THE UNIVERSITY OF ALBERTA

A LITERATURE REVIEW OF SETTLEMENT BEHAVIOUR OF SANITARY LANDFILLS AND THEIR APPLICATION TO ALBERTA

by

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A REPORT

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Abstract

This report presents a literature review of the properties used to identify refuse and the combined behaviour of municipal solid wastes as they relate to sanitary landfills. Vertical movements in sanitary landfills evolve through a complex combination of bio-chemical decomposition, physio-chemical degredation and mechanical responses. Each of these relations have been persued in detail.

During the course of this work other landfilling techniques have been considered. Milling, baling and recycling offer distinct advantages over routine sanitary landfill techniques in terms of settlement behaviour. Economic benefits may also be realized.

The conclusions and recommendations arising from this study are; that a consistent classification scheme for solid waste composition is needed, loss of mass on combustion should become a standard test for purposes of indexing refuse, semi-aerobic sanitary landfill construction as well as leachate recycling should be investigated and that more attention be paid to milling, baling and recycling of refuse.

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

The environmental impact of a landfill of any description is so complex that the further it is studied the greater is the spinoff for further study. Before seeking to describe what occurs in a sanitary landfill in any detail, it is necessary to have an understanding of chemistry, biology, and physics. This may appear an exaggeration of the problem requirements, however, if one considers how complex a particular environment is before mankind disposes of his wastes one would see what a gross assault waste disposal is. What may have taken countless geological years to equilibrate to some extent is now impinged upon in a brief space of time by an entirely new set of conditions. This observation is not new by any means, however, if we are to try and describe the common features and differences between landfills, it serves to impress the fact that for every gross generalization made, there will likely be several sites which contradict or depart form the particular generalization. Given the identical landfill, several different sites will yield an equal number of different landfill responses. For the same landfill and same site but a different machine operator, one may observe different settlements. If one now introduces the variables in composition and placement techniques, it is possible to begin to appreciate the broad scope of the problem.

This report presents the observations and opinions of many authors on the subject of sanitary landfill settlements. Many of the reports have been generated from California and from other states which exhibit contrasting environments to that of Alberta. Therefore, while magnitudes of settlements may be presented, their relevancy to Alberta is, at best, difficult to ascertain and may not be possible. What is most important, is trying to achieve some level of uniformity in construction and to develop new techniques to minimize settlements. Although, a good understanding of the factors contributing to refuse is conveyed in the literature, only the beginnings of a practical solution to settlement predictions of untreated wastes in sanitary landfills has been developed at this time.

1.1 Background

Solid waste disposal is often overlooked by the public as a major source of pollution. Relatively efficient municipal waste collection systems have tended to remove people from the problem. As the old cliche says "Out of sight, out of mind". Nonetheless, at muncipal waste generation rates of 1.6 to 1.8 kg (3.5 to 4.0 pounds) per person daily (Miller, 1980), Alberta alone produces a volume of refuse equivalent to 2000 tandem truck loads each day. Dealing with these and ever increasing volumes, without damaging our environment, presents a major challenge to our society.

Historically muncipal refuse was dumped openly into wetlands, ravines or gullies. These sites soon attracted rodents, harboured disease and were subject to uncontrolled fires. In addition, people were plagued with wind blown paper and undesirable odours. Hence, with time incineration became a more attractive method of disposing of the waste. Later studies, however, showed this method to have several shortcomings. Most offensive of these was air pollution. Furthermore, in addition to the expense of burning the refuse, there still remained the problem of where and how to dispose of the ashes. The advent of the sanitary landfill emerged in response to these problems and now is found in widespread use throughout the world. A definition of a sanitary landfill is presented in section 1.2.

Today, our expanding knowledge of the impact of sanitary landfills and landfills in general on our environment, has prompted further studies to establish the most effective manner with which to dispose of wastes. The scientific community has devoted much time and expense to the problems of gas and leachate production and migration in landfills. More recently, however, interest is developing in the settlement characteristics of landfills and more specifically, with respect to sanitary landfills.

High land costs have created the incentive to return landfills to useful forms of real estate. At present expired sanitary landfills are frequently used as parks and golf courses. Other sanitary landfills have been successful in supporting highways (Chang and Hannon, 1976) and light structures (MacFarlane, 1970). Most ambitious, however, is the use of sanitary landfills in Morgantown, West Virginia and Meridan, Connecticut for airport developments (Glover, 1972). In order to continue to impose greater demands on sanitary landfills it is desirable to have a thorough understanding of those mechanisms controlling settlement and, if possible, the ability to predict settlement magnitudes.

1.2 Definition of a Sanitary Landfill

Many definitions of sanitary landfill appear in the literature, however, one of the most comprehensive descriptions was presented by Neely and Nicholas (1972). In their paper a true sanitary landfill must meet the following qualifications.

1. It is operated and managed by trained personnel.
2. It is fenced to keep out persons who would indescriminately dump refuse and leave it uncovered.
3. It has water service to be used to water down refuse, to reduce dust from dumping operations and when necessary, put out fires caused by combustible wastes.
4. It has adequately paved roads to the site, scales to weigh the refuse for the purpose of charging dumpers by weight of refuse, and equipment to compact wastes in place in the fill.

