model, the Power Creep Law underestimates primary settlement and overestimates secondary. From a design perspective this is a conservative error and is more tolerable than an variations in the other direction. Problems with the model include the lack of typical published values for the given parameters, and lack of physical understanding of the coefficients. Since the model has seen very limited use with respect to estimating landfill settlement this is expected.

4.3.8 Hypothesis Testing

The various hypotheses tested in this experiment are as follows:

H_{o1}: Biological enhancement reduces environmental stabilization time.

H_{o2}: Leachate recycle reduces the organic carbon concentration of leachate.

H_{o3}: Addition of water results in an immediate settlement under no applied load.

H_{o4}: Addition of water to refuse field capacity increases initial settlement.

H_{o5}: Addition of water to refuse field capacity increases primary settlement.

H_{o6}: Lower initial landfill density increases initial and primary settlement.

H_{o7}: Biological enhancement increases the secondary compression rate (C_{ae}) and the amount of secondary settlement.

H_{o8}: Biological enhancement decreases the time required for physical stabilization.

Hypothesis one is confirmed by the fact that enhanced cells undergo biological decomposition while inhibited cells do not. Since landfill gas production occurs as organic carbon sources in the refuse are converted to methane and carbon dioxide, stabilization is proceeding. Cells where biodegradation is not encouraged have little to no gas production corresponding to poor environmental stabilization. As previously discussed in this document, if municipal waste is prevented from undergoing biological decomposition, it will remain unaltered until some time in the future when conditions for biological decay become favorable.

Hypothesis two can be validated by examining Figure 5.8 as it visibly indicates that leachate recycle results in a net reduction of total organic carbon (TOC) in the reactor leachate. This effect has been confirmed by many researchers, specifically Pohland (1974).

Hypothesis three was confirmed by examining the settlement that occurred when refuse in test cells 1, 2, and 3 were "irrigated" with water. Settlements corresponding to 30% of the total original height were observed on average, after the addition of enough water to achieve field capacity and generate leachate. This observation led to an examination of the cause of this compression. Judging from the equation describing initial compression settlements (equation 9), it was inferred that the addition of water results in a reduction in the refuse modulus of elasticity. This consequently results in an immediate increase in settlement when water is added and the change occurs.

Hypothesis four was evaluated using a one-sided paired t-test comparing average values of strain during initial compression of cells 1 to 3 and cells 4 and 6. Cell 5 was excluding from the analysis because of confounding effects due to its low initial density. It was found that the addition of water significantly increased the amount of initial compression that occurred ($t_{calculated}$=2.601, $t_{tabulated}$=2.353, significant at 95% confidence interval).

Hypothesis five was analyzed using a one-sided paired t-test comparing average values for primary compression strain between test cells 1 to 3 and 4 to 6. It was found that the addition of water significantly increased the amount of primary compression that occurred ($t_{calculated}$=3.116, $t_{tabulated}$=2.132, significant at 95% confidence interval).

Hypothesis six can only be confirmed by observing the fact that test cell 5 experiences more initial, primary, and secondary settlement than the replicate cells that have higher initial densities (cells 4 and 6). This hypothesis is fairly intuitive and has been confirmed in the literature by various researchers (Sowers, 1973; Charles, 1984; Moore and Pedler, 1977).

Hypothesis seven was evaluated using a one-sided paired t-test comparing average values for the rate of secondary compression between reactors 1 to 3 and cells 4 to 6. It was found that neither the addition of water or biological enhancement had a significant effect on the amount or rate of secondary compression (t_{calc}=0.332, t_{tab}=2.132, not significant at 95% confidence interval).

Hypothesis eight cannot be proven this early in the study duration. Effects of biodegradation have not been statistically significant to date, therefore inferences regarding shorter physical stabilization periods due to biological enhancement are speculatory.

4.3.9 Decomposition Sensitivity Analysis

Since decomposition was not found to increase the settlement rate in this study, an explanation was sought. As previously discussed, biodegradation results in a net loss of solid organic matter which previously occupied landfill space. Once solubilized and removed from the system, settlement of corresponding magnitude theoretically should occur. Since there was no statistical difference between secondary settlement rates in the test cells, it is likely that either the effects of decomposition are not significant this early in the study or are not significant at all. To determine which explanation is more probable the percentage of carbon decomposed to date and estimated five year predictions were compared to present and future secondary settlements. First order decomposition rate constants measured in the study ranged from 0.0312 to 0.0478 yrs^{-1} (half lives of 15 to 22 years).

The total mass of solids decomposed to date accounts for a small fraction of the total solids (approximately 1%). Secondary settlement for this period accounts for a deformation of approximately 4%. Although these numbers are of the same order of magnitude, a comparison between inhibited and enhanced reactors revealed that decomposition does not have a significant effect on the rate of secondary settlement ($t_{calculated}$ = 0.332, not significant at 95% confidence interval). At this point in time the contribution of decomposition to settlement may be masked by bridging between refuse particles or other mechanisms.

Five year future extrapolations indicate that roughly 14 to 22% of the total solids mass will decompose. Secondary settlement corresponding to this time period is approximately 8%. Comparing the magnitudes of these values suggests that decomposition will become more significant over longer time periods. A plot was constructed with data from reactor 2 to demonstrate the differences between first order decomposition and secondary compression. From Figure 4.26 it can be seen that settlement occurs initially at a faster rate than decomposition but then slows considerably. This indicates that decomposition becomes increasingly significant over time.

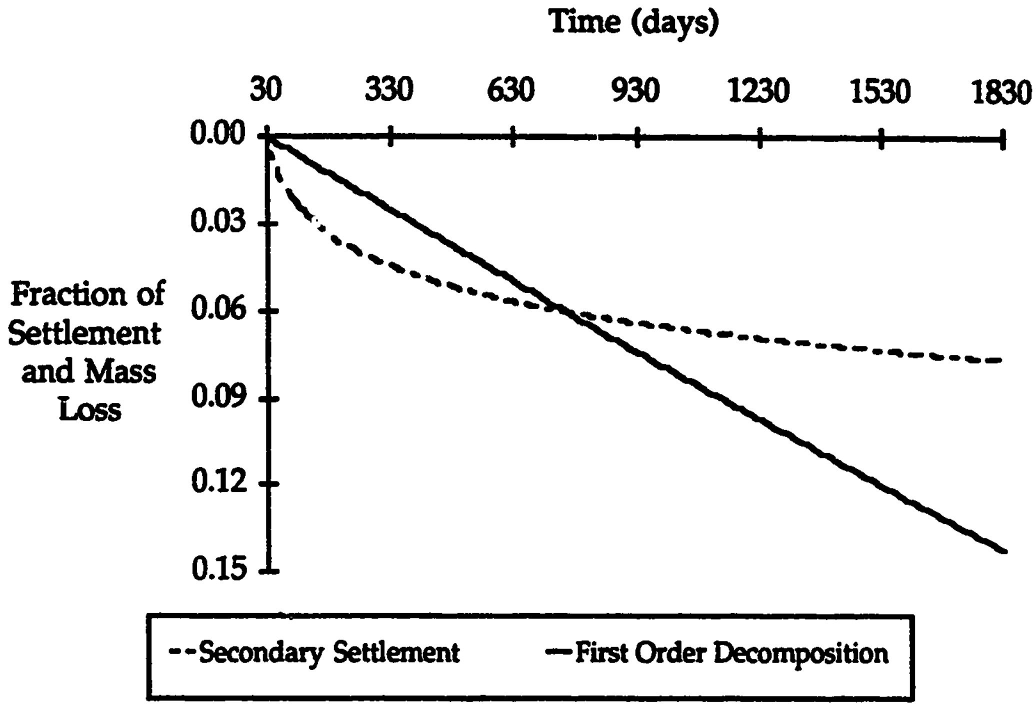

Figure 4.26 - Settlement and Decomposition Models

In the literature, there is support of the hypothesis that settlement contributions due to degradation are insignificant within the rates commonly found in landfills. Chen (1974) performed a sensitivity analysis on the settlement effects of decomposition using a numerical model he derived for milled refuse settlement. He found that settlement was insensitive to biological decomposition for rate constants in the range of 0.012 to 0.788 yrs^{-1}. It should be noted that the upper rate is indicative of quite rapid degradation and is much higher than rates observed in this study.

At this point in time it is not possible to reach a definitive conclusion regarding the effects of biodegradation on settlement. However, the extrapolation of the test results indicate that over longer periods of time the contribution of settlement from biological decomposition may likely become significant.

4.4 COMMUNITY SURVEY

The objective of the community survey is to determine the land development needs of a typical host community and establish residents' views on the development types they feel are suitable and unsuitable for closed landfills.

4.4.1 Site Descriptions of Survey Areas

As discussed in Chapter three, two survey areas were selected to participate in the community land use survey. The first location was in northern Edmonton bordering the presently reclaimed Beverly landfill. The second location was in south Edmonton bordering the presently reclaimed Southside landfill.

North Study Location (Beverly Landfill)

The north location is south of 118th Avenue, between 30th Street and the North Saskatchewan river. The Beverly landfill was opened in 1957 and continued operation until closure in 1972. Land bordering the west side of the site was developed for residential use in approximately 1965.

The site is now classified as a metropolitan recreation district under City of Edmonton planning guidelines. It consists of a public golf course with an adjoining park and recreation area. Facilities at the site include a playground, tennis courts, a soccer field, baseball diamonds, bicycle and walking trails, and a community center. Development bordering the west side of the site is predominantly single family residential, however some row housing and low rise apartments are situated at the north end. Directly north of the site is 118th Avenue, an arterial road that provides transportation access for northeast residents. The west side of the site follows the North

Saskatchewan river valley, which greatly enhances the aesthetic value of the park.

South Study Location (Southside Landfill)

The south location is east of 66th Street and south of the Whitemud Freeway. It was opened in 1958 and continued operation until 1975 when it was closed. Residential development surrounding the site was completed in 1978.

The site is now classified as a public parks district under the City of Edmonton planning description. Use of the site is limited to a public golf course, and no additional recreational facilities are provided. Development directly bordering the site is only on its south side and consists of single family residential housing. On the east end of the site lies a natural area that is undeveloped. To the west of the site is 66th Street, an arterial road that provides access for more southerly residents. The north portion of the golf course is bordered by the Whitemud Freeway, a major roadway providing access from the east or west side of the city.

4.4.2 Survey Participation

Of a total of 111 households considered, 91 questionnaires were sent to individuals who expressed interest in participating, 54 of which were returned (60% of interested households). Figures 4.24, 4.28, and 4.29 detail the basic survey participation and demographic data.

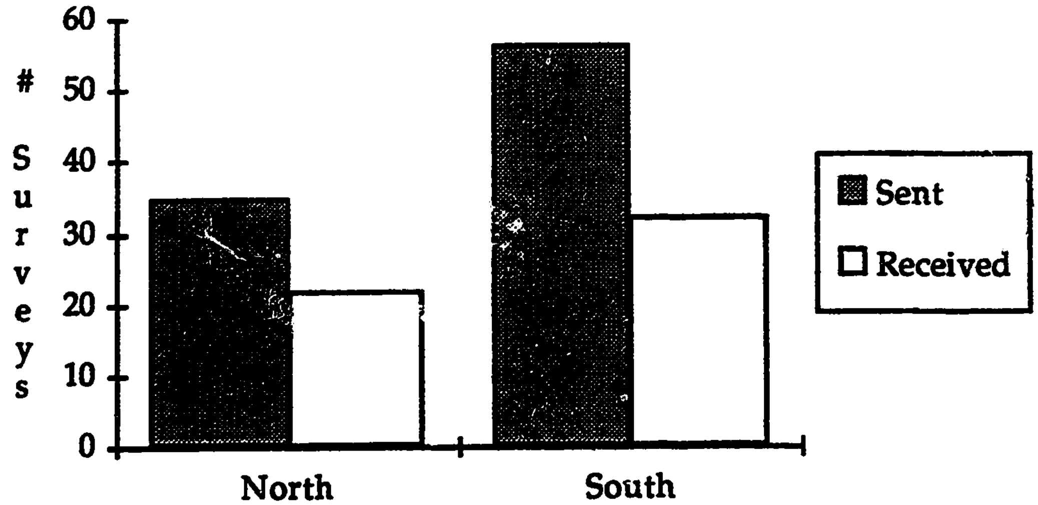

Figure 4.27 - Participation Rates by Community

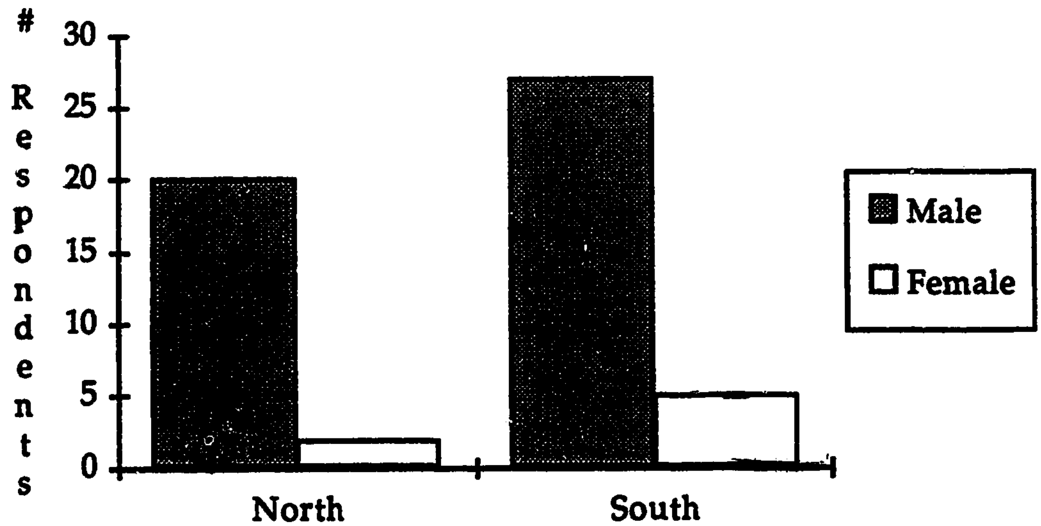

Figure 4.28 - Gender Proportions of Respondents by Community

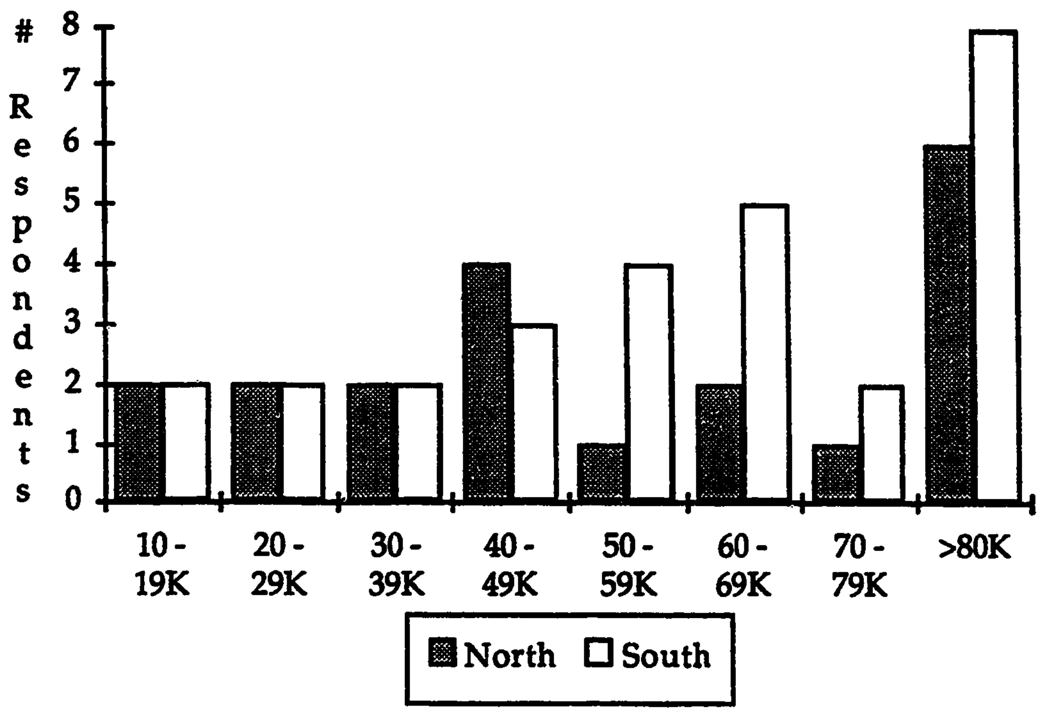

Figure 4.29 - Total Gross Household Earnings by Community

Physically, homes appear to be indicative of an upper middle-class neighborhood. Above average household earnings for the south location are not surprising for an upper middle-class area, with lower household earnings generally attributed to retired families.

4.4.3 Perceived Land Use Requirements

Households were asked an open-ended question regarding the types of development they felt their community needed more of. Responses were quite varied, with significant differences between the north and south study locations and are illustrated in Figure 4.30.