5. At the end of each day, the compacted waste is covered with an earth layer, to eliminate blowing of paper and eliminate breeding grounds for rats which often inhabit open dumps. Flies and vermin are also eliminated in this way.
6. Design of the landfill provides adequate drainage so that rain water percolating through the fill will not pollute groundwater resources or rivers in the area.

To provide some basis for comparison the United States Environmental Protection Agency definitions of dump, landfill, sanitary landfill and secured landfill are also presented.

Dump: An uncovered land disposal site where solid and/or liquid wastes are deposited with little or no regard for pollution control or aesthetics. Dumps are susceptible to open burning and are exposed to the elements, vectors, and scavengers.

Landfill: A land disposal site located without regard to possible effects on water resources, but which employs intermittent or daily cover to minimize scavenger, aesthetic, vector, and air pollution problems.

Sanitary Landfill: A land disposal site employing an engineered method of disposing of solid wastes on land in a manner that minimizes environmental hazards by spreading the solid wastes in thin layers, compacting the solid wastes to the smallest practical volume and applying and compacting cover material at the end of each operating day.

Secured Landfill: A land disposal site that allows no hydraulic connection with natural waters, segregates the waste, has restricted access, and is continually monitored. (Miller, 1980)

1.3 Where in Alberta

While the introduction of the sanitary landfill method of handling refuse dates back to the 1930's in North America (Yen and Scanlon, 1975), today many landfill sites still remain as open dumps. Only large urban areas have been able to provide the capital funding necessary to establish proper sanitary landfill sites. In Alberta, 90 percent of the waste disposal sites do not qualify as sanitary landfills (Alberta Environment Pollution Control Division Waste Management Branch, 1980). In response to this deplorable situation, the Alberta govenment has been participating in regional waste management schemes. These schemes involve several communities sharing a common sanitary landfill site. In this manner less land is consumed by waste disposal and, jointly, the communities can afford to maintain a sanitary landfill.

2. CHARACTERISTICS OF SOLID WASTE IN SANITARY LANDFILLS

2.1 Definition of Municipal Refuse

Throughout the literature, presentations of solid waste compositions are found. In order to develop an understanding of the significance of these, as they relate to the sanitary landfill, it is worthwhile describing what the term "solid wastes" refers to and how its various components relate to this literature review.

The legal and scientific description of "solid wastes" in the United States is *"any garbage, refuse, sludge from a waste treatment plant, water supply treatment plant or air pollution control facility and other discarded material including solid, liquid, semisolid or contained gaseous material resulting from industrial, commercial, mining and agricultural operations and from community activities but does not include solid or dissolved material in domestic sewage, or solid or dissolved materials in irrigation return flows or industrial discharges which are point sources subject to permits under section 402 of the Federal Water Pollution Control Act, as ammended or source, special nuclear, or by product material as defined by the Atomic Energy Act of 1954, as amended."* (DeGeare Jr. 1977)

It is apparent from the preceding definition that the term "solid wastes" covers a very wide range of materials. For further clarity, solid wastes have been subdivided into the following categories according to source (ASCE Manual and Reports on Engineering Practice No. 39, 1976).

Agricultural - The solid waste that results from the rearing and slaughtering of animals and the processing of animal products and orchard and field crops.

Commerical - Solid waste generated by stores, offices, and other activities that do not actually turn out a product.

Industrial - Solid waste that results from industrial processes and manufacturing.

Municipal - Residential and commercial solid waste generated within a community.

Pesticide - The residue resulting from the manufacturing, handling, or use of chemicals for killing plant and animal pests.

Residential - All solid waste that normally originates in a residential environment; sometimes called domestic solid waste.

The Bureau of Solid Waste Management (BSWM) in the United States does not entirely agree with this breakdown and chooses to group residential, commercial and institutional wastes under the term "municipal wastes". Furthermore, an additional source of solid wastes is identified as mining wastes (Yen and Scanlon, 1975).

While these definitions appear to be a tedious formality, their strict application in the future can negate any confusion in the interpretation of the literature by interested parties. Frequently, authors will refer interchangeably to municipal solid wastes as being "domestic" refuse, "residential" refuse, or even more vaguely as just "refuse", "solid waste" or "waste", without ever clarifying at the outset exactly what type of solid waste, in the strictest sense, is being referred to.

In the majority of cases, it is the author's opinion, that the unspecified compositions which are prepared on the basis of material actually recorded from working sanitary landfills can be classified as municipal refuse. However, in the majority of "test" landfills, the refuse is comprised of domestic or residential refuse and hence excludes commerical and institutional fractions.

To complicate matters further, it is prudent to recognize that most sanitary landfills may also accept pesticides, agricultural and industrial solid wastes, which can greatly influence the sanitary landfill behavior. The amount and types of such fractions are highly dependent on the regional economy.

2.2 Composition of Municipal Refuse

Different approaches by authors, to classify the various components have hindered comparisons of composition. Klee and Carruth (1970) investigated numerical methods of determining representative compositions from various size random samples. During the course of this work they found the most valuable method of classification to be that recognized by the BSWM. The following categories are used in this system.