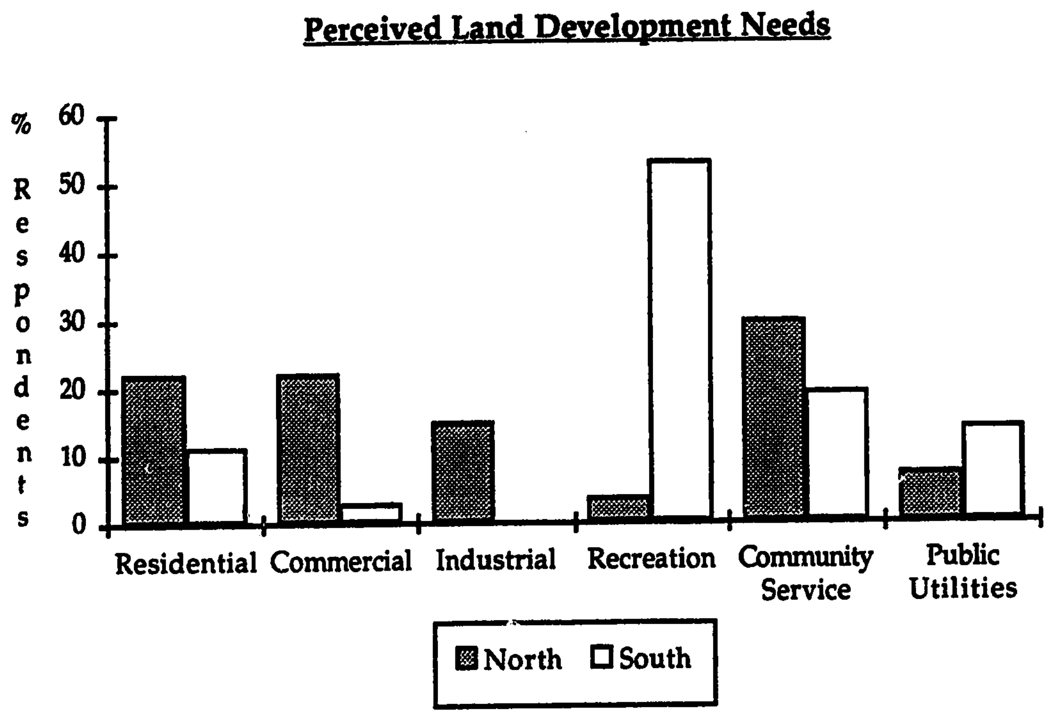

Figure 4.30 - Perceived Land Development Needs

Residents in the south had a strong desire for recreational development, while residents at the north location were satisfied with current levels. One possible explanation of these results is that the south location, while having a scenic golf course, lacks an integrated park facility similar to the north site. Statements were made by residents in the south that golf courses benefit a small number of individuals and need to be accompanied by public areas with a variety of uses.

Another obvious difference between locations is that a significant number of respondents in the north area feel they need more commercial development, possibly due to the lack of shopping facilities in the immediate area. Conversely, people in the south location are closer to shopping areas and do not desire more in their community.

4.4.4 Community Land Use Ranking

Households were asked to rank various types of land development based on what they felt their community needs more of. They were given a scale of 1 to 5, with 1 being needed the most and 5 being needed the least. The various types of development assessed were: commercial, industrial, residential, community service, public utilities, and recreational. The results of ranking by each community location are shown in Figures 4.31 to 4.36.

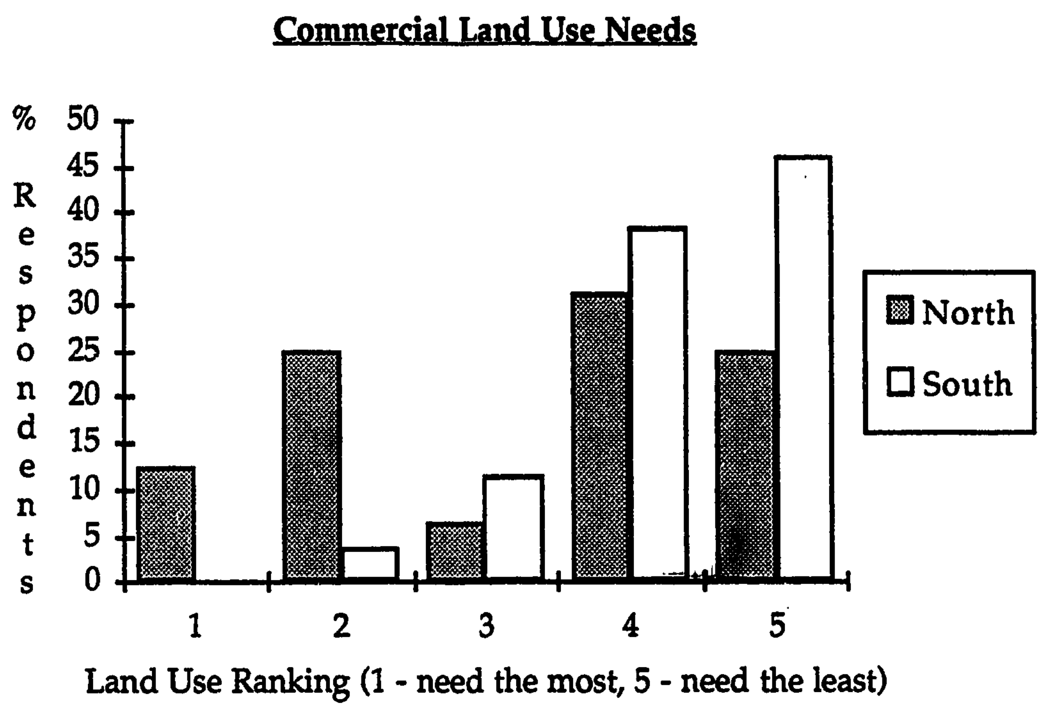

Figure 4.31 - Commercial Development Needs

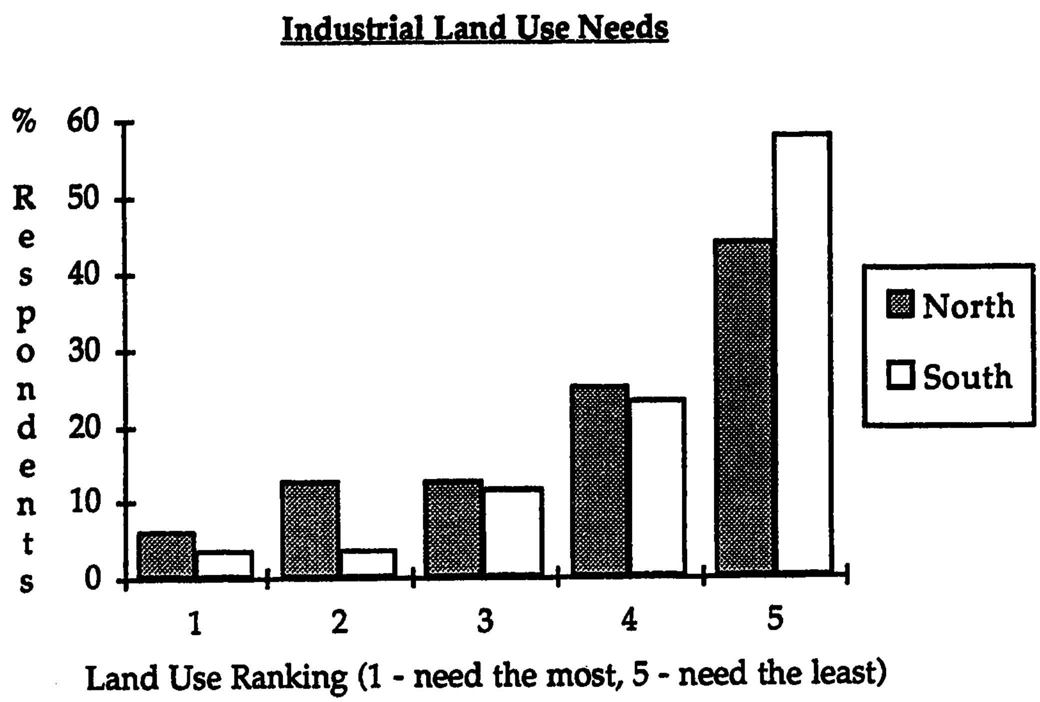

Figure 4.32 - Industrial Development Needs

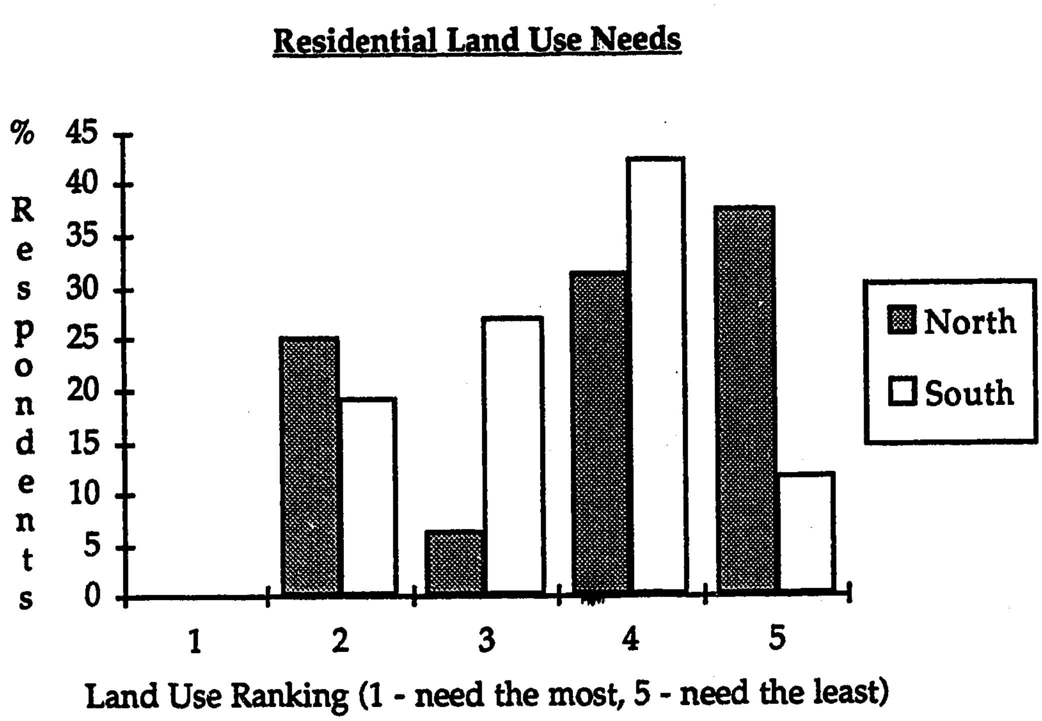

Figure 4.33 - Residential Development Needs

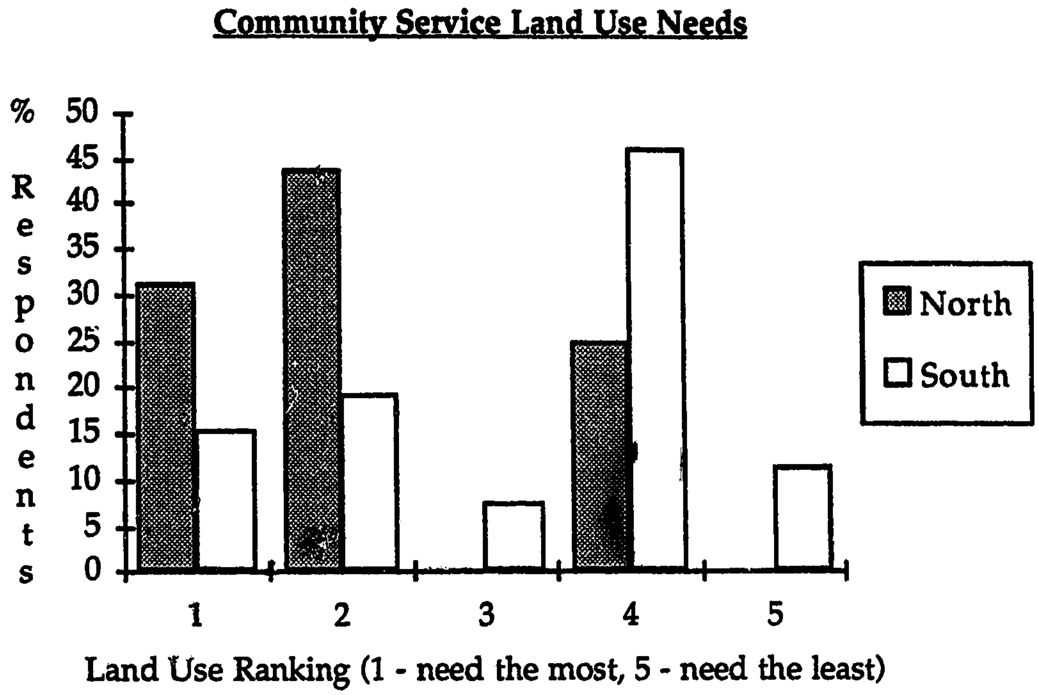

Figure 4.34 - Community Service Development Needs

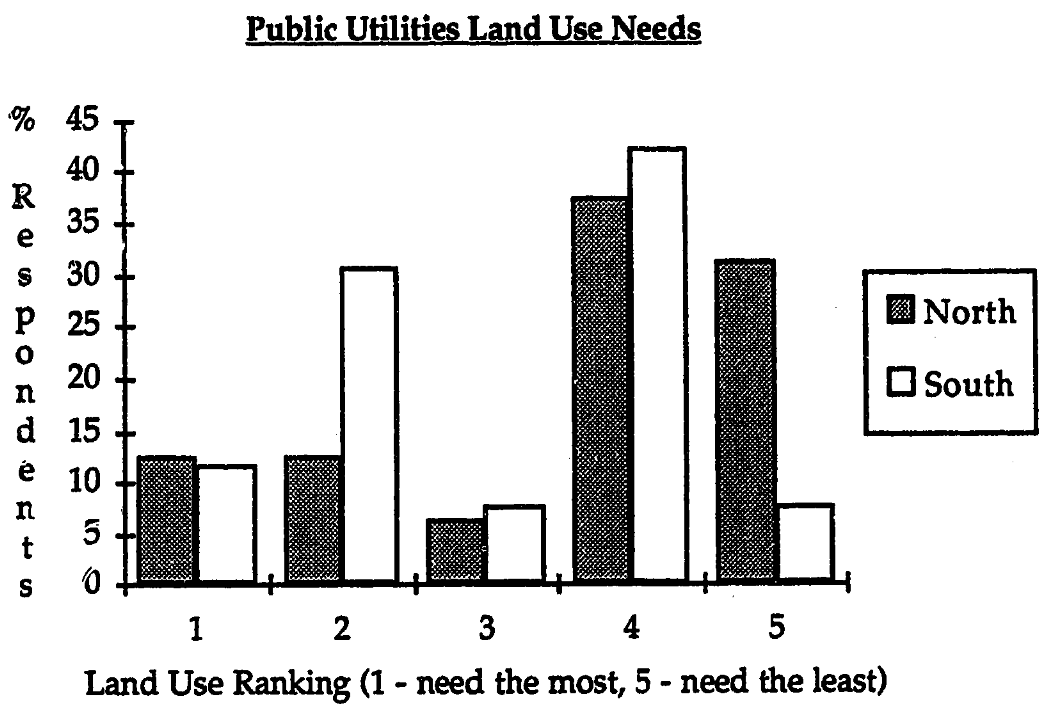

Figure 4.35 - Public Utilities Development Needs

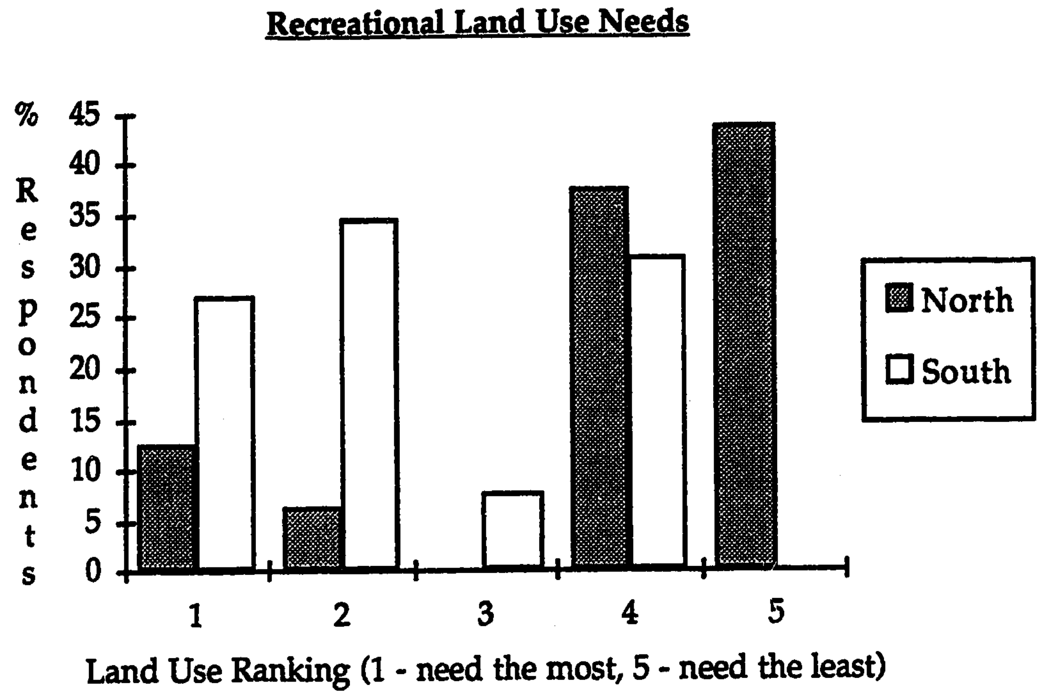

Figure 4.36 - Recreational Development Needs

Some general trends can be observed in the previous Figures on land development needs. Respondents at the south location generally do not feel they need more commercial development. In the north, a small number of respondents strongly feel they need more commercial development, however, the majority feel they do not need any. Figure 4.32 clearly indicates that the majority of people do not want industrial development in their community. Figure 4.33 shows that residents at both locations are indifferent regarding the need for more residential development in their area. There is a strong desire to obtain more community services at the north location. This is likely due to the small number of school and hospital facilities in this area (Salomaa, 1992). In the south, people are roughly split between strongly wanting more community services, and wanting none at all. Figure 4.35 indicates that a small amount of respondents want more public utilities, but the majority do not want any. Regarding recreational development, residents in the south location strongly want more while residents at the north site feel they do not need any more. This can be explained by differences between the two existing recreation facilities as previously discussed.

4.4.5 Specific Land Use Ranking

Of the land development options listed above, communities were asked to rank specific types of development in each category. This was done to determine their land use needs more specifically. Figures C.1 to C.8 detail rankings for types of commercial, industrial, residential, and recreational development for each community and can be found in Appendix C.

People at the north location have a preference for small businesses over shopping centres and convenience stores. There is, however, a lack of concensus in this neighborhood regarding commercial needs. Conversely, respondents from the south still indicate that they do not require further commercial development. Questions on industrial development yielded the expected result, with respondents feeling no need for further industry in their area. Both south and north communities indicated the need for more single family residential housing and less higher density areas. Once again, north location residents indicated their satisfaction with recreational development. In the south, respondents requested more public park areas as opposed to golf courses and community centres.