1. Food Waste
2. Garden Waste
3. Paper Products
4. Plastic, Rubber and Leather
5. Textiles
6. Wood
7. Metal Products
8. Glass and Ceramic Products
9. Ash, Rock and Dirt

The above groups offer the advantage of; easy identification, they describe materials of a similar nature and of the various systems used in the literature, this system lends itself best to comparing previous studies.

Based on a review of papers presented by Klee and Carruth (1970), Sowers (1973), Frost et. al. (1974) and others, Table 1 is believed to be representative of the variability of the various municipal waste components. From this table it might be interpreted that in some cases municipal refuse may be comprised of as much as 60 percent inorganic materials. In fact this is very rarely the case and in the majority of the studies of municipal waste composition, cellulose accounts for 60 to 70 percent of the total waste. The ranges presented in Table 1 have been plotted on Figure 1 and typical compositions for Calgary and

Table 1 Municipal waste composition

Category	Percent of Total Weight
Food Waste	10 - 35
Garden Waste	5 - 20
Paper Products	20 - 55
Plastic, Rubber, etc.	2 - 15
Textiles	1 - 2.5
Wood	1 - 15
Metal Products	6 - 15
Glass and Ceramic Products	2 - 15
Ash, Rock, Dirt	0 - 15

Table 2 Summary of typical refuse moisture contents

(Adapted from Leckie, et. al. 1977)

Category	Moisture Content as a Percentage of Dry Weight
Food Waste	131
Garden Waste	90
Paper	33
Plastic, Rubber, etc.	19
Textiles	30
Wood	17
Metals	5
Glass, Ceramics	1
Ash, Rock, Dirt	16
Fines	48
Total Random Sample	37

California have been superimposed to illustrate the regional differences.

2.3 Indices for Municipal Refuse

Indices commonly used to describe a sample of refuse include: water content, bulk density and dry density. Table 2 presents the water contents of individual components found in fresh untreated composite samples of refuse. Collectively these components will yield average water contents 15 to 50 percent on a dry weight basis, depending on the exact combination and the climate.

Bulk densities of refuse may vary between 120 and 300 kg/m^3 as delivered and tipped, to between 600 to 1200 kg/m^3 after placement (Sowers, 1968; Bell, 1977). Relative to soil bulk densities, which may frequently reach natural densities of 2200 kg/m^3, it is apparent that refuse is extremely porous and has a low specific gravity. Bell (1977) reported average specific gravities of refuse to lie between 1.7 and 2.5.

Dry density is frequently used in reference to moisture density relationships to be consistent with soil mechanics practice. The difficulty in drying samples to yield representative water contents and dry density is to find a compatible oven temperature which will dry the samples thoroughly without burning off the organic materials. In light of this, wet densities are more frequently found in