4.4.6 Development on Closed Landfills

Households were asked several questions regarding landfill reclamation and the land uses they consider desirable and undesirable for these sites. When asked if a golf course is a good use of an old landfill in their community, 100% of the north respondents and 98% of the south respondents answered yes.

The Clover Bar landfill located on the North East outskirts of the city is Edmonton's current active landfill site. It is scheduled to close in 1995 and is to be developed into a toboggan and kite flying hill. Residents of both areas surveyed were asked if this was a desirable use for the land. Results of the end use rating are shown in Figure 4.37. In the same theme, households were given the opportunity to suggest better end uses for the Clover Bar landfill. Table 4.13 lists resident preferences for this site. Most residents felt that this was a good to excellent use for the landfill, however when given a choice, a significant number of residents felt that a public park or golf course was a more desirable use.

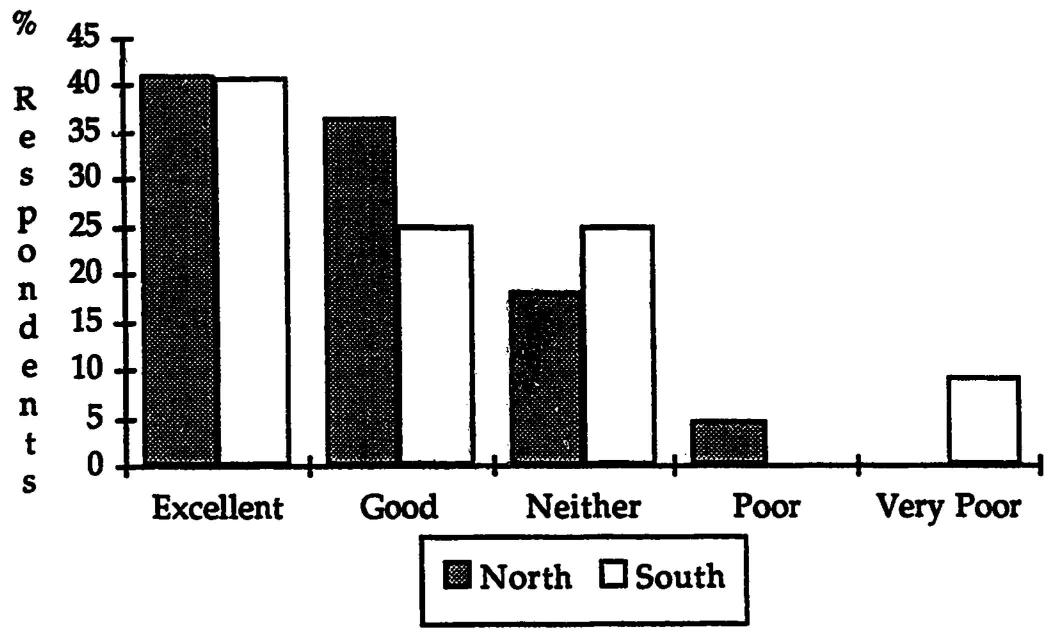

Figure 4.37 - Clover Bar Landfill End Use Plan

Table 4.13 - Preferred End Uses for the Clover Bar Landfill

Clover Bar End Use	% of Respondents North	% of Respondents South
Public Park	40.9	25.0
Golf Course	9.1	28.1
Ski Hill	9.1	12.5
Light Industrial Area		6.3
Equipment Yard		3.1
Recycling Operations	4.5	
Natural State	4.5	
Bike Trails		3.1
Water Park		3.1
Motocross Track	4.5	
Camper / Trailer Park	4.5	
Gun / Archery Range	4.5	
Government Offices / City Hall		3.1

Finally, residents were asked which types of land uses they felt were undesirable or unacceptable for closed landfill sites. Respondents felt quite strongly that residential housing or structural development is either unacceptable or undesirable for closed landfill sites. Results of this are shown in Table 4.14. The general consensus from the survey regarding landfill end use is that they be used for some kind of integrated recreational area.

Table 4.14 - Undesirable End Uses for Closed Landfills

Undesirable Landfill End Use	% of Respondents	
	North	South
Residential Housing	40.9	40.6
Commercial Development	22.7	12.5
Industrial Development	18.2	3.1
Buildings / Structures	22.7	9.4
Playgrounds	4.5	6.3
All but Recreational		9.4
Picnic Areas	4.5	
Abandoned Field		3.1
Heavy People Usage		3.1
Agricultural		3.1
Parking Facilities	4.5	
Cemetaries	4.5	
Non Revenue Generating		3.1

4.4.7 Land Use Needs Summary

From the results of the community survey, several trends in perceived land use needs can be identified. Residents in the south location surrounding the Millwoods golf course feel their immediate community needs more recreational development. They would like a recreational area that has a more integrated use focus so it benefits more people in the community.

Their preferences are towards large public parks with connecting bicycle paths and various playing fields. Residents in the north location surrounding Rundle Park and golf course feel that their community does not need any more recreational development. This can be attributed to the fact that Rundle Park is an integrated recreational facility with a wider range of services. Regarding their land use needs, residents in the north location offer balanced responses, with no single discernible need. However they, along with residents in the south, suggest that they need additional single family residential and community service development. For community service, both areas would like more junior and senior high schools, with north residents also requesting more medical facilities.

Through discussions with City of Edmonton land development planners Salomaa and Morris (1992) the validity of residents' needs were evaluated for both the north and south location.

<u>North Survey Area</u>

Briefly, the resident survey at the north location indicated the following points:

1) No need for recreational development
2) Need for junior and senior high schools and medical facilities
3) Need for single family residential housing

When planning officials were asked if these perceptions were typical of city neighborhoods they responded as follows:

1) Not typical, usually residents request more recreational areas
2) Varies, depends on the specific neighborhood and area
3) Yes typical, due to the fear of high density development

When planners were asked if the perceived needs by residents were valid based upon their own knowledge of the surrounding land use, they responded as follows:

1) Yes valid, they have an extensive recreational facility
2) Yes valid, schools and medical facilities are not close
3) Not valid, residents have an affinity for what they are used to

<u>South Survey Area</u>

Briefly, the resident survey at the south location indicated the following points:

1) Strong need for recreational development (parks, etc.)
2) Need for junior and senior high schools
3) Need for single family residential housing

When planning officials were asked if these perceptions were typical of city neighborhoods they responded as follows:

1) Yes typical, usually residents request more recreational areas
2) Varies, depends on the specific neighborhood and area
3) Yes typical, due to the fear of high density development

When planners were asked if the perceived needs by residents were valid based upon their own knowledge of the surrounding land use, they responded as follows:

1) Yes valid, golf course simply open space not for general use
2) Yes valid, schools are not close
3) Not valid, there is an adequate supply

When asked, looking back on the development, if there were any changes they would have liked to have made, they had few regrets. Additionally, planners noted that they receive very little feed back from residents regarding their satisfaction or dissatisfaction with the community.

4.4.8 Community Survey Review

The community survey indicated that residents do have additional land use needs beyond what is existing in their neighborhood. However, residents felt that landfills should not be used for development other than recreation. Although they appear to be firm in this belief there are indications of possible bias. Media coverage of problematic landfills and public opinion could potentially condition people into thinking that landfills should be used only for recreational development. Educating residents on the fact that landfills can effectively be used for other types of development would be difficult and likely ineffective at changing their opinions regarding landfill end use.

4.5 LANDFILL END USE

Determining a suitable end use for landfills requires that both technical and social constraints be considered. To be technically feasible, development must be able to tolerate future settlement and gas production. Social compatibility deals with satisfying the land use needs of the community while incorporating residents' concerns regarding landfill re-development.

4.5.1 Social Compatibility With Needs

Residents' land use needs basically included recreational, single family residential, and community service development types. In addition to this, residents in both areas strongly felt that residential and structural development are inappropriate or unacceptable for closed landfill sites. The preferred end use by both survey areas for closed landfill sites was recreational development. When asked if golf courses were good uses of closed landfill sites in their communities, almost all residents approved. Their only reservations were that golf courses benefit too few people in the community and should be accompanied by integrated public park areas.

4.5.2 Technical Compatibility With Needs

The ability of landfills to meet land use needs from a technical perspective is dependent upon settlement and gas control measures. As the sophistication and structural loading of the development increases, construction costs start to become prohibitive. Due to the large surface areas of schools and hospitals, and their need for reliability and safety, their development on closed landfills is not recommended. Residential housing has been both successfully and unsuccessfully developed on municipal landfills. However, for reliable housing performance considerable design measures must be adopted to control settlement and gas migration.

When determining settlement criteria, it must be remembered that differential settlement rather that total settlement causes distortion and damage to buildings (Charles, 1984). Frequently, limiting the total settlement is used as an indirect means of controlling the amount of differential settlement (Canadian Geotechnical Society, 1985). A common maximum slope used for the differential settlement of various structures is 1/500, and the highest tabulated value is 1/100 (Canadian Geotechnical Society, 1985). Using a span length of 7.62 m (25 ft) and the above rotations, allowable differential settlements are 1.5 cm and 7.6 cm respectively. Downie and Treharne (1979) suggest that a maximum settlement of 10 cm with a maximum distortion due to differential settlement of 1/400 be used as a design criteria for a warehouse. Using the secondary settlement results from this study and a design life of 25 years, predicted settlements were calculated for each test cell. Results are shown in Table 4.15.

Table 4.15 - Predicted and Allowable Settlements

Parameter	Active			Inert		
	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
Design Life (yrs)	25	25	25	25	25	25
H_p (m)	0.647	0.625	0.634	1.036	0.925	0.986
C_{ae}	0.033	0.043	0.056	0.039	0.049	0.037
Strain	0.0820	0.1068	0.1391	0.0969	0.1217	0.0919
$S_{predicted}$ (cm)	5.3	6.7	8.8	10.0	11.3	9.1
$S_{preload\ 2\ yrs}$ (cm)	2.4	3.0	4.0	4.5	5.1	4.1
$S_{allowable}$ (cm)	10	10	10	10	10	10

Predicted settlements for immediate construction are all very close to the suggested allowable maximum. Judging from predictions, it is likely that development of structures with a design life of 25 years could be placed on the refuse in the test cells. However, as conditions change with respect to load magnitude, depth of fill, and type of structure, new calculations will have to be performed. Table 4.14 demonstrates that a significant reduction in settlement can be achieved by preloading the landfill with an equivalent surcharge, thus allowing for a significant percentage of the settlement to occur before development is started (in this case 2 years was chosen). It is reasonable to conclude that developments of a structural nature can be placed on a municipal landfill, however construction costs may become prohibitive. Also, structural development uses may not be wanted, as residents surveyed in this study indicated.

The National Center for Resource Recovery (1974) suggests that the construction of buildings on a completed landfill often present more problems than they are worth. They also note that special attention should be paid to the design and placement of service lines (sewer, gas & water) so that they will not rupture as settlement occurs. Allowances must be made for the ventilation of combustible landfill gas that might make its way into buildings by these and other pathways. Furthermore, they recommend that one-storey buildings be placed on floating foundations, with higher structures requiring piles founded below the refuse.

It would appear from Table 4.14 that enhanced test cells (1,2 & 3) undergo smaller settlements than inhibited cells (4, 5 & 6), but this is misleading. The reason for lower settlements in the enhanced cells is that the previous addition of water caused settlements that resulted in a lower height of refuse and therefore lower predicted settlements. In actual field conditions design grades would usually be adhered to, therefore more refuse would simply be landfilled if water addition was practiced. Judging from the predicted strains, it can then be concluded that biological enhancement did not result in an increase of "developability" with regards to physical stabilization.

4.5.3 Recommended Uses For Landfills

Judging from community response and developmental constraints, it appears that recreational development is the most appropriate use for landfill sites. The principal advantages include favorable public reaction, reduced development costs, increased tolerability to settlement and gas production, availability of concurrent use, and reduction in waiting time prior to development.

Characteristics that make landfill sites especially suited for recreational development are optimum location and topographic relief. As discussed in Chapter 2, landfills are usually sited along major transportation corridors near urban centers. As time proceeds they frequently become encompassed by the growing host community, which will probably require the additional open and recreational space that can be provided by the landfill site. The fact that landfills frequently have, or can be easily made to have, topographic relief lends itself to good aesthetics, wind reduction, and enjoyable walking trails.

Types of recreational development are selected on the basis of what is best suited for individual sites. Specific selection criteria include: location and access, size and shape, and topography (Weiss, 1974). Usually, the location of landfills lends itself to future recreational use and easy access, however, this may not always be the case. Sites located close to the urban fringe are well suited to intensive use recreational development such as parks, playing fields, and community centers. Locations that are further away from the urban center are suited for less intensive uses such as camping, hiking, and picnicking (Weiss, 1974). The size and shape of a landfill area will be a factor when considering certain specific recreational uses such as playing fields and golf courses. For example, active use facilities like tennis courts and soccer fields are rectangular in design and will require land area of similar shape. Developments such as 18 hole golf courses require at least 150 acres of land (Weiss, 1974). The topography of the landfill site is controllable from an operational standpoint, however certain surface contours are best suited to specific uses. Terrain with hills suggests uses such as hiking, climbing, and winter activities; north and northeast slopes provide shelter from the sun and wind. Flat areas can be utilized for playing fields and camping areas (Weiss, 1974).

In order to more effectively make use of a landfill upon closure, it is important to have an end use plan in place during the active landfilling stage. Various operational measures that control surface topography and active landfilling areas can be altered to accommodate the final use of the site. For example: flat areas or hills can be constructed by following predetermined design grades, future locations of buildings and parking lots can kept free of refuse by using them for weigh scales and administrative areas while landfilling. In some cases, progressive development can occur concurrently with active landfilling, thus minimizing future manpower and cost requirements and making the land available sooner.

5.0 SUMMARY AND CONCLUSIONS

5.1 SUMMARY

The objective of this research was to test the ability of enhanced landfill biodegradation to expedite landfill stabilization and thus beneficial land use. In doing so, the study was required to: 1. Identify the effects of biodegradation on landfill surface settlement; 2. Provide mechanistic explanations and compare models for landfill settlement and biological decomposition; 3. Develop test cells to model landfill behavior and obtain experimental data on settlement and biodegradation; 4. Test the effect of enhanced biodegradation on physical and environmental landfill stabilization time; 5. Determine if biological enhancement increases the end use potential of landfill sites; and 6. Assess which types of development are technically and socially compatible with closed landfill sites.

To accomplish this, existing theories on landfill decomposition, settlement, site selection, and urban development patterns were reviewed. This led to the formulation of a set of hypotheses which were then tested experimentally. The experimental program utilized six specially designed test cells to model and contrast the decomposition and settlement processes in secure vault and bioreactor landfills. Any differences were therefore attributed to the effect of biological enhancement. To determine the compatibility of completed landfill sites with community development a questionnaire was developed. The community survey examined the development needs of two neighborhoods bordering completed landfills and assessed residents' preferences on landfill end use. Specific findings of the study as a whole are best summarized in three main categories: landfill decomposition, landfill settlement, and landfill end use.

Landfill Decomposition

Surprisingly, of the three bioreactor cells, only one produced quantities of landfill gas and methane. As expected, all inhibited vault cells showed no indications of biological activity, decomposition, or the production of leachate. In the successful bioreactor (3), gas production was observed to occur in two phases: an initial aerobic phase followed by a subsequent anaerobic phase. Methane concentrations steadily increased during the second gas production phase, but at relatively slow rates. Cumulative production to date has generated 71.4 litres, approximately 1% of the total methane potential of 8082 liters. The enhanced test cells were operated under the conditions of leachate recycle for the first 79 days of the study. Values for total organic carbon during this period indicated that leachate recirculation caused a reduction in the leachate organic carbon concentration. During periods of leachate recycle, carbonate buffer was added in order to raise pH in the reactors. Even when leachate pH was raised to 7 prior to recirculation, the pH of the subsequent leachate was seldom higher than 6.

By analyzing reactor mass balance data, it was determined that biodegradation was well represented by a first order kinetic model. Carbon balance calculations indicate that only 1% of the total refuse mass has decomposed to date, which is equivalent to a first order rate constant of 0.0391 yrs^{-1}. Based on observations of leachate organic content during periods of distilled water addition, an estimated maximum decomposition rate constant of 0.0970 yrs^{-1} was established.

Landfill Settlement

As expected settlement of refuse under an applied load was observed to take place in three identifiable stages: initial compression, primary compression, and secondary compression. Prior to load application, the addition of water to refuse field capacity resulted in an immediate settlement of 30%. This moisture addition caused changes in the refuse which significantly increased the magnitudes of initial and primary settlement that occurred when the test cells were loaded. Initial compression was observed to take place immediately and accounted for a 26% decrease in refuse height for wetted refuse (enhanced cells) and 17% for as delivered refuse (inhibited cells). After load application, primary compression occurred within the first 30 days and resulted in a further settlement of approximately 15% (based on the refuse height after initial compression). Primary settlement over this period was observed to be linear with the logarithm of the square root time. Experimentally determined values for the primary compression index were within expected ranges for full size landfills. Contrary to initial and primary settlement, secondary compression was not significantly increased by the addition of water. Similarly, biological enhancement did not significantly increase the rate of secondary compression. In the first 225 days of this study secondary compression accounted for a 4% settlement in the biologically enhanced test cells and 2% in the inhibited cells (based on the refuse height after primary settlement). Settlement during this time period was observed to be linear with respect to the logarithm of time and exhibited typical landfill values for the secondary compression index.

Several settlement models were tested against experimental settlement data to determine visual and statistical fit. Because of continual overestimations of primary settlement and underestimations of secondary settlement, the rheological model of Gibson and Lo was found to be unacceptable. Conversely, the Power Creep Law provided a good representation of both primary and secondary landfill settlement but tended to underestimate primary settlement and overestimate secondary. Of the settlement models studied, the extension of Terzaghi theory as used by Sowers seems to provide the best representation of secondary settlement. One advantage it has over the other models is that typical parameter values are more firmly established and can be verified by field tests. However, the model is only valid for secondary compression and Terzaghi theory must be used to predict primary settlement.

Landfill End Use

Predicted secondary settlements over a 25 year period were calculated to be 5 cm for enhanced cells and 11 cm for inhibited cells. Although there were no significant differences in secondary settlement rates between enhanced and inhibited cells, initial refuse heights varied because of previous water addition to enhanced reactors. Larger initial refuse heights for inhibited cells resulted in larger settlements for the same settlement rate. By preloading a landfill with an equivalent surcharge for 2 years, future settlements (25 years) can be reduced by more than 50%.

Residents' land use needs as determined by the community survey basically included recreational, single family residential, and community service development types. Respondents of the community survey strongly felt that residential and structural development are unacceptable or inappropriate for closed landfill sites. They firmly supported recreational development as being the best use for closed landfills, even when they had indicated a much stronger need for other types of development in their community. Residents also indicated that the type of recreational development must have a broad appeal; uses such as golf courses benefit a small number of people and need to be accompanied by public areas with a variety of uses.

5.2 CONCLUSIONS

Judging from the inhibition of reactors one and two, and the slow rate of methane production in reactor 3, biological processes in a landfill environment are very sensitive to environmental conditions and are easily inhibited. Biological enhancement techniques used in this experiment were effective at stimulating refuse decomposition, but not to the degree expected. The lower levels of leachate pH indicate that quantities of buffer need to be increased to maintain optimum conditions.

Cellulose hydrolysis was established as the decomposition step that results in solids loss and therefore settlement. Test cell decomposition data was represented reasonably well by a first order kinetic model. Measured first order rate constants ranged from 0.0312 to 0.0478 yrs^{-1} corresponding to refuse half lives of 15 to 22 years. When compared to literature values these ranges are typical for moderately degradable materials in actively decomposing landfills, but seem low for enhanced bioreactors. It is hypothesized that current secure vault landfilling strategies will further slow down the landfill biodegradation process, likely resulting in lower rate constants and longer stabilization times than observed in this study.

The effects of biodegradation were not observed to significantly influence the magnitude or rate of secondary settlement in the first 225 days of this study. However, using calculated first order rate constants from this study to predict decomposition over a 5 year period indicates that the fraction of mass lost due to decomposition will exceed the predicted fraction of secondary settlement. This suggests that contribution of settlement from decomposition will become significant over time.

Results from this study indicate that the first order decomposition model is distinctly different from the linear with log time model used for secondary compression. This would suggest one or more of the following explanations: 1. Decomposition does not significantly contribute to settlement; 2. Refuse solubilization does not follow first order kinetics; and 3. Secondary compression may not remain linear with logarithm time. Results from this study suggest that explanation one is probable for test durations less than one year. However, as time proceeds the effects of biodegradation on settlement become more pronounced. It is therefore likely that over longer time periods settlement may not be linear with log time.

Judging from the similarities between full-size landfill settlement curves and curves for the test cells, the same mechanisms are likely responsible for settlement. This conclusion is also demonstrated by the identical settlement curves found in inhibited and enhanced cells, and the fact that calculated settlement parameters for the Sowers model are representative of values observed in actual landfills. The close resemblance of experimental behavior to full-size observations suggests that the test cells can effectively model actual landfill behavior.

Biological enhancement, by encouraging the decomposition process and leachate and gas production, will result in shorter periods required for environmental stabilization. Future increases in settlement due to biological decay could have detrimental effects on development placed on a landfill if not accounted for. As a proactive approach, enhanced biodegradation addresses this problem by reducing the duration of active decomposition, thus minimizing environmental and, possibly, physical stabilization time.

As secure vault design inhibits biological decomposition from occurring, environmental and physical stabilization should not be achieved in a foreseeable time. If at some time in the future water enters the landfill, several events may take place: first, there could be an immediate settlement from the infiltration of water; secondly, if biodegradation starts to actively occur, leachate and gas emissions will probably commence; and thirdly, as decomposition proceeds, the settlement rate will likely increase due to its effects. These events, if unaccounted for, could have serious consequences to development placed on the landfill.

A definitive conclusion regarding the ability of biological enhancement to increase the end use potential of landfills cannot be made at this time. Since the process of biological enhancement involves the addition of significant quantities of water to refuse, there will be an associated settlement. As this will reduce the thickness of the refuse layer, incremental settlements will be smaller, thus resulting in improved physical behavior. However, an alternate case can be made as water addition likely occurs during the operational stage of landfilling, and, as a result, any space generated by the addition of water is probably utilized for more refuse.

Technical development criteria for settlement suggest that landfills operating under similar conditions as found in this study can be utilized for structural development if initial and primary settlement can be accommodated during construction. Because of the decreasing rate of landfill settlement with time, preloading the landfill for 2 years prior to development can result in settlement reductions of over 50%.

The social compatibility between landfills and typical host communities was demonstrated by the survey results. Residents strongly preferred integrated recreational uses for completed landfills, even when they had previously expressed a stronger need for other types of development. The use of landfill areas for recreational facilities and parks is also desirable from a technical perspective, since subsequent settlement and methane production pose less of a problem to them.

By combining both the technical and social compatibility of various development types with landfills, it appears that recreational development is the most appropriate use for completed landfill sites. In order to most effectively make use of a landfill upon closure, it is important to have an end use plan in place during the active landfilling stage. By planning post-closure use in this fashion, future areas of structural development can be kept free of refuse by using them for weigh scales and administrative areas while landfilling.

5.3 IMPLICATIONS

The conclusions of this study have several implications regarding landfill design, operation, and future research. In order to properly design municipal landfills there must be a concensus on what the landfilling of municipal waste is supposed to accomplish. Once goals have been determined, design strategies can be adjusted accordingly. If the objective of landfilling is to provide a means of treatment for the waste, then landfills should be designed as some form of bioreactor. Conversely, if the purpose of landfilling is to provide for long-term storage of waste, then they should be designed as secure vaults. Regardless of the design strategy, landfills frequently come into contact with urban development, and are subsequently incorporated into the community. Having an end use plan in place at the time of landfill design results in a more effective use of the site after closure.

Once a design strategy has been established, there are several operational techniques that need to be evaluated. If the bioreactor approach is used, landfill operation will focus necessarily on biological enhancement, and could involve refuse shredding, moisture addition, leachate recirculation, and buffering. If secure vault strategies are adopted, operational methods should focus on the prevention of moisture entry into the landfill. As predictive settlement models become more accurate, landfill final design grade calculations may take surface settlement into account.

The foremost requirement of future research is the need to examine comprehensively the long-term effects of landfill biodegradation on settlement. Only studies sustained for extended periods will be capable of evaluating the link between secondary compression and refuse decomposition. Secondly, more detailed studies are required on the kinetics of cellulose hydrolysis in a landfill environment. This will help to better establish the mathematical connection between refuse solubilization and landfill settlement. Thirdly, the effects of larger load increments and test cell sizes need to be evaluated. In future experiments, operational methods that enhance biodegradation need to be more closely monitored and adhered to. Possible improvements include larger additions of buffer being used, leachate being completely recirculated, and the use of higher temperatures.

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7.0 APPENDICES

APPENDIX A - BIODEGRADATION DATA

Table A.1 - Carbon Balance Data - Cell 1

TIME (days)	LEACHATE out (l)	LEACHATE recirc (l)	TOC (mg/l)	TIC (mg/l)	SLUDGE in (ml)	TOC C in (g)	TIC C in (g)	SLUDGE C in (g)	TOC C out (g)	TIC C out (g)	NET C LOST (g)	CUMULATIVE C LOST (g)
9	13.7	4	22206	134	0	88.8	0.5	0.0	304.2	1.84	216.70	216.70
16	3.4	3.4	24100	40	0	81.9	0.1	0.0	81.9	0.14	0.00	216.70
23	2.7	2.7	22300	50	0	60.2	0.1	0.0	60.2	0.14	0.00	216.70
30	2.7	2.7	22120	60	0	59.7	0.2	0.0	59.7	0.16	0.00	216.70
37	2.7	2.7	21915	70	0	59.2	0.2	0.0	59.2	0.19	0.00	216.70
44	3.2	3.2	21030	80	0	67.3	0.3	0.0	67.3	0.26	0.00	216.70
51	3.4	3.4	20755	90	200	70.6	0.3	1.7	70.6	0.31	-1.67	215.03
58	3.7	3.7	21165	100	200	78.3	0.4	1.7	78.3	0.37	-1.67	213.37
65	3.9	3.9	20800	100	200	81.1	0.4	1.7	81.1	0.39	-1.67	211.70
72	4	4	20840	100	200	83.4	0.4	1.7	83.4	0.40	-1.67	210.03
79	4	4	20420	100	200	81.7	0.4	1.7	81.7	0.40	-1.67	208.37
86	4	1	20415	95	200	20.4	0.1	1.7	81.7	0.38	59.86	268.23
93	3.8	1	18270	95	0	18.3	0.1	0.0	69.4	0.36	51.42	319.65
100	4	1	17097	90	200	17.1	0.1	1.7	68.4	0.36	49.90	369.55
107	4	0	16285	90	0	0.0	0.0	0.0	65.1	0.36	65.50	435.05
172	4.5	0	18400	85	0	0.0	0.0	0.0	82.8	0.38	83.18	518.23
225	4.4	0	18985	84	200	0.0	0.0	1.7	83.5	0.37	82.24	600.47

Table A.2 - Carbon Balance Data - Cell 2

TIME (days)	LEACHATE out (l)	LEACHATE recirc (l)	TOC (mg/l)	TIC (mg/l)	SLUDGE in (ml)	TOC C in (g)	TIC C in (g)	SLUDGE C in (g)	TOC C out (g)	TIC C out (g)	NET C LOST (g)	CUMULATIVE C LOST (g)
9	7.8	4	27116	114	0	108.5	0.5	0.0	211.5	0.89	103.47	103.47
16	3.5	3.5	29356	64	0	102.7	0.2	0.0	102.7	0.22	0.00	103.47
23	3.2	3.2	28430	80	0	91.0	0.3	0.0	91.0	0.26	0.00	103.47
30	2.8	2.8	27545	100	0	77.1	0.3	0.0	77.1	0.28	0.00	103.47
37	2.3	2.3	26175	120	0	60.2	0.3	0.0	60.2	0.28	0.00	103.47
44	2.5	2.5	22910	140	0	57.3	0.4	0.0	57.3	0.35	0.00	103.47
51	3	3	22495	160	200	67.5	0.5	1.7	67.5	0.48	-1.67	101.80
58	3.3	3.3	21620	180	200	71.3	0.6	1.7	71.3	0.59	-1.67	100.14
65	3.5	3.5	20940	200	200	73.3	0.7	1.7	73.3	0.70	-1.67	98.47
72	4	4	20690	200	200	82.8	0.8	1.7	82.8	0.80	-1.67	96.81
79	3.4	3.4	21570	195	200	73.3	0.7	1.7	73.3	0.66	-1.67	95.14
86	3.5	1	20515	190	200	20.5	0.2	1.7	71.8	0.67	50.10	145.24
93	3.4	1	19570	185	0	19.6	0.2	0.0	66.5	0.63	47.41	192.65
100	3.8	1	18935	180	200	18.9	0.2	1.7	72.0	0.68	51.86	244.50
107	3.7	0	19065	175	0	0.0	0.0	0.0	70.5	0.65	71.19	315.69
172	5.5	0	20623	170	0	0.0	0.0	0.0	113.4	0.94	114.36	430.05
225	3.7	0	20280	167	200	0.0	0.0	1.7	75.0	0.62	73.99	504.04

Table A.3 - Carbon Balance Data - Cell 3

TIME (days)	GAS VOL (l)	CO2 (%)	CH4 (%)	LEACHATE out (l)	LEACHATE recirc (l)	TOC (mg/l)	TIC (mg/l)	SLUDGE in (ml)	TOC C in (g)	TIC C in (g)	SLUDGE C in (g)	TOC C out (g)	TIC C out (g)	CH4 C out (g)	CO2 C out (g)	NET C LOST (g)	CUM. C LOST (g)
4	4	27	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.53	0.53
5	3.3	33.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.55	1.08
5.5	4.2	42	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.87	1.95
7	35.9	47	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	8.3	8.33	10.28
8	35.8	50.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	8.9	8.93	19.20
9	35.7	54	0	6	4	19225	70	0	76.9	0.3	0.0	115.4	0.4	0.0	9.5	48.11	67.31
10	35.2	57.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	9.99	77.30
11	41	59.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	12.04	89.35
12	28.7	61.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	8.7	8.71	98.06
14	43.7	63.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	13.7	13.70	111.76
16	35.3	64.5	0	2.3	2.3	19998	347	0	46.0	0.8	0.0	46.0	0.8	0.0	11.2	11.24	123.00
17	31.4	65.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	10.2	10.15	133.15
17.5	2.4	66.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.79	133.94
18	23.2	67	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	7.7	7.67	141.62
20	27.2	67.5	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	9.06	150.68
22	2.5	68	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.84	151.52
23	0	0	0	2	2	19190	300	0	38.4	0.6	0.0	38.4	0.6	0.0	0.0	0.00	151.52
27	24.6	67	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	8.14	159.66
28	2.1	66	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.68	160.34
29	32.6	66	0	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	10.6	10.62	170.96
30	0	0	0	2.6	2.6	19245	250	0	50.0	0.7	0.0	50.0	0.7	0.0	0.0	0.00	170.96
37	0	0	0	2	2	19855	250	0	39.7	0.5	0.0	39.7	0.5	0.0	0.0	0.00	170.96
44	0	0	0	3.3	3.3	19575	250	0	64.6	0.8	0.0	64.6	0.8	0.0	0.0	0.00	170.96
51	0	0	0	3.8	3.8	19255	250	200	73.2	1.0	1.7	73.2	1.0	0.0	0.0	-1.67	169.30
58	0	0	0	2.9	2.9	19385	250	200	56.2	0.7	1.7	56.2	0.7	0.0	0.0	-1.67	167.63
65	0	0	0	3	3	18235	250	200	54.7	0.8	1.7	54.7	0.8	0.0	0.0	-1.67	165.96
72	0	0	0	3.4	3.4	18055	250	200	61.4	0.9	1.7	61.4	0.9	0.0	0.0	-1.67	164.30
79	0	0	0	3.4	3.4	18500	250	200	62.9	0.9	1.7	62.9	0.9	0.0	0.0	-1.67	162.63
86	0	0	0	5.6	1	18185	200	200	18.2	0.2	1.7	101.8	1.1	0.0	0.0	82.91	245.54

93	0	0	0	4.2	1	16680	200	0	16.7	0.2	0.0	70.1	0.8	0.0	0.0	54.02	299.55
100	0	0	0	4	1	16380	200	200	16.4	0.2	1.7	65.5	0.8	0.0	0.0	48.07	347.63
106	2	36.2	9.8	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.45	348.08
107	3.3	35	9.8	4.2	0	15655	150	0	0.0	0.0	0.0	65.8	0.6	0.2	0.6	67.11	415.19
113	3.3	33.8	12	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.6	0.75	415.94
116	2	34.6	13	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.47	416.41
125	1.7	31.4	14	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.38	416.79
127	4.3	31.8	14	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.98	417.77
128	2.5	31.8	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.57	418.34
129	2.7	32.2	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.63	418.97
131	1.7	31	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.39	419.35
132	3.3	32.2	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	0.77	420.12
133	1.4	31.8	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.33	420.45
134	3.5	31.4	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.3	0.5	0.81	421.26
137	1.9	29.4	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.42	421.68
141	3	30.6	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.5	0.68	422.36
142	2.3	30.6	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.52	422.88
145	4.2	30.2	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.3	0.6	0.94	423.83
146	2.4	31	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.56	424.39
147	2.4	30.6	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.55	424.93
149	0.8	30.2	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.18	425.12
154	30.8	28.2	15	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.3	4.3	6.62	431.74
162	25	29.4	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.0	3.6	5.62	437.37
170	30	27.8	16	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.4	4.1	6.51	443.88
172	0	0	0	5.5	0	18020	150	0	0.0	0.0	0.0	99.1	0.8	0.0	0.0	99.94	543.81
177	27	28.2	17	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.2	3.8	5.97	549.78
185	34	27.8	17	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.8	4.7	7.51	557.29
191	26.9	28.2	18	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.4	3.7	6.10	563.39
198	28.3	28.6	19	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.7	4.0	6.66	570.05
204	25.6	29.4	21	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.6	3.7	6.31	576.37
211	29.8	29.4	22	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	3.3	4.3	7.60	583.96
219	29.7	30.2	23	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	3.4	4.4	7.85	591.82
225	25	30.6	26	4.4	0	17420	114	200	0.0	0.0	1.7	76.6	0.5	3.1	3.8	82.40	674.22
229	20	30.6	26	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	2.5	3.0	5.53	679.75