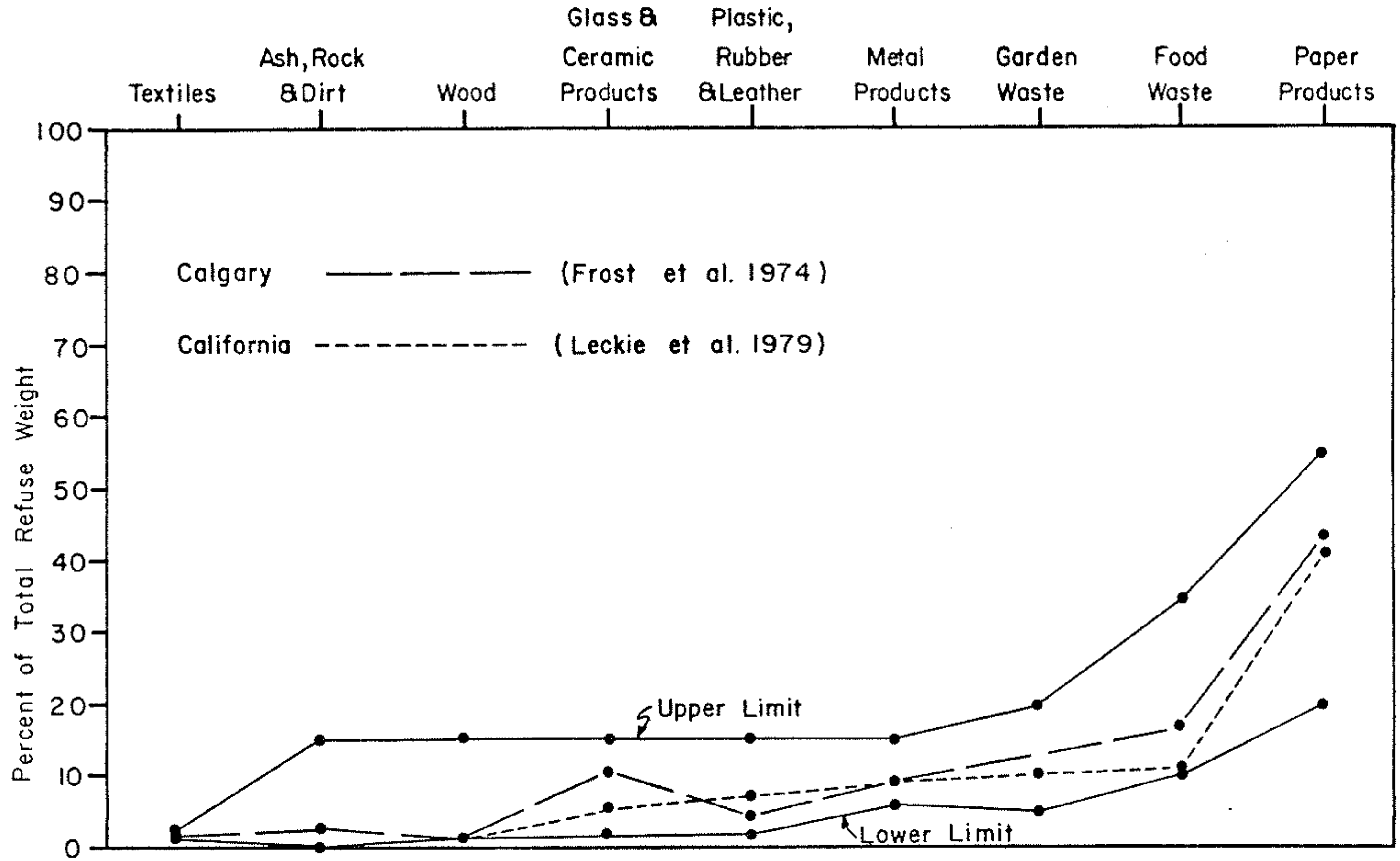

Figure 1 Typical municipal waste compositions

the literature pertaining to refuse.

An index which should be used, in addition to those above, is the loss of mass on combustion. Most refuse is comprised of at least 50 to 60 percent cellulose. Both burning and decomposition release carbon and therefore the more advanced the state of decomposition the smaller will be the amount of carbon left to thermally oxidize. Therefore the value of this index can be realized when trying to discern the level of decomposition in a sanitary landfill. Harris (1979) strongly endorsed this and performed tests on fresh and aged refuse to illustrate this reasoning. Briefly, Harris describes the test as placing a "2 gm"(?) sample of refuse in a muffled furnace at a temperature of 500°C for 4 hours. Results of these tests showed a 50 percent loss of mass for the fresh refuse as opposed to 20 percent loss of mass on the aged refuse. Other reported figures include a reduction of 80 percent to 18 percent loss of mass on combustion by Mitchell (1960) and 85 to 95 percent at the outset, to 12.9 percent combustible material after 1 1/2 years (Committee on Sanitary Engineering Research, 1959). It was not stated, by the latter two sources, how their tests were performed, however, irrespective of the method, the results do reflect the expected trend.

In spite of the apparent attractiveness of this index, it is prudent to recognize the variability of refuse and hence, comparisons between different landfills must be approached cautiously. With repeated use and detailed

3. SETTLEMENT OF SANITARY LANDFILLS

3.1 Settlement Mechanisms

Settlements within a given landfill will be controlled by material composition, environment and loading history. How settlements will manifest themselves was first clearly stated by Sowers (1973) who considered four major categories. Underlying all settlement behaviour of a municipal waste matrix are biological and physio-chemical decomposition of the waste components. The various contributions of these factors to the rate of settlement and the overall magnitude of settlement will depend upon how suitable the environment is and upon the placement method. Either self weight or imposed loading will yield mechanical settlements which reflect a characteristic response similar to soil behavior. Between decomposition and mechanical responses are settlements associated with ravelling. Ravelling is a spontaneous response of localized portions of the matrix to small changes in environment and/or loading. This settlement behaviour and those described above are persued in greater detail in the following sections.

3.1.1 Biological Decomposition

Bio-chemical decay is one of the most complex aspects of settlement behaviour. While it is known that it is a contributor to the total settlement of a landfill, a scientific formulation relating bio-chemical decay and settlements does not exist for untreated wastes. The rate of decomposition can be roughly controlled by creating an environment condusive to microbial growth. Whether or not oxygen is present in any quantity will determine what type of organism will be most active. Temperature, pH and moisture will also exhibit major control on the behaviour of the microbial population.

Stone (1975) has studied aerobic and anaerobic decomposition in some detail. As the names imply, aerobic decomposition relies on oxygen while anaerobic decomposition occurs in the absence of oxygen. Unfortunately, aerobic conditions yield the fastest rates of decomposition yet are the most difficult to sustain for any period of time. Table 3 presents the chemical formulation of both aerobic and anaerobic decomposition. The most striking features of these equations are the relative number of equations and the heat generated. Aerobic decomposition generates 12 times as much heat and because of the fewer steps involved and the associated microbials, it occurs at a much faster rate. The rapidity with which oxygen is depleted in landfills immediately after placement has been investigated by Lin (1966) in Morgantown, West Virginia. Only 1/2 percent of oxygen was reported to remain after 3 days. This observation was supported by Songonuga (1969) in a separate report in which less than 1 percent of the oxygen was found after only two days.