APPENDIX B - SETTLEMENT DATA

Table B.1 - Test Cell Settlement Data

Time 1 (hrs)	Height 1 (cm)	Time 2 (hrs)	Height 2 (cm)	Time 3 (hrs)	Height 3 (cm)	Time 4 (hrs)	Height 4 (cm)	Time 5 (hrs)	Height 5 (cm)	Time 6 (hrs)	Height 6 (cm)
	100.3		101.60		101.60		147.30		142.30		143.50
0.00	79.6	0.00	75.3	0.00	78.30	0.00	121.60	0.00	110.90	0.00	117.00
0.50	77.1	0.50	73.8	0.50	76.30	0.25	120.50	0.25	109.10	0.25	115.20
1.00	74.6	1.00	72.8	1.00	75.30	0.50	119.40	0.50	108.50	0.50	114.30
1.50	74.1	1.50	71.3	1.50	75.30	0.75	118.80	0.75	107.70	0.75	113.80
2.00	73.6	2.00	71.3	2.00	74.80	1.00	118.40	1.00	107.20	1.00	113.20
2.50	73.1	2.50	70.8	2.50	74.30	1.25	118.10	1.25	106.80	1.25	112.80
3.00	72.6	3.00	70.3	3.00	74.30	1.75	117.50	1.50	106.60	1.50	112.50
3.50	72.1	3.50	70.3	3.50	73.30	2.25	117.10	2.00	106.00	1.75	112.10
4.00	72.1	4.00	69.8	4.00	72.80	2.75	116.70	2.50	105.60	2.25	111.50
4.50	71.8	4.50	69.8	4.50	72.30	3.75	116.10	3.00	105.30	2.75	111.20
5.00	71.6	5.00	69.6	5.00	72.30	4.75	115.50	4.00	104.50	3.25	110.70
14.00	69.9	5.50	69.5	5.50	71.90	5.75	115.10	5.00	103.80	4.25	110.20
23.50	69.3	14.50	67.8	6.00	71.60	19.25	112.30	6.00	103.20	5.25	109.60
28.00	69.1	24.00	67.2	15.00	69.50	30.25	111.30	19.50	100.60	6.25	109.20
41.50	68.5	28.50	66.8	24.50	68.60	44.25	110.30	30.50	99.50	19.75	106.70
45.00	68.4	42.00	66.2	29.00	68.30	59.25	109.60	44.50	98.70	30.75	105.80
50.50	68.4	45.50	66	42.50	67.90	73.75	109.10	59.50	98.00	44.75	104.80
65.00	68.1	51.00	66	46.00	67.70	91.75	108.70	74.00	97.50	59.75	104.20
76.00	68	65.50	65.7	51.50	67.70	115.25	107.90	92.00	97.00	74.25	103.70
90.00	67.8	76.50	65.7	66.00	67.60	140.25	107.40	115.50	96.40	92.25	103.30
105.00	67.6	90.50	65.4	77.00	67.50	164.75	107.00	140.50	96.00	115.75	102.60
119.50	67.4	105.50	65.1	91.00	67.30	187.75	106.60	165.00	95.70	140.75	102.20
137.50	67.1	120.00	65.1	106.00	67.10	215.25	106.30	188.00	95.40	165.25	102.00
161.00	66.8	138.00	64.8	120.50	67.10	235.75	106.10	215.50	95.00	188.25	101.60
186.00	66.6	161.50	64.6	138.50	67.00	260.25	105.90	236.00	94.70	215.75	101.30
210.50	66.4	186.50	64.6	162.00	66.80	282.75	105.70	260.50	94.40	236.25	101.00
233.50	66.3	211.00	64.3	187.00	66.80	307.25	105.50	283.00	94.40	260.75	100.70
261.00	66.2	234.00	64.2	211.50	66.80	331.75	105.40	307.50	94.20	283.25	100.60
281.50	66.1	261.50	64.2	234.50	66.80	355.25	105.20	332.00	94.00	307.75	100.50
306.00	65.9	282.00	64.1	262.00	66.70	383.75	105.10	355.50	93.80	332.25	100.40
328.50	65.9	306.50	63.9	282.50	66.60	408.75	104.90	384.00	93.70	355.75	100.20
353.00	65.8	329.00	63.8	307.00	66.50	426.75	104.80	409.00	93.60	384.25	100.00
377.50	65.8	353.50	63.7	329.50	66.50	452.75	104.70	427.00	93.50	409.25	99.80
401.00	65.6	378.00	63.5	354.00	66.50	476.75	104.50	453.00	93.40	427.25	99.70
429.50	65.6	401.50	63.4	378.50	66.40	500.25	104.40	477.00	93.20	453.25	99.60
454.50	65.5	430.00	63.3	402.00	66.40	524.25	104.30	500.50	93.10	477.25	99.40
472.50	65.4	455.00	63.2	430.50	66.40	573.75	104.10	524.50	93.00	500.75	99.30
498.50	65.3	473.00	63.2	455.50	66.20	596.75	104.10	574.00	92.90	524.75	99.10
522.50	65.2	499.00	63.1	473.50	66.10	619.25	104.00	597.00	92.80	574.25	99.00
546.00	65.1	523.00	63	499.50	66.00	644.25	103.80	619.50	92.70	597.25	99.00
570.00	65.1	546.50	62.9	523.50	65.80	665.25	103.70	644.50	92.60	619.75	98.90
619.50	64.9	570.50	62.8	547.00	65.70	692.75	103.60	665.50	92.60	644.75	98.80
642.50	64.9	620.00	62.7	571.00	65.60	840.25	103.20	693.00	92.50	665.75	98.70
665.00	64.9	643.00	62.7	620.50	65.60	858.75	103.20	840.50	91.90	693.25	98.60
690.00	64.8	665.50	62.6	643.50	65.60	885.25	103.10	859.00	91.90	840.75	98.30
711.00	64.8	690.50	62.6	666.00	65.50	911.25	103.00	885.50	91.80	859.25	98.30

738.50	64.7	711.50	62.6	691.00	65.30	963.25	102.90	911.50	91.70	885.75	98.20
886.00	64.3	739.00	62.5	712.00	65.20	985.25	102.80	963.50	91.60	911.75	98.10
904.50	64.3	886.50	62.3	739.50	65.20	1003.75	102.80	985.50	91.50	963.75	97.90
931.00	64.3	905.00	62.3	887.00	64.90	1027.75	102.80	1004.00	91.40	985.75	97.80
957.00	64.2	931.50	62.2	905.50	64.90	1098.75	102.70	1028.00	91.40	1004.25	97.80
1009.00	64.2	957.50	62.2	932.00	64.90	1122.75	102.70	1099.00	91.30	1028.25	97.80
1031.00	64.2	1009.50	62.1	958.00	64.80	1147.75	102.60	1123.00	91.30	1099.25	97.70
1049.50	64.2	1031.50	62	1010.00	64.60	1172.25	102.60	1148.00	91.20	1123.25	97.70
1073.50	64.2	1050.00	62	1032.00	64.50	1195.75	102.50	1172.50	91.20	1148.25	97.60
1144.50	64.1	1074.00	62	1050.50	64.40	1225.75	102.40	1196.00	91.10	1172.75	97.60
1168.50	64.1	1145.00	61.9	1074.50	63.70	1267.75	102.30	1226.00	91.00	1196.25	97.50
1193.50	64.1	1169.00	61.8	1145.50	63.40	1322.25	102.20	1268.00	90.90	1226.25	97.40
1218.00	64.1	1194.00	61.8	1169.50	63.30	1414.75	102.00	1322.50	90.90	1268.25	97.30
1241.50	64	1218.50	61.8	1194.50	63.20	1460.25	102.00	1415.00	90.70	1322.75	97.30
1271.50	64	1242.00	61.7	1219.00	63.10	1508.25	101.90	1460.50	90.60	1415.25	97.20
1313.50	63.9	1272.00	61.7	1242.50	63.00	1532.25	101.90	1508.50	90.50	1460.75	97.10
1368.00	63.9	1314.00	61.6	1272.50	62.90	1583.75	101.90	1532.50	90.50	1508.75	97.10
1460.50	63.8	1368.50	61.5	1314.50	62.90	1629.75	101.90	1584.00	90.30	1532.75	97.10
1506.00	63.8	1461.00	61.5	1369.00	62.80	1677.75	101.80	1630.00	90.20	1584.25	97.00
1554.00	63.8	1506.50	61.4	1461.50	62.60	1701.25	101.80	1678.00	90.20	1630.25	97.00
1578.00	63.8	1554.50	61.3	1507.00	62.50	1751.75	101.70	1701.50	90.20	1678.25	96.90
1629.50	63.7	1578.50	61.3	1555.00	62.40	1800.25	101.60	1752.00	90.10	1701.75	96.90
1675.50	63.7	1630.00	61.3	1579.00	62.40	1849.75	101.50	1800.50	90.10	1752.25	96.80
1723.50	63.6	1676.00	61.2	1630.50	62.30	1894.25	101.50	1850.00	90.10	1800.75	96.70
1747.00	63.6	1724.00	61.2	1676.50	62.30	1940.25	101.40	1894.50	90.00	1850.25	96.70
1797.50	63.6	1747.50	61.1	1724.50	62.20	1989.75	101.40	1940.50	90.00	1894.75	96.60
1846.00	63.6	1798.00	61.1	1748.00	62.20	2037.75	101.30	1990.00	90.00	1940.75	96.60
1895.50	63.5	1846.50	61.1	1798.50	62.10	2111.25	101.30	2038.00	89.90	1990.25	96.60
1940.00	63.5	1896.00	61	1847.00	62.10	2157.25	101.20	2111.50	89.90	2038.25	96.50
1986.00	63.5	1940.50	61	1896.50	62.00	2204.25	101.10	2157.50	89.80	2111.75	96.50
2035.50	63.5	1986.50	61	1941.00	61.90	2324.25	101.10	2204.50	89.70	2157.75	96.40
2083.50	63.5	2036.00	61	1987.00	61.90	2399.25	101.00	2324.50	89.60	2204.75	96.40
2157.00	63.5	2084.00	60.9	2036.50	61.80	2445.75	101.00	2399.50	89.50	2324.75	96.30
2203.00	63.5	2157.50	60.9	2084.50	61.80	2517.75	100.90	2446.00	89.50	2399.75	96.20
2250.00	63.4	2203.50	60.9	2158.00	61.80	2588.75	100.90	2518.00	89.40	2446.25	96.20
2370.00	63.4	2250.50	60.9	2204.00	61.80	2684.75	100.80	2589.00	89.30	2518.25	96.10
2445.00	63.4	2370.50	60.9	2251.00	61.70	2734.75	100.70	2685.00	89.20	2589.25	96.00
2491.50	63.4	2445.50	60.8	2371.00	61.60	2832.25	100.60	2735.00	89.10	2685.25	96.00
2563.50	63.3	2492.00	60.8	2446.00	61.60	2928.25	100.60	2832.50	89.10	2735.25	96.00
2634.50	63.3	2564.00	60.8	2492.50	61.60	3047.75	100.50	2928.50	89.00	2832.75	95.90
2730.50	63.2	2635.00	60.8	2564.50	61.50	3189.25	100.50	3048.00	88.90	2928.75	95.80
2780.50	63.1	2731.00	60.7	2635.50	61.40	3333.25	100.30	3189.50	88.80	3048.25	95.70
2878.00	63	2781.00	60.6	2731.50	61.40	3458.75	100.20	3333.50	88.60	3189.75	95.70
2974.00	63	2878.50	60.6	2781.50	61.30	3575.75	100.10	3459.00	88.60	3333.75	95.60
3093.50	62.9	2974.50	60.6	2879.00	61.20	3716.75	100.10	3576.00	88.50	3459.25	95.50
3235.00	62.9	3094.00	60.6	2975.00	61.20	3954.25	100.00	3717.00	88.40	3576.25	95.50
3379.00	62.8	3235.50	60.6	3094.50	61.10	4220.75	99.90	3954.50	88.30	3717.25	95.50
3504.50	62.8	3379.50	60.4	3236.00	61.10	4389.25	99.80	4221.00	88.10	3954.75	95.40
3621.50	62.7	3505.00	60.3	3380.00	61.00	4560.25	99.80	4389.50	88.00	4221.25	95.20
3762.50	62.7	3622.00	60.2	3505.50	61.00	4724.25	99.70	4560.50	87.90	4389.75	95.10
4000.00	62.7	3763.00	60.2	3622.50	61.00	4893.75	99.60	4724.50	87.80	4560.75	95.00

4266.50	62.6	4000.50	60.1	3763.50	60.90	5037.25	99.60	4894.00	87.70	4724.75	94.90
4435.00	62.5	4267.00	60	4001.00	60.70	5207.75	99.50	5037.50	87.60	4894.25	94.80
4606.00	62.5	4435.50	59.9	4267.50	60.60			5208.00	87.50	5037.75	94.70
4770.00	62.5	4606.50	59.8	4436.00	60.40					5208.25	94.60
4939.50	62.4	4770.50	59.8	4607.00	60.30						
5083.00	62.4	4940.00	59.7	4771.00	60.30						
5253.50	62.4	5083.50	59.7	4940.50	60.20						
		5254.00	59.6	5084.00	60.20						
				5254.50	60.10						

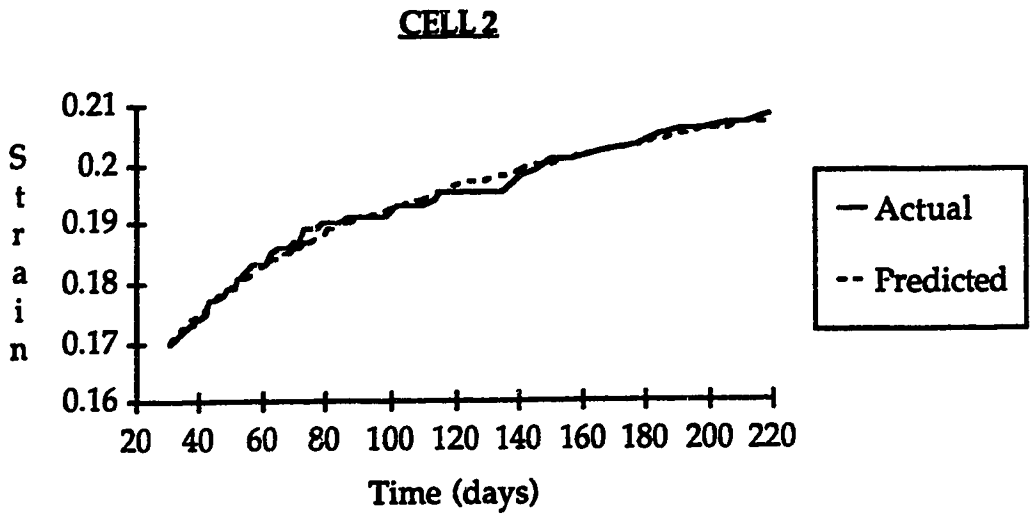

Figure B.1 - Strain vs Time (Sowers Model) - Cell 2

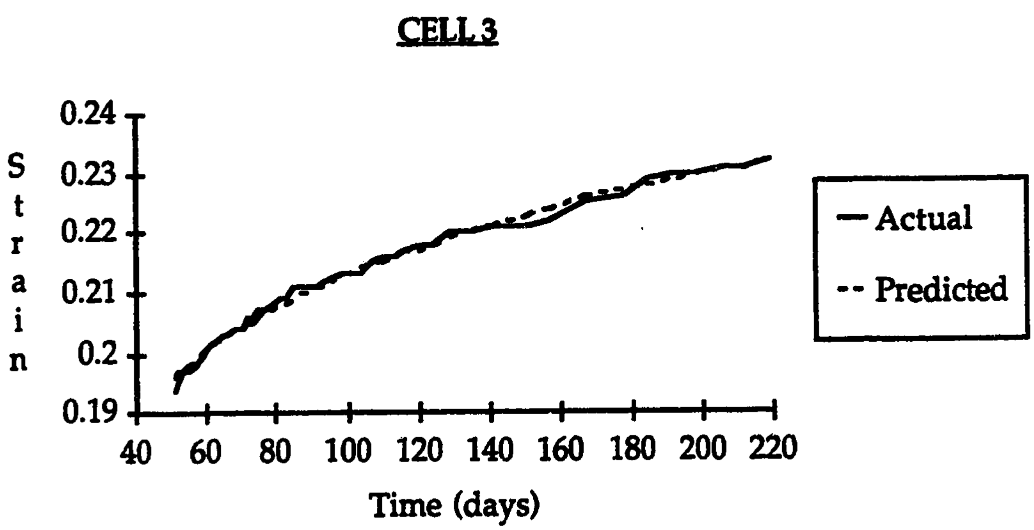

Figure B.2 - Strain vs Time (Sowers Model) - Cell 3

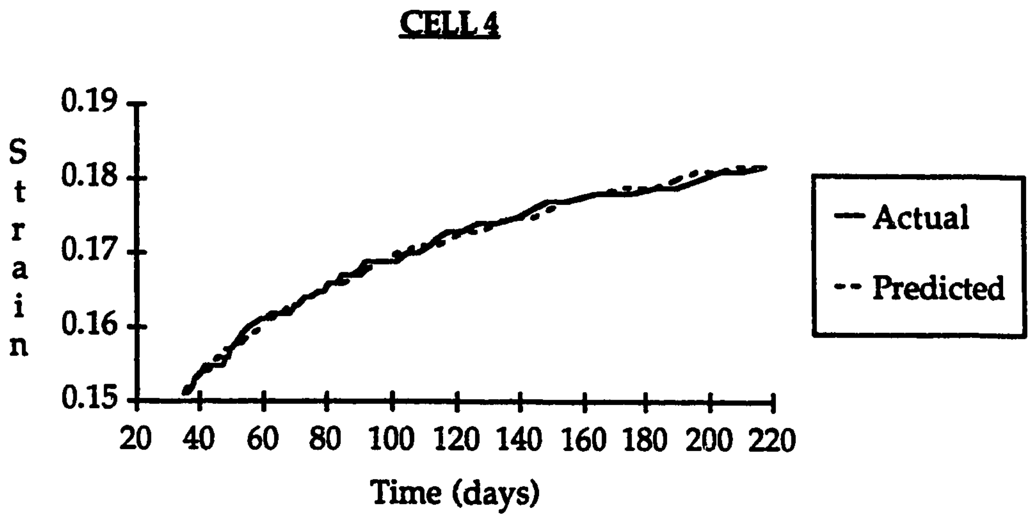

Figure B.3 - Strain vs Time (Sowers Model) - Cell 4

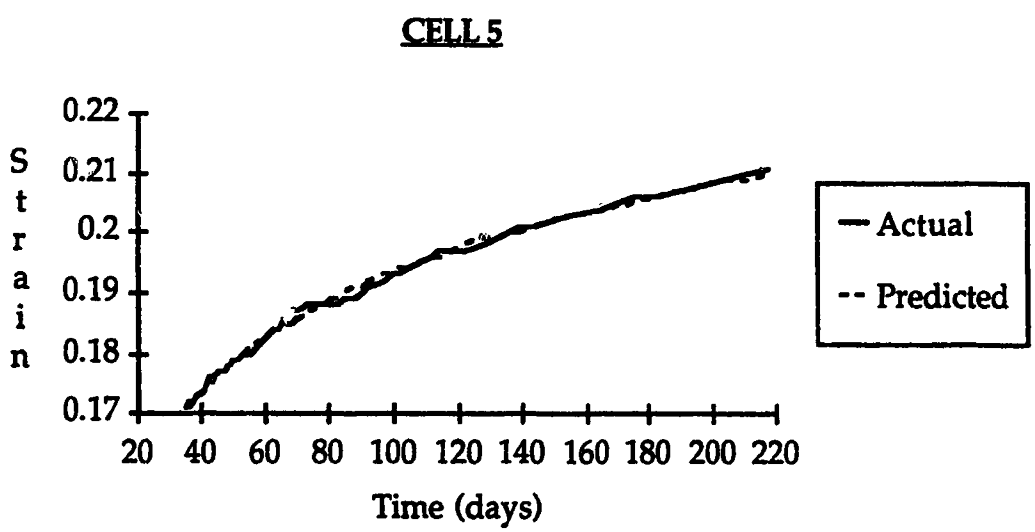

Figure B.4 - Strain vs Time (Sowers Model) - Cell 5

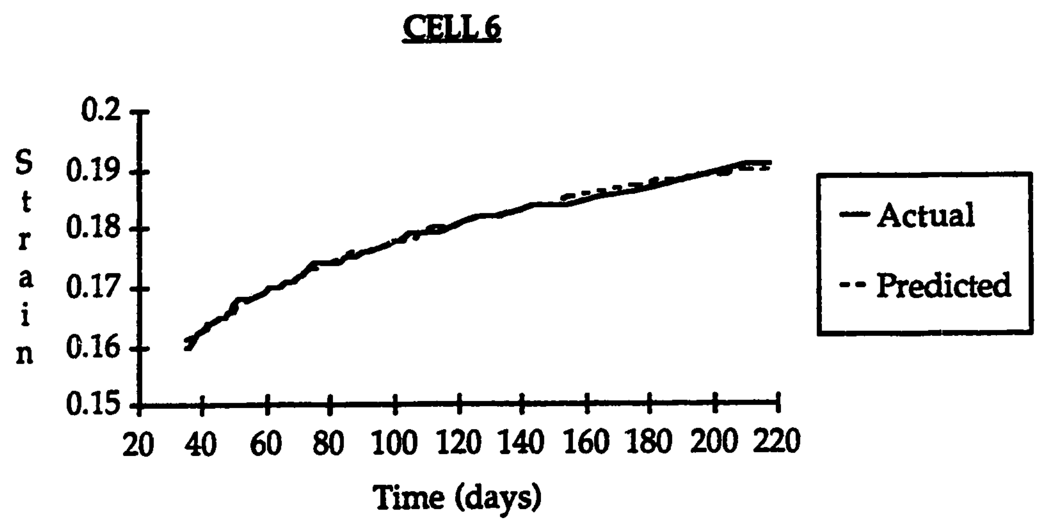

Figure B.5 - Strain vs Time (Sowers Model) - Cell 6

CELL 2

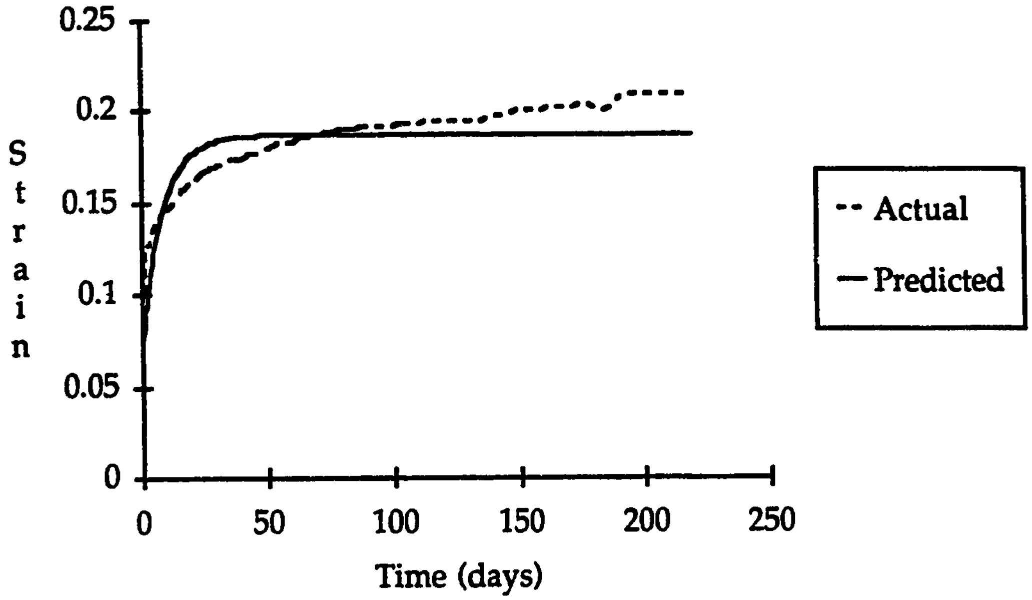

Figure B.6 - Strain vs Time (Gibson and Lo Model) - Cell 2

CELL 3

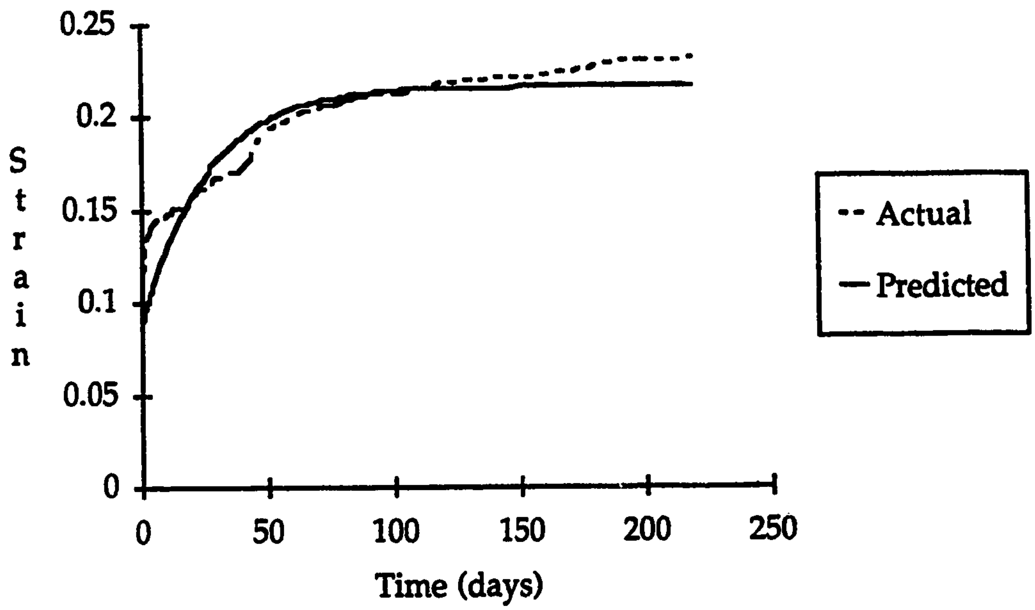

Figure B.7 - Strain vs Time (Gibson and Lo Model) - Cell 3

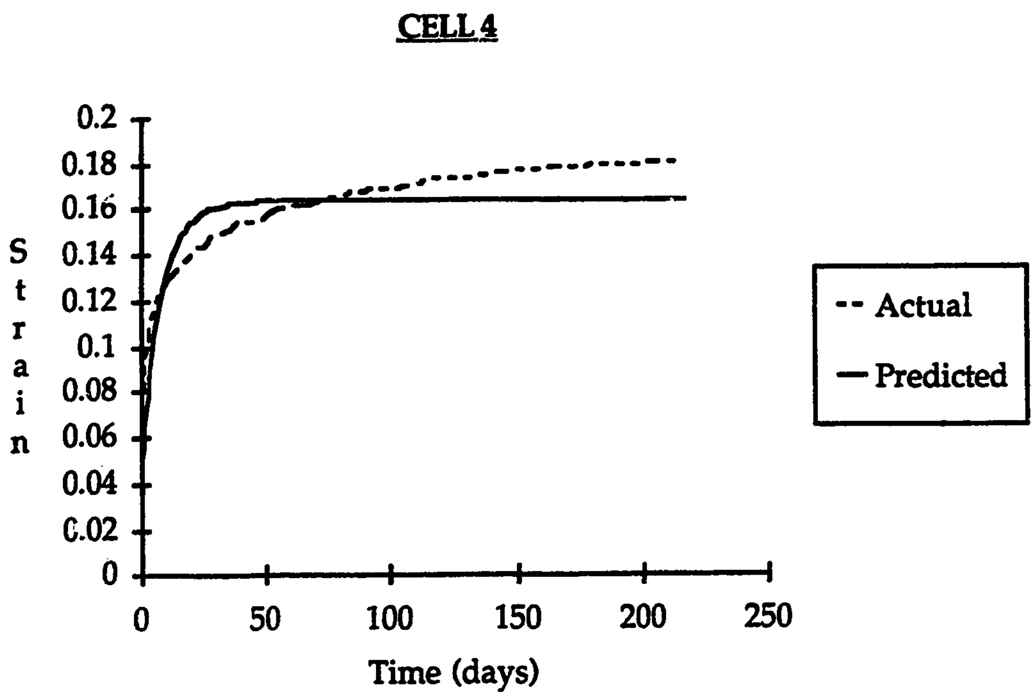

Figure B.8 - Strain vs Time (Gibson and Lo Model) - Cell 4

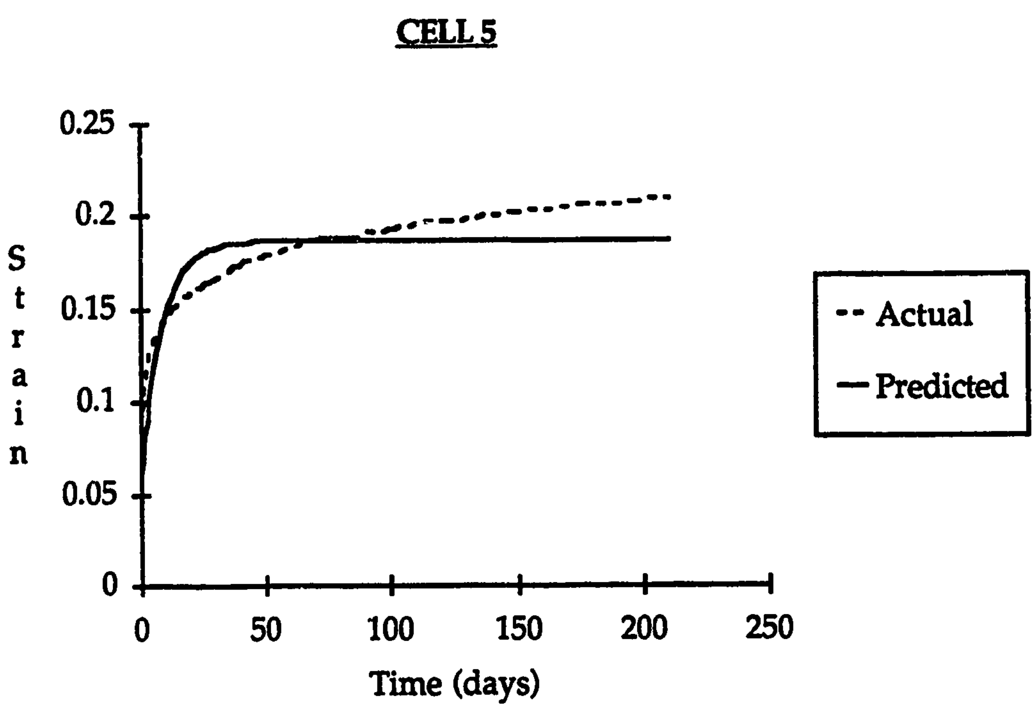

Figure B.9 - Strain vs Time (Gibson and Lo Model) - Cell 5

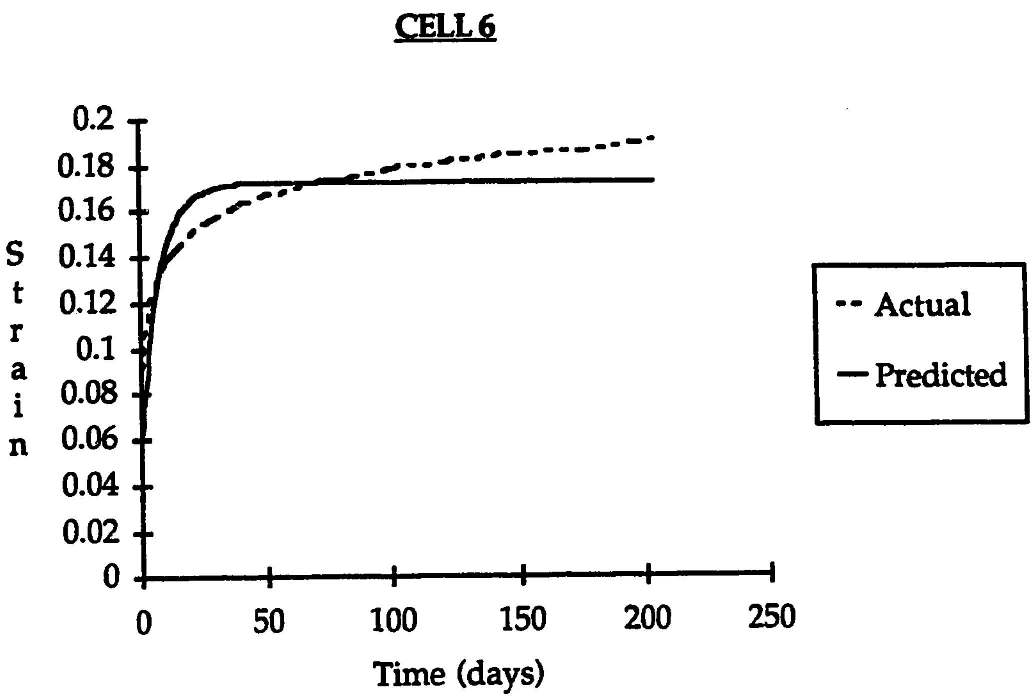

Figure B.10 - Strain vs Time (Gibson and Lo Model) - Cell 6

CELL 2

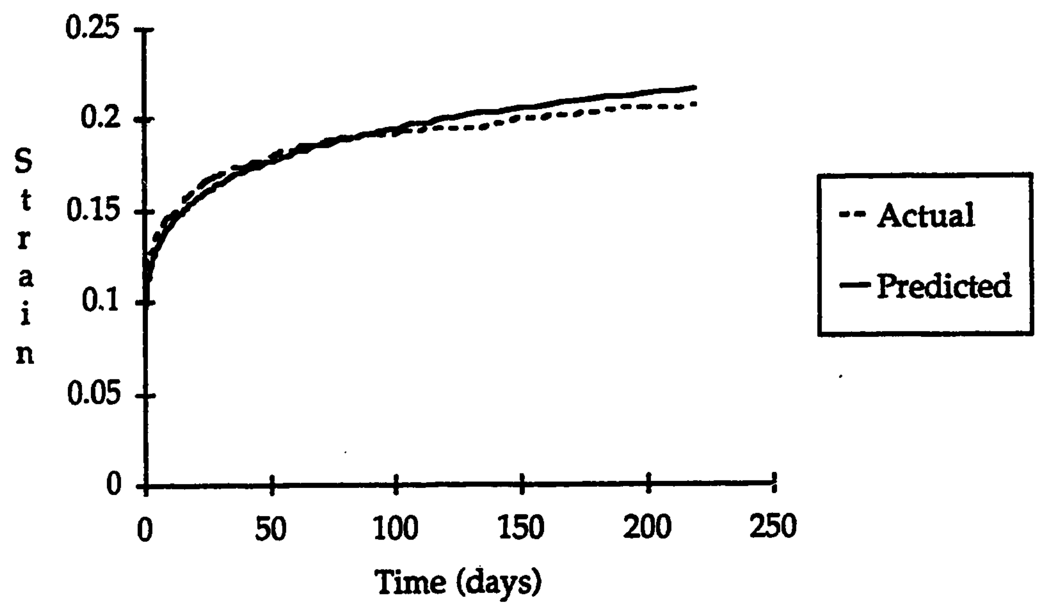

Figure B.11 - Strain vs Time (Power Creep Model) - Cell 2

CELL 3

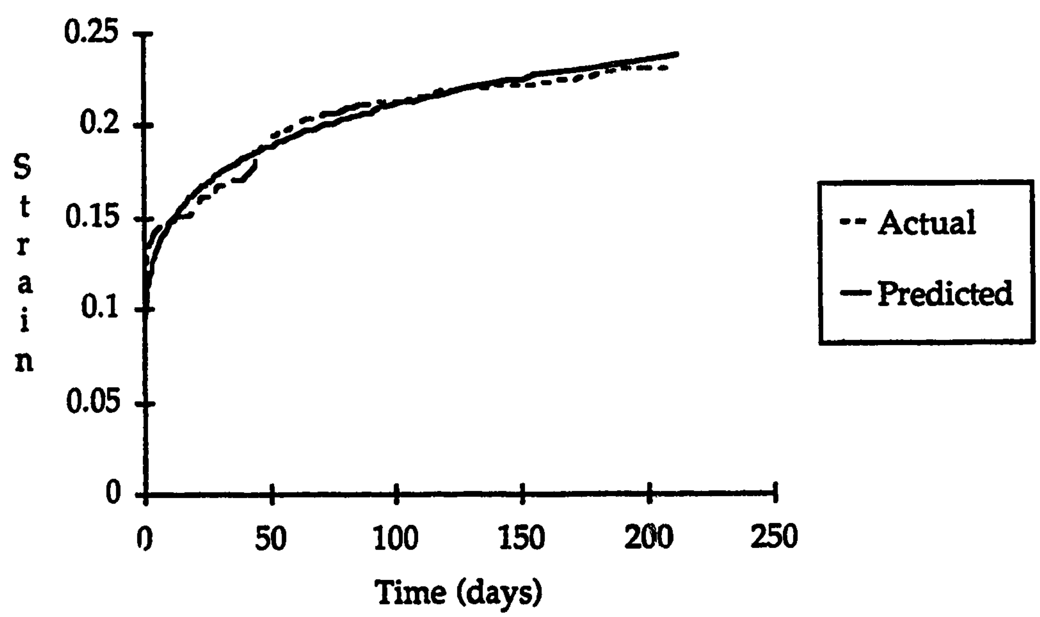

Figure B.12 - Strain vs Time (Power Creep Model) - Cell 3

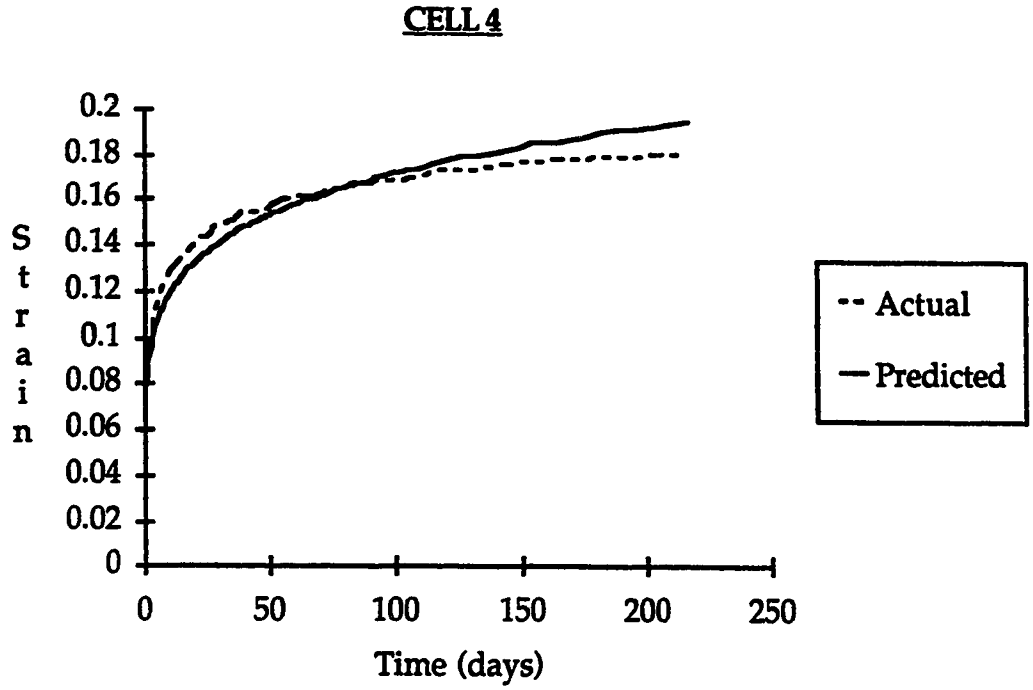

Figure B.13 - Strain vs Time (Power Creep Model) - Cell 4

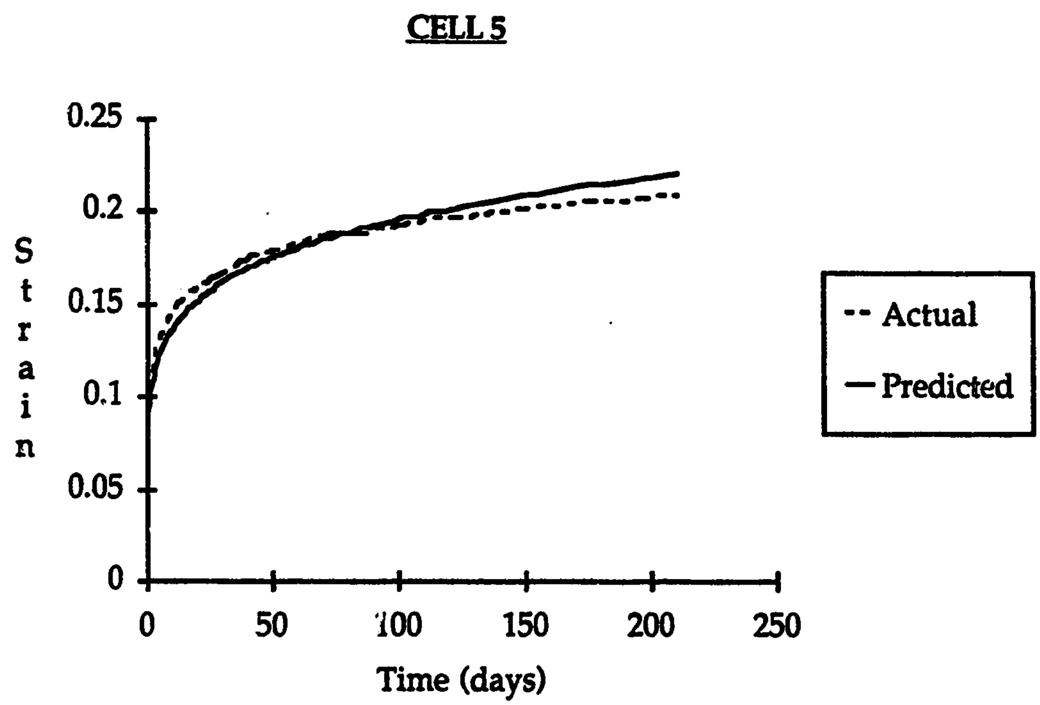

Figure B.14- Strain vs Time (Power Creep Model) - Cell 5

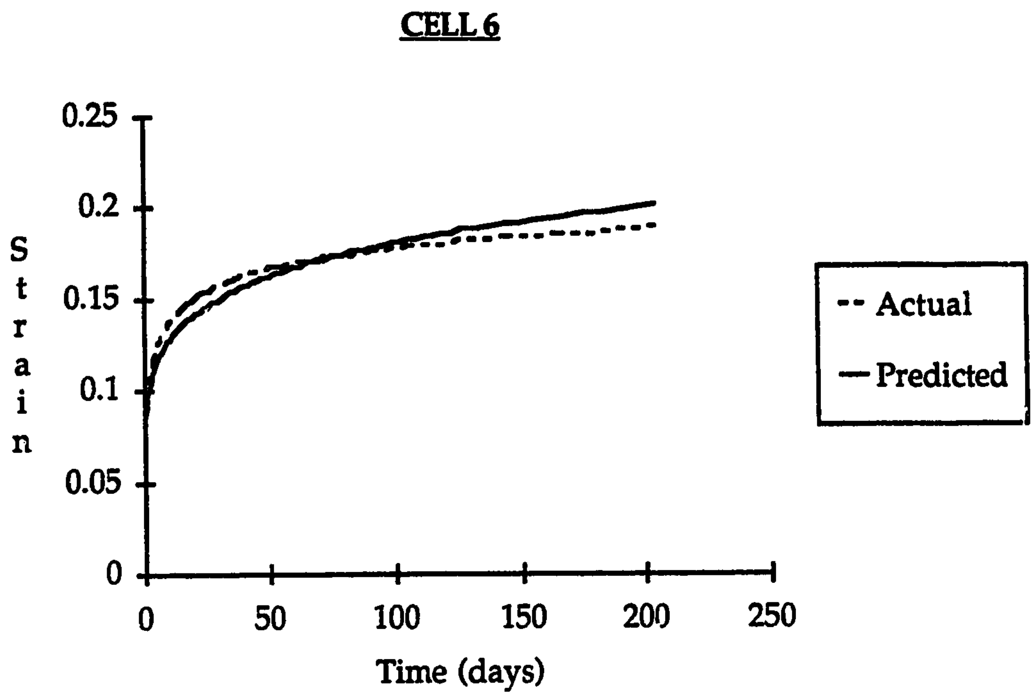

Figure B.15 - Strain vs Time (Power Creep Model) - Cell 6

APPENDIX C - COMMUNITY SURVEY RESULTS

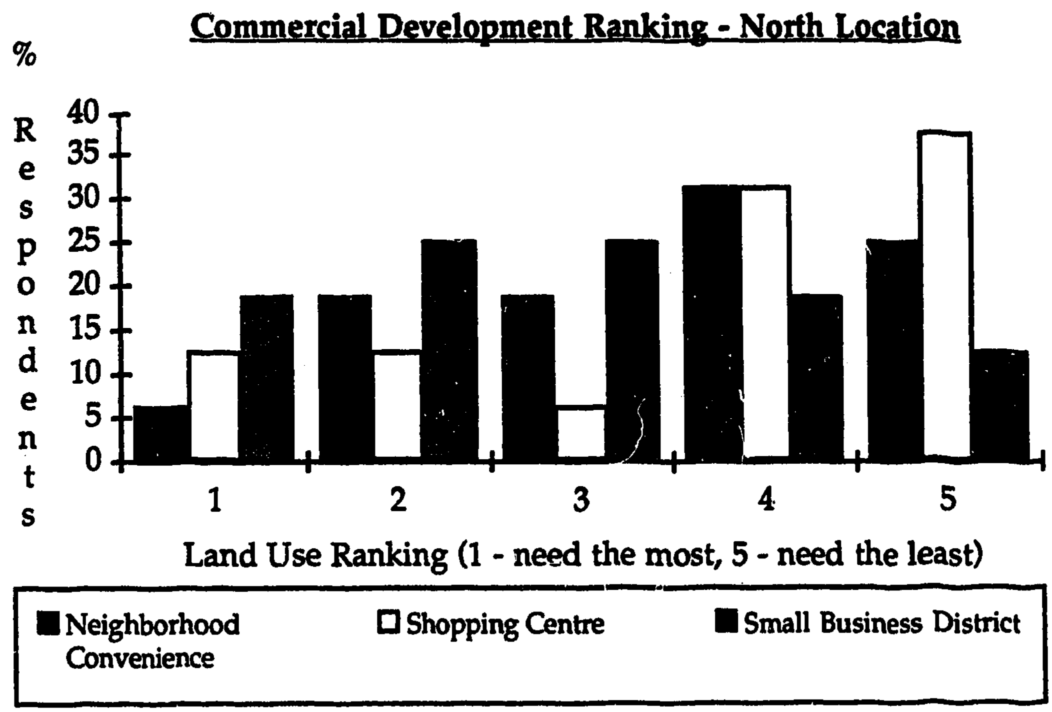

Figure C.1 - Commercial Development Ranking: North Location

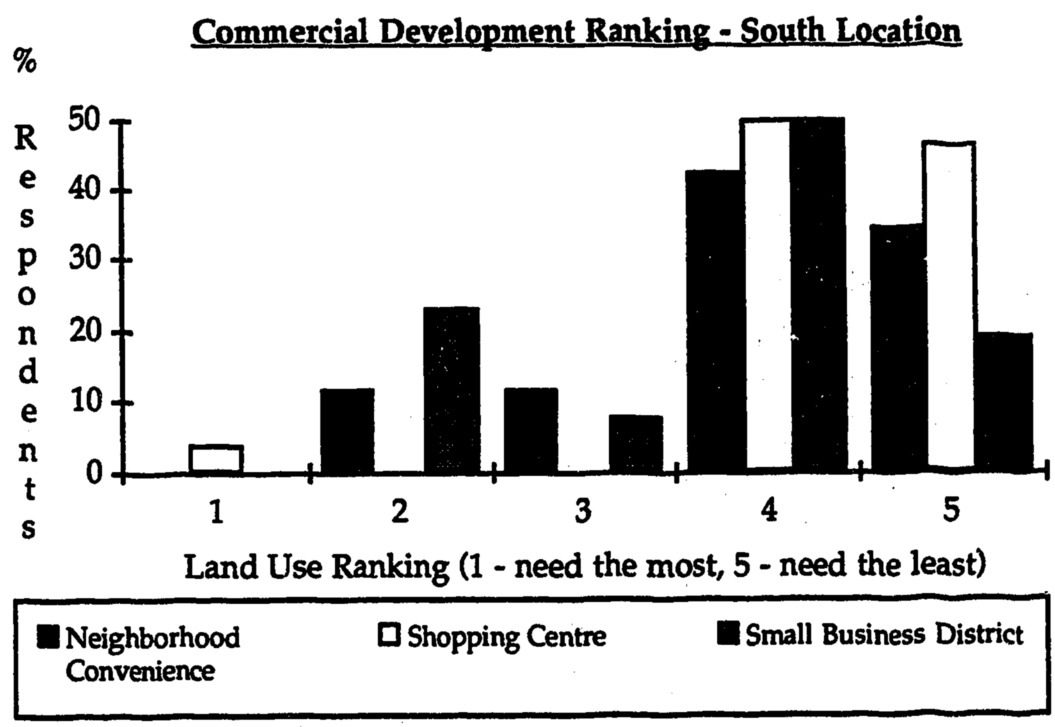

Figure C.2 - Commercial Development Ranking: South Location

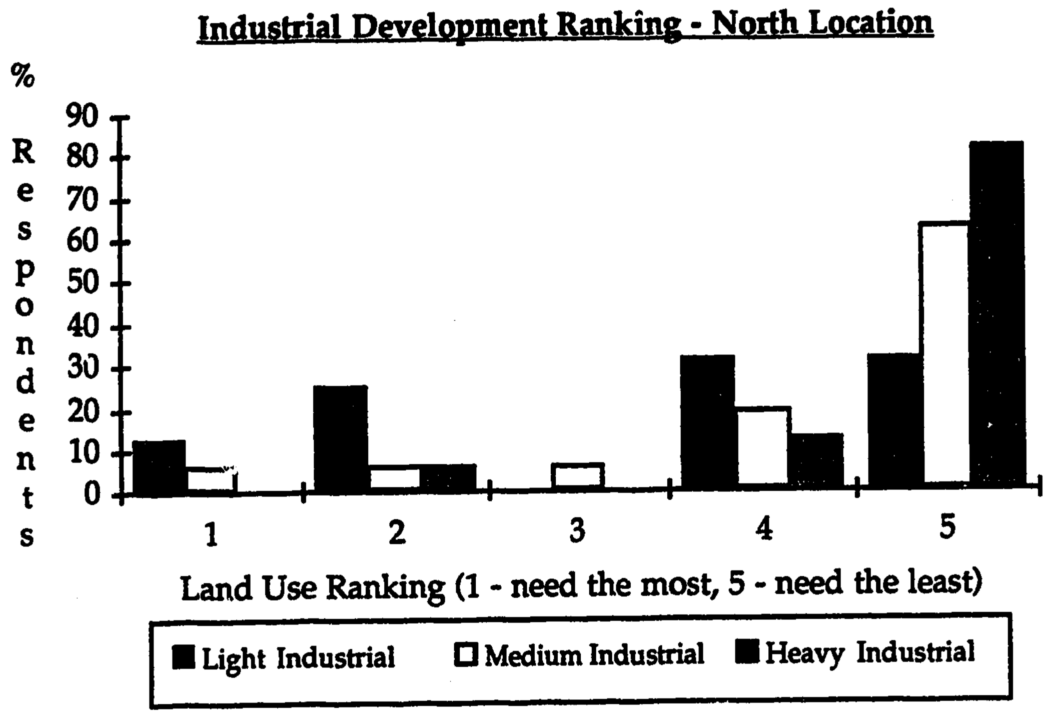

Figure C.3 - Industrial Development Ranking: North Location

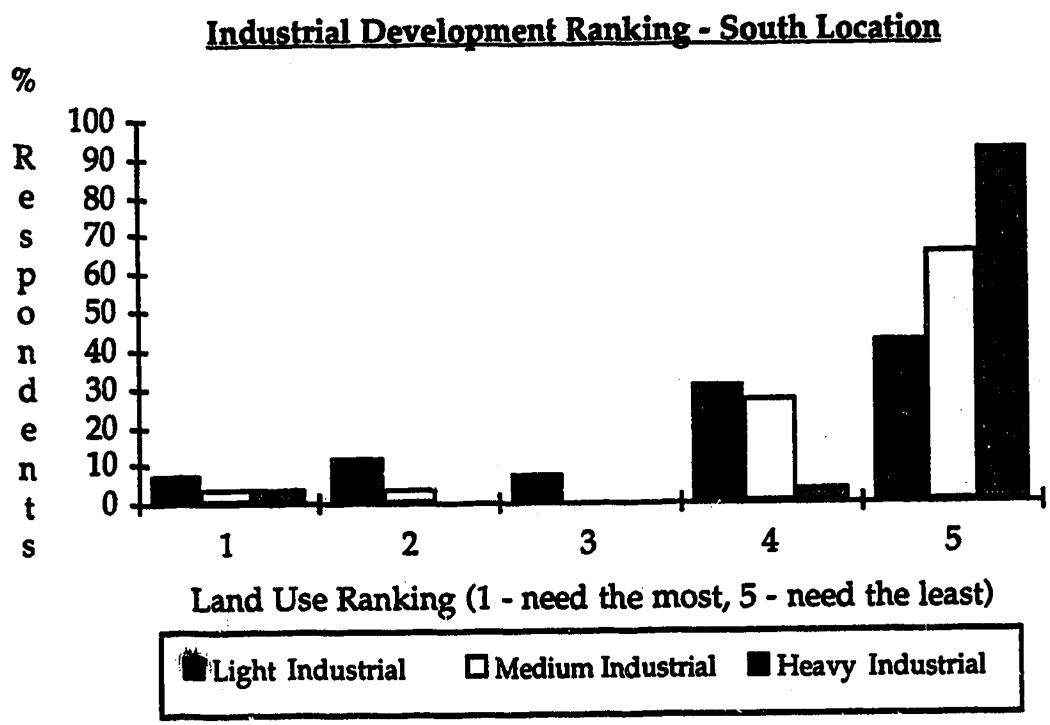

Figure C.4 - Industrial Development Ranking: South Location

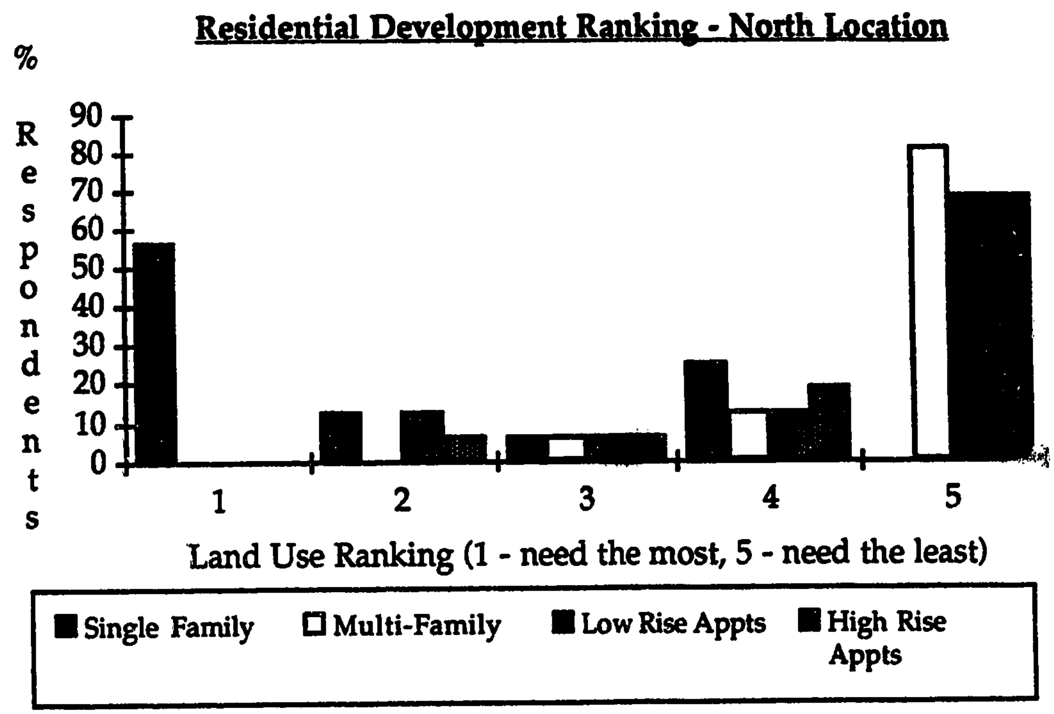

Figure C.5 - Residential Development Ranking: North Location

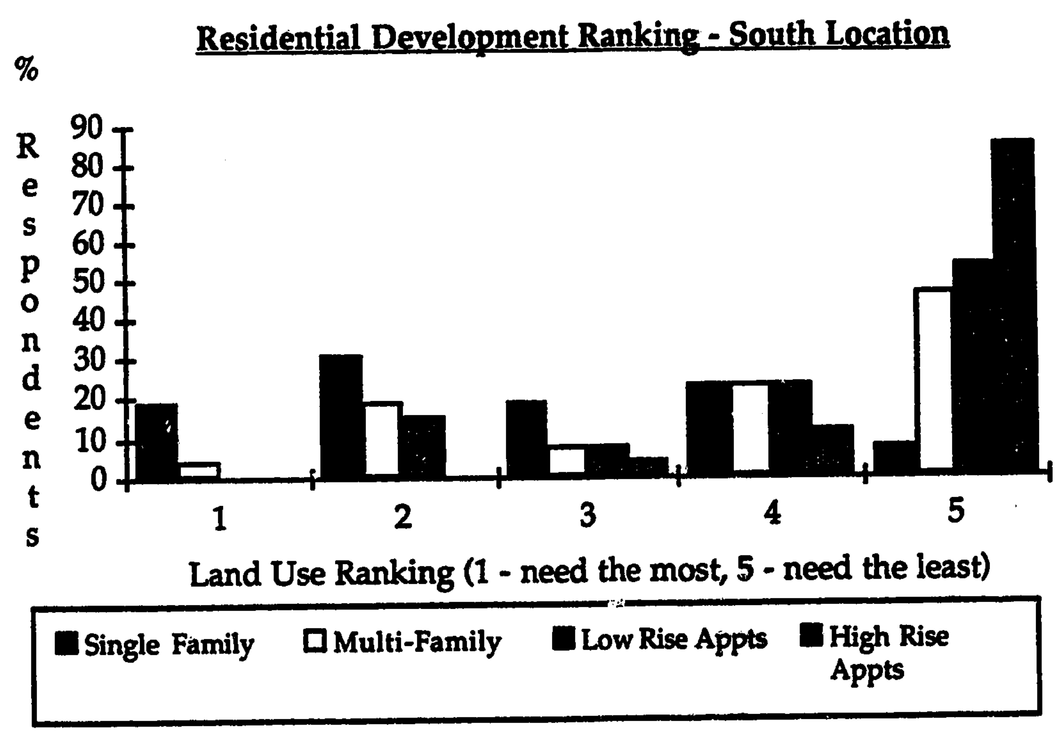

Figure C.6 - Residential Development Ranking: South Location

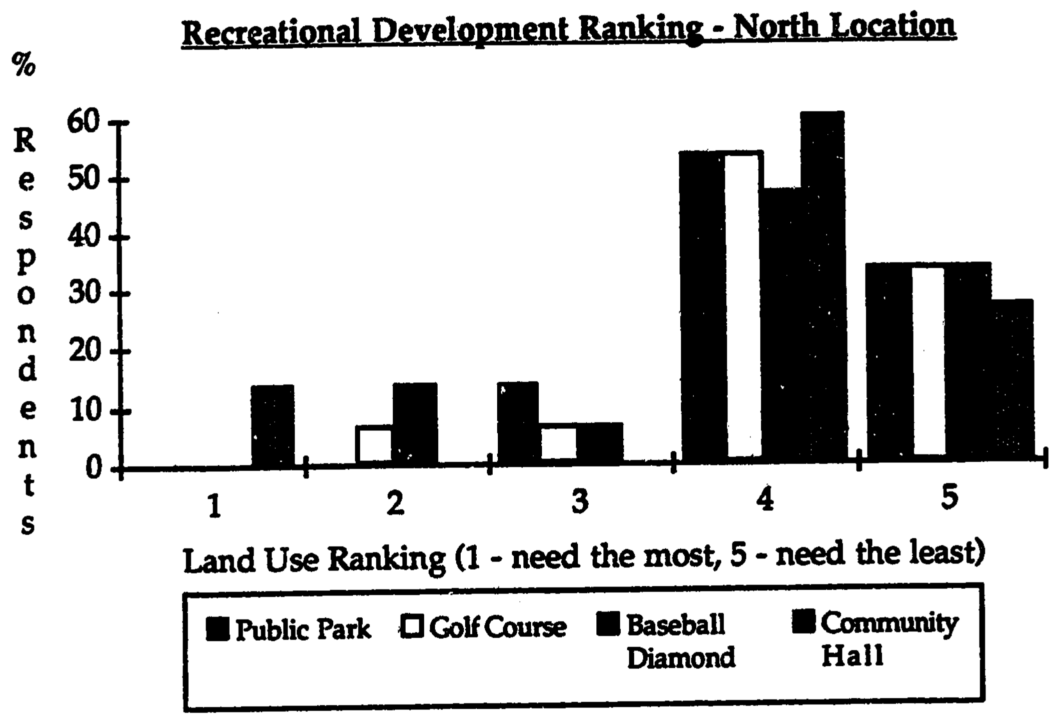

Figure C.7 - Recreational Development Ranking: North Location

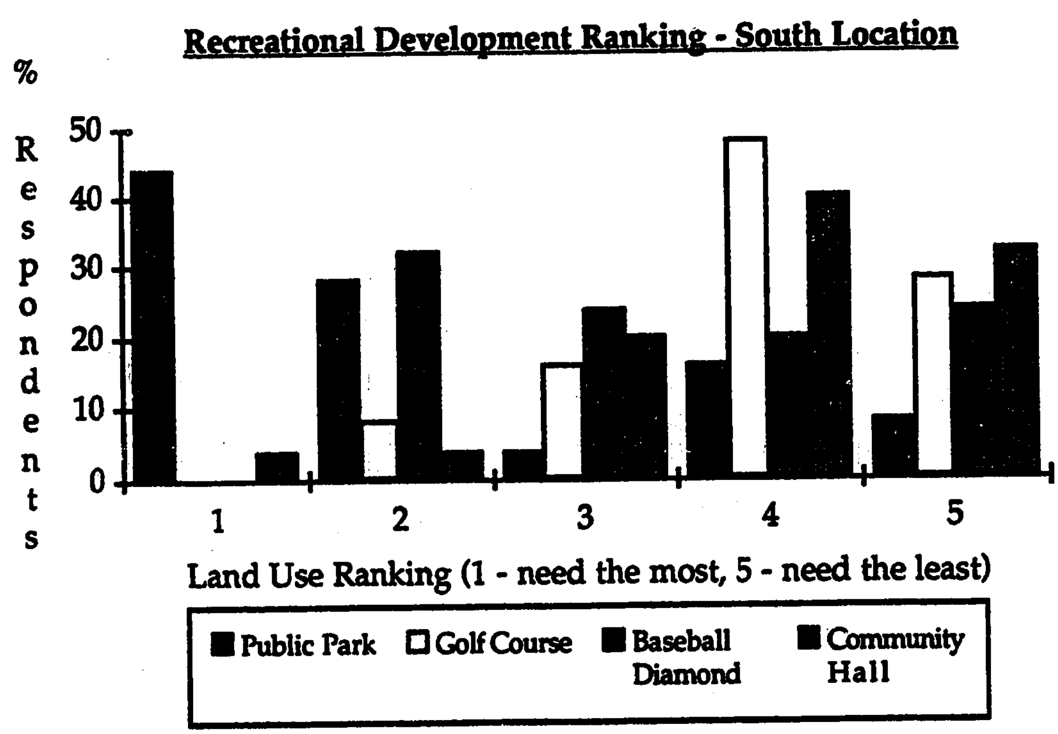

Figure C.8 - Recreational Development Ranking: South Location

APPENDIX D - COMMUNITY SURVEY

COMMUNITY LAND USE SURVEY

The Civil Engineering Department at the University of Alberta is trying to determine your views on the types of land development you prefer in your community. The information gained will be used to help to decide what types of land development are desirable for closed landfill areas.

This questionnaire requires no special technical knowledge, nor does it have any deceptive questions. You are asked only to provide "gut level" answers based on the opinions that you hold. Completion of the questionnaire is voluntary, you may skip any questions that you wish or stop at any time. All surveys will be kept confidential and results will be used only in summary form.

This research is being conducted as part of a M.Sc. thesis by Dean Wall under the supervision of Dr. Chris Zeiss. We can be reached at 492-3441 and 492-5122 respectively for any comments or questions.

The word "**landfill**" is used within this questionnaire to describe a municipal garbage disposal site.

The word "**community**" is used within this questionnaire to describe your immediate neighbourhood (roughly within 10 blocks of your house).

Please return the completed form in the envelope provided.

Thank you for your interest and cooperation.

1) What types of development do you think your community <u>needs</u> more of? (in the order of most needed to least)

(1) ____________________

(2) ____________________

(3) ____________________

2) From the needed development above, what development would <u>you like</u> to see more of in your community? (in the order of most preferred to least)

(1) ____________________

(2) ____________________

(3) ____________________

RESIDENCE QUESTIONS

Here are some necessary questions about your home.

3) Do you own or rent this house? (Circle number)

1 Own

2 Rent

4) When was this house built? (approximately) ______