Table 3 Chemical formulation of decomposition (Stone, 1975)

Aerobic Decomposition	Anaerobic Decomposition
1. $(C_6H_{10}O_5)_n \xrightarrow{\text{microbial cellulase}} n(C_6H_{12}O_6)$ cellulose → glucose	1. $(C_6H_{10}O_5)_n \xrightarrow{\text{microbial cellulase}} n(C_6H_{12}O_6)$ cellulose → glucose
2. $n(C_6H_{12}O_6) + 6n(O_2) \xrightarrow{\text{microorganisms}} 6n(CO_2) + 6n(H_2O)$ glucose, oxygen → carbon dioxide, water + n(688,000 calories) heat energy	2. $n(C_6H_{12}O_6) \xrightarrow{\text{microorganisms}} 2n(CH_3CH_2OH) + 2n(CO_2)$ ethanol, carbon dioxide + n(57,000 calories) heat energy
Sum: $(C_6H_{10}O_5)_n$ $6n(O_2) \xrightarrow{\text{microorganisms}} 6n(CO_2) + 6n(H_2O)$ cellulose, oxygen → carbon dioxide, water + n(688,000 calories) heat energy	3. $2n(CH_3CH_2OH) + n(CO_2) \xrightarrow{\text{Methanobacterium omelianskii}} 2n(CH_3COOH) + n(CH_4)$ ethanol, carbon dioxide → acetic acid, methane
	4. $2n(CH_3COOH) \xrightarrow{\text{methane bacteria}} 2n(CH_4) + 2n(CO_2)$ acetic acid → methane, carbon dioxide
	Sum: $(C_6H_{10}O_5)_n \xrightarrow{\text{microorganisms}} 3n(CO_2) + 3n(CH_4) + n(57{,}000 \text{ calories})$ cellulose → carbon dioxide, methane, heat energy

Aerobic conditions have been sustained in the prototype construction of an experimental landfill in California (Stone 1975). While simple in design the method is much more labour intensive and, in addition, its applicability to seasonally colder climates such as found in Alberta has not been demonstrated. Hence, bearing in mind the location of the test, Stone reported the aerobic landfill to accomplish in 90 days what most anaerobic landfills achieve in several years. Over a year of study, the aerobic cell showed a 25 percent greater volume reduction than its anaerobic counterpart.

Anaerobic decomposition has received considerable attention and, as will be discusssed in a later section (Section 4.2), responds favourably to moisture control, pH control and seeding with sewage sludge. The practical applicability of these treatments becomes a complex issue again, as leachate control and human aspects are considered.

The most negative aspects of anaerobic decomposition include the slow rate at which it occurs and the dangerous gas by-products. Samples taken from 40 year old backfills have uncovered newspaper which can still be read. Hence, under certain circumstances degradation of refuse will take numerous generations, to reach an equilibrium condition. Methane is the principal dangerous gas produced. Structures constructed on and around landfills without proper provisions, risk the hazard of an explosion or health impairment. Nonetheless, on a more optimistic tone, methane could be tapped from the landfills of the future to be used as fuel.

3.1.2 Physio-Chemical Degradation

Physio-chemical degradation is equally complex as bio-chemical decomposition and equally difficult to associate with settlement magnitudes. Oxidation and corrosion are very active in sanitary landfills and are a major deterrent to construction on the finished fill. Combustion is generally arrested in the sanitary landfill by the use of soil cover as a preventive measure or more directly, by direct extinguishment after a breakout. Consequently, combustion contributes very little to total settlements.

3.1.3 Mechanical Settlements

Sanitary landfills under self weight or external loading will undergo elastic compression, primary consolidation and secondary compression just as soils do. However, this is where the similarities between mineral soil and refuse end. What is lacking is the stability of the individual components within the matrix and the relative consistency found in most natural soil deposits. A geotechnical comparison can be drawn if one visualizes a mixture of several soil types including oil sands, tailings, peats, clays, etc. all randomly combined. To simulate decomposition, perhaps sporadic permafrost can be introduced to this conglomeration of soils. Under such circumstances elastic compression, primary consolidation and secondary compression would also be occurring but, to predict the behaviour of such a mass would be extremely difficult to formulate and to achieve any reliable precision would be impossible.

Just as the major constituent of the configuration described above would likely be silicon, in municipal refuse the major component is cellulose. This fundamental difference alone puts refuse in a separate category of behaviour which is shared in many respects by peat. A brief review of some of the principals involved in settlement will help convey the similarities and the futility of seeking a scientific formulation for settlement of untreated wastes in sanitary landfills.

3.1.3.1 Elastic Compression

Elastic compression is a basic concept in engineering. The first introduction appears in the form of Hookes Law, that is, a linear stress-strain relationship. Further study will show various nonlinear behaviours, but basically all solids and confined fluids will exhibit some elastic behaviour. Hence, it is no surprise that refuse will exhibit some elastic behaviour, but what is important is to establish a consistent behaviour or, rather, to define an elastic modulus. Because of the heterogeneity of refuse few investigators have attempted to establish such a constant.

Moore and Pedler (1977) attempted to establish a modulus of subgrade reaction. This modulus is highly dependent on the shape and size of the loading instrument and the elastic modulus of the refuse. Results of this work are presented in Figure 2. The scatter of the data in this figure confirms the fact that it is pointless to assign a particular modulus to refuse.

Effects of density, soil cover and preload were investigated and served only to support the anticipated basic trends. Other investigations providing similar conclusions were performed by Fang et. al. (1976a) and Fang et. al. (1976b).

3.1.3.2 Primary Consolidation

Primary consolidation of mineral soils as formulated by Terzaghi is an illustration of one of the most uncompromising applications of scientific principals to a geotechnical problem. Therefore, it is with a reasonably high level of confidence that the source of primary settlements can be described. Unfortunately, primary consolidation is very brief in most practical landfills. Furthermore, nearly all the basic assumptions of the primary consolidation theory are in gross error when used to describe the settlement of a sanitary landfill and, therefore, some reservations must be exercised in applying the formulation used for soils.

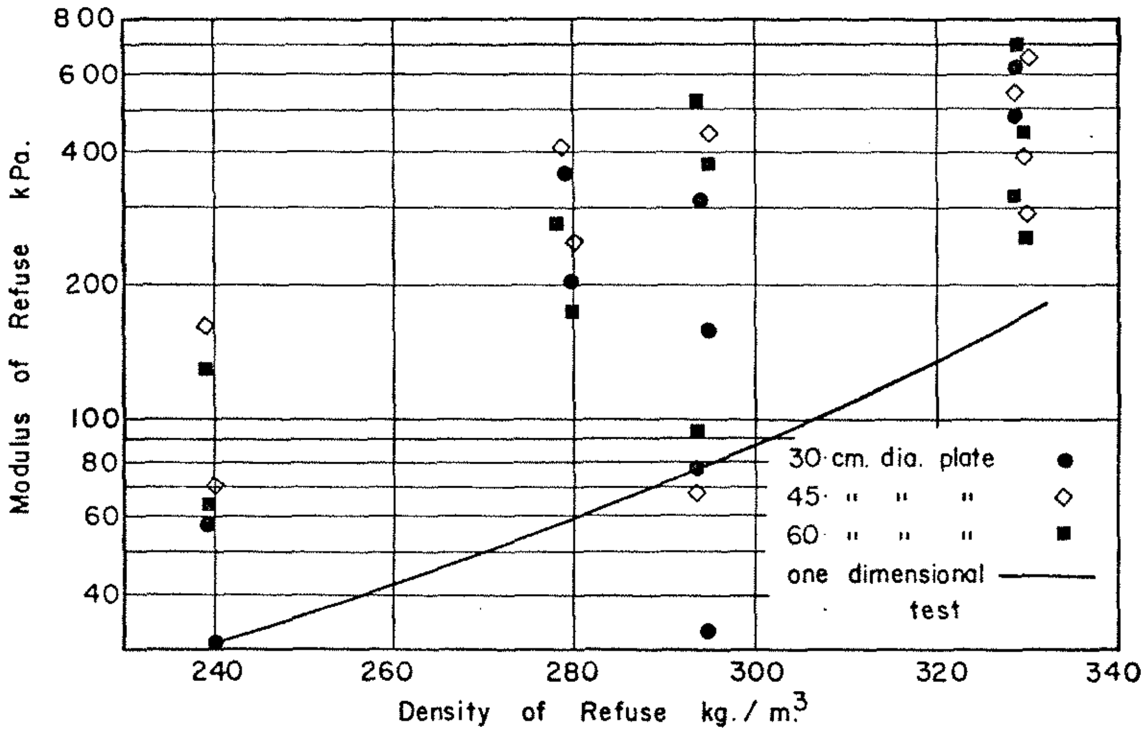

Figure 2 Moduli at subgrade reaction (Moore and Pedler, 1977)

For example, Terzaghi assumed his model to be completely saturated with water. In recent years almost all sanitary landfills have been constructed above the groundwater table and remote from any surface water. In addition, most refuse is unsaturated. Natural water contents vary from 16 to 50 percent while the saturated water content approaches that of the "field capacity" defined in Section 4.1 and reported to measure between 110 and 140 percent (Harris, 1979).

Without much additional elaboration, it is apparent that strains, velocities and stress increments are not small. Refuse, as it deposited, is far from homogeneous. Permeability, modulus of volume change and other related parameters vary drastically with stress and strain, the pore fluid will likely not be pure water and the fluid may or may not flow according to Darcy's law.

The only assumption which may have any application is that during primary consolidation strains in the matrix skeleton are controlled exclusively by effective stress via a linear time dependent relationship.

For a more detailed treatment of these departures, reference to work done by Rao (1974) is advised.

Sowers (1973) assembled data from tests by Merz and Stone (1962);Stoll, (1971); and Law (various dates), on refuse compressed in 1 to 2 metre diameter test cells and concluded that initial elastic settlements and primary consolidation occur in less than 1 month with "little or no pore pressure build-up". Just as for solids, he found the following relationship to be applicable:

$$S = -C \log[(t_0 + \Delta t)/t_0]$$

From his collection of data he assembled the graph presented in Figure 3. This work was valuable from the standpoint of understanding initial and primary settlements, however, for purposes of application to sanitary landfills constructed of untreated wastes there is limited practical value because of the difficulties in establishing the initial void ratio and establishing the relative amount of organics necessary to enter Figure 3.

3.1.3.3 Secondary Settlements

Throughout the life of a sanitary landfill the most prevalent source of settlement is secondary compression. This is not unique to refuse and has been carefully studied in geotechnical practice in the context of peat, organic silts and clays. Taylor's (1942) concept of secondary settlements was developed largely in reference to colloidal materials but is appropriate in many respects for all soils and refuse. The following concepts form the basis of this theory.