5) How long have you lived in this house? ______

6) Do you live North or South of the North Saskatchewan River Valley? (Circle number)

1 North

2 South

COMMUNITY LAND USE REQUIREMENTS

The word **"community"** is used within this questionnaire to describe your immediate neighbourhood (roughly within 10 blocks of your house).

7) Please rate the following types of **land development** on the basis that you think your community **needs** more of?

(RANKING CATEGORIES - use to rank each land use option)

1 - need much more (need the most)
2 - need some more
3 - don't care either way
4 - don't really need
5 - don't need at all (need the least)

(LAND USE OPTIONS)

___ Commercial - convenience stores, shopping centres, etc.
___ Industrial - manufacturing, processing, repair facilities
___ Residential - homes, apartment buildings
___ Community Service - schools, day care, hospitals, etc.
___ Public Utilities - roads, water and sewer services, etc.
___ Recreational - public parks
___ Other (please specify): ________________

From the types of land **development** that you think your community needs, what **would you like** to see more of in your community?

1 - would like very much (want the most)
2 - would like more of
3 - don't care either way
4 - don't really want
5 - would not like at all (want the least)

___ Commercial - convenience stores, shopping centres, etc.
___ Industrial - manufacturing, processing, repair facilities
___ Residential - homes, apartment buildings
___ Community Service - schools, day care, hospitals, etc.
___ Public Utilities - roads, water and sewer services, etc.
___ Recreational - public parks
___ Other (please specify): ________________

LAND DEVELOPMENT QUESTIONS

Now that you have stated your preferences on general types of land development, here are some questions regarding specific types of development

Residential Development

8) Please rate the following types of **residential development** on the basis that you think your community **needs** more of?

(RANKING CATEGORIES)

1 - need much more (need the most)
2 - need some more
3 - don't care either way
4 - don't really need
5 - don't need at all (need the least)

(LAND DEVELOPMENT OPTIONS)

___ Single Family Residential
___ Multi-family Residential (Townhouse, Duplex, 4-plex)
___ Low Rise Apartments
___ High Rise Apartments
___ Other (please specify): ________________

From the types of **residential development** that you think your community needs, what **would you like** to see more of in your community?

1 - would like very much (want the most)
2 - would like more of
3 - don't care either way
4 - don't really want
5 - would not like at all (want the least)

___ Single Family Residential
___ Multi-family Residential (Townhouse, Duplex, 4-plex)
___ Low Rise Apartments
___ High Rise Apartments
_ Other (please specify): ________________

<u>Commercial Development</u>

9) Please rate the following types of **commercial development** on the basis that you think your community <u>**needs**</u> more of?

(RANKING CATEGORIES)

1 - need much more (need the most)
2 - need some more
3 - don't care either way
4 - don't really need
5 - don't need at all (need the least)

(LAND DEVELOPMENT OPTIONS)

___ Neighbourhood Convenience - day to day needs
___ Shopping Centre - large shopping centre development
___ Small Business District - office and service uses
___ Other (please specify): ____________________

From the types of **commercial development** that you think your community needs, what <u>**would you like**</u> to see more of in your community?

1 - would like very much (want the most)
2 - would like more of
3 - don't care either way
4 - don't really want
5 - would not like at all (want the least)

___ Neighbourhood Convenience - day to day needs
___ Shopping Centre - large shopping centre development
___ Small Business District - office and service uses
___ Other (please specify): ____________________

Industrial Development

10) Please rate the following types of **industrial development** on the basis that you think your community **needs** more of?

(RANKING CATEGORIES)
1 - need much more (need the most)
2 - need some more
3 - don't care either way
4 - don't really need
5 - don't need at all (need the least)

(LAND DEVELOPMENT OPTIONS)
___ Light Industrial - autobody repair shop, lumber yard, etc.
___ Medium Industrial - manufacturing or processing plant, distribution warehouse, etc
___ Heavy Industrial - gas plant, oil refinery, saw mill, etc.
___ Other (please specify): ____________________

From the types of **industrial development** that you think your community needs, what **would you like** to see more of in your community?

1 - would like very much (want the most)
2 - would like more of
3 - don't care either way
4 - don't really want
5 - would not like at all (want the least)

___ Light Industrial - autobody repair shop, lumber yard, etc.
___ Medium Industrial - manufacturing or processing plant, distribution warehouse, etc
___ Heavy Industrial - gas plant, oil refinery, saw mill, etc.
___ Other (please specify): ____________________

HOUSEHOLD QUESTIONS

Here are some necessary questions about your household.

11) What is your gender? M / F

12) Do you have any children under the age of 18 living in your household?

1 Yes

2 No

13) What year were you born? ______

14) What is the highest level of education that you have completed? (Circle number)

1 Grade School

2 Grade 9

3 High School Diploma

4 Apprenticeship Program

5 College Diploma

6 University Degree

7 University Masters or Doctoral Degree

8 Other ____________________

15) Please describe the usual occupation of the principal wage earner(s) in your household. (If retired, describe the usual occupation before retirement.)

Title: ____________________

Kind of work you do: ____________________

Kind of company or business: ____________________

16) What was your approximate total gross household income (from all wage earners), before taxes, in 1991? (Circle number)

1 Less than $10,000

2 10,000 to 19,999

3 20,000 to 29,999

4 30,000 to 39,999

5 40,000 to 49,999

6 50,000 to 59,999

7 60,000 to 69,999

8 70,000 to 79,999

9 Over 80,000

Recreational Development

17) Please rate the following types of **recreational development** on the basis that you think your community **needs** more of?

(RANKING CATEGORIES)

1 - need much more (need the most)
2 - need some more
3 - don't care either way
4 - don't really need
5 - don't need at all (need the least)

(LAND DEVELOPMENT OPTIONS)

___ Public Park
___ Golf Course
___ Baseball Diamond
___ Community Hall
___ Other (please specify): ____________________

From the types of **recreational development** that you think your community needs, what **would you like** to see more of in your community?

1 - would like very much (want the most)
2 - would like more of
3 - don't care either way
4 - don't really want
5 - would not like at all (want the least)

___ Public Park
___ Golf Course
___ Baseball Diamond
___ Community Hall
___ Other (please specify): ____________________

EDMONTON LANDFILLS

Here are some specific questions about landfill sites in Edmonton.

18) Both the Rundle Park Golf Course and the Millwoods Golf Course are built on old landfills. Do you consider this a good use of land in your community?

__ Yes
__ No

19) Would you have liked to have seen something else built on the landfill nearby your home?

__ Yes
__ No

If yes, what? ____________________
If no, why? ____________________

20) What was the status of the now closed landfill in your neighbourhood when you moved into this house?

__ Landfill not there yet
__ Landfill there and operating
__ Landfill closed but not developed yet
__ Landfill closed and re-developed into a golf course

21) The Clover Bar landfill is Edmonton's currently active landfill site. After it closes (in approximately 1994) it is going to be developed into a toboggan and kite flying hill. Do you feel that this is a desirable use for the land?

__ excellent use
__ good
__ neither good or bad
__ poor
__ very poor

22) What better use or uses would you prefer for the Clover Bar landfill?

----

23) What types of land uses do you feel are unacceptable or undesirable for closed landfill sites?

QUESTIONNAIRE FEEDBACK

24) How did you find the length of this questionnaire?

1 Acceptable
2 Too Long
3 Too Short

25) How did you find the questions?

1 Easy to Understand
2 Confusing
3 Average

26) Please feel free to make any additional comments that you have.

____

____

____

____

____

____

____

Thanks again for your help.