1. Primary and secondary consolidation are part of a single continuous process.

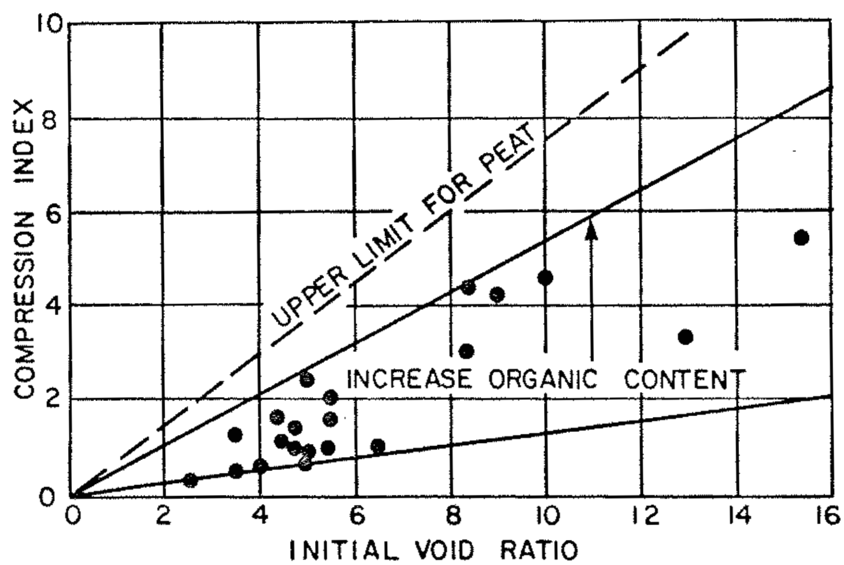

Figure 3 Compressibility of waste disposal fills

2. The seat of secondary consolidation or 'creep' effects is the gradual readjustment of the skeleton following the disruption or remoulding caused during primary consolidation.
3. The rate at which the 'secondary consolidation' proceeds is strongly influenced by the viscous effects of the adsorbed double layer. Taylor (1942)

Hence, in light of the preceding statements, Taylor believed it was fundamentally wrong to separate consolidation into two distinct events. Instead, secondary consolidation should be visualized as accompanying primary consolidation at the outset and gradually exerting more influence on the settlement behaviour as primary settlements subside. As Taylor stated, "Time lag is not due to escape of pore water alone but also due to secondary consolidation effects".

Other authors advanced this theory and described the causes of secondary settlement in colloidal materials to be, *"gradual readjustment of frictional forces, plastic deformation of the absorbed water, jumping of clay bonds and viscous structural reorientation caused by shear stress"* (Wahls 1962).

The settlement rate was also shown to be stress, temperature and time dependent (Mitchell et al, 1968). Therefore, it is apparent that secondary settlement of colloidal materials have been well researched, however, the mechanisms remain somewhat inconclusive for soils which are not colloidal.

Zimmerman et. al. (1977) felt that, since cellulose is the major constituent of refuse, an in-depth assessment of the material would help establish the source of secondary settlements. In addition to examining the molecular and cellular makeup, they presented the following description of paper and assessed it respectively:

> "Microscopic examination of paper shows two levels of structure, which can be considered as a random agglomerate of fibers, containing micropores, interwoven by a network of macropores. This suggests the possibility of a micropore structure being responsible for secondary consolidation effects of such materials. The three phase concept used for soil applies equally well to cellulose masses, except that the solid phase is not truly solid, but in the microscopic aspect, a secondary system of biological cellular structures with contained liquid and/or gas."

Barden (1968) had made a similar assessment of peats and may be considered the first to imply that secondary settlements in materials of high cellulose content may be caused partly by pore pressure reduction on a macro-micropore scale (Zimmerman, 1972). In refuse and in peat, the permeability may be reduced by several orders of magnitude and hence not only do the cellulose materials contain micropores, but as consolidation proceeds, the macropores which exist between components may be reduced to a level of micropores because of the compressibility factor involved. The fact that a 'pore pressure mechanism' may be involved at a secondary level, reinforced Taylor's perception that primary and secondary consolidation occur simultaneously.

Other factors contributing to secondary settlement are bio-chemical and physio-chemical decay, compressibility of the fibrous organics and plastic structural resistance to compression of the varous components. The relative influence of each of these factors as well as the micropore effects will be largely controlled by the degree of saturation and other environmental effects.

Bio-chemical and physio-chemical decomposition will contribute to the continued settlement by: direct loss of mass, influence on the degree of saturation and viscosity of the pore fluid and by such subtle effects as heat generation and other interactive processes. Chen et. al. (1977) investigated the effects of the rate of decomposition on the consolidation behaviour of milled refuse by solving the governing partial differential equations proposed in their paper using different values of the rate of decomposition constant. It was assumed for these calculations, that the refuse was fully saturated and that a negligible amount of liquid generation (all gases generated go into solution) would occur. Surprisingly, the consolidation behaviour was insensitive to the rate of decomposition for the full range of values reported in the literature (0.012 to 0.788 per year). Unfortunately, little evidence exists to support this observation for unsaturated conditions, which are believed to be representative of most sanitary landfills.

Bio-chemical and physio-chemical decay will generate gases in sufficient volume to significantly alter the degree of saturation under most circumstances. Zimmerman (1972) summarized the effect of saturation level under the influence of gas generated by decay as follows:

1. "The rate of response of the unsaturated models can vary greatly, depending on the degree of saturation. If saturation is below the residual value, only gas will flow, and the rate of settlement will be controlled by creep. On the other hand, for a case when saturation is greater than the residual, the fluid pressure dissipation will also affect the behaviour. In this case, the pressure dissipation is hindered by the presence of gas which may block the fluid flow channel. Also the expansion of the gas due to the relief of the fluid pressures tends to delay consolidation."
2. "Production of gas and/or pore fluid will cause a delay in the settlement response, and may even dominate the material's behaviour. If gas is adsorbed, however, the consolidation rate will increase."

It becomes apparent with further review of the literature that a destinction must be made at this time between the terms creep, secondary consolidation, secondary compression and secondary settlements. "Creep", as used in the context of the preceding quotations refers to secondary settlements which occur without reduction in pore pressures but are caused rather, by structural deformations associated with other mechanisms already discussed. "Secondary consolidation", has been used interchangeably with creep, secondary settlements and secondary compression. In view of the micro-pore levels of pore pressure reduction it becomes relevant that the term "consolidation" in its strictest sense should denote a pore pressure response. Secondary settlements or secondary compression may be and are used interchangeably to encompass the combined effects of both creep and secondary consolidation. This does not imply that both creep and consolidation must be occurring.

The more subtle effects of the bio-chemical and physio-chemical processes on secondary settlements may either increase or decrease the rate of settlement. Heat generation, for example, may have a self stimulating effect on the microrganisms which in turn may propagate further until other negative byproducts created by their own growth will offset the positive results. This type of influence has relatively little impact on any regular settlement prediction however it plays an important role in experimental studies aimed at the inducement of higher rates of decomposition.

Compressibility of the fibrous organics might be considered part of the same category to which plastic structural resistant belongs. What is important to note, is that as the various components are subjected to load by various transfer mechanisms, they will respond elastically, plastically or some variation thereof. These settlements are believed equivalent in many respects to Sower's (1973) perception of distortion, bending, crushing and reorientation of the soil particles.

3.1.4 Ravelling

Characteristically ravelling occurs after the development of a void which leaves the surrounding refuse bridging the void, in a metastable condition. With decay of the surrounding materials, a very slight change of temperature, loading or other disturbance triggers the infilling of the void space. This can then initiate further mechanical settlements or activate further degradation.

The reasoning behind treating ravelling as a separate cause of settlements is interpreted to be the total inability to predict its occurrence. Nonetheless, in the author's opinion, it is very much an interactive process between decay and mechanical effects.

3.1.5 Prediction of Settlement

Efforts to predict settlements of fills comprised of refuse have been approached in one of two ways; either curve fitting techniques or theoretical formulation. Investigators using the former technique include Tan (1971), Sowers (1973) and Rao (1974) while those taking the latter approach include Zimmerman (1972) and Chan (1974).

Tan's work represents one of the most direct forms of curve fitting possible and is applicable to all materials showing large secondary settlements. Briefly, Tan proposes that all settlements after the dissipation of excess pore pressures can be described by the relation:

$$t/s = Mt + C$$

where t is time in any unit, s is settlement in any appropriate unit, M is the slope of the t/s vs. t graph on an arithmetic scale side and C is the ordinate intercept.

The magnitude of C is shown to decrease with increasing primary settlements and serves no other purpose than to act as an index. The value of M is that if its inverse were taken the ultimate settlement is directly given. Tan presents several comparisons and shows that, for practical purposes, this technique can be a valuable tool. In a later paper, Tan (1977) describes the successful application of this method to a site underlain by refuse. As simple as this approach is, it deserves further study and application to other sites to develop a higher level of confidence on the part of the user. The problem with this approach is that any predictions for a particular site prior to construction require an accurate laboratory simulation of the field settlement behaviour. As will be mentioned in each of the following cases, this is perhaps the major stumbling block in predicting settlements of any waste landfill.

Sowers (1973) took a different approach, assembling what little data was available and then applying some fairly gross assumptions. As has been shown in Section 3.1.3.2, Sowers considered the standard void ratio-effective stress relationship to describe accurately initial elastic compression and primary settlements. Following in this same vain, he used the following modified version of Terzaghi's equation for primary settlements to model secondary settlements.

$$S = \alpha \log (t_2/t_1)$$

The coefficient α is, in effect, a "variable constant" which Sowers related to void ratio. This relationship is shown in Figure 4. From this figure Sower suggested that for conditions most unfavourable to decay α is 0.03 (E_0) while for favourable conditions α is 0.09 (E_0). Subsequent to this work, Yen and Scanlon (1975) produced a further report which presented observations of sanitary fill settlements under self-weight which compared well with Sower's limits.

While the formulation does expose some trends, it does not provide a precise method for solution of potential settlements. Major oversights are load increment ratio effects, depth of fill effects, and duration of loading. These influences have been discussed in the preceding paragraphs. The evaluation of the initial void ratio (E_0) is a difficult task and hence it is problematic even to enter the graph of α versus Eo.

Rao investigated the various theoretical approaches conceived to predict secondary settlements for soils and tried to match field observations with one of the theoretical curves. Two techniques were used for matching purposes. The first, was a laboratory program developed to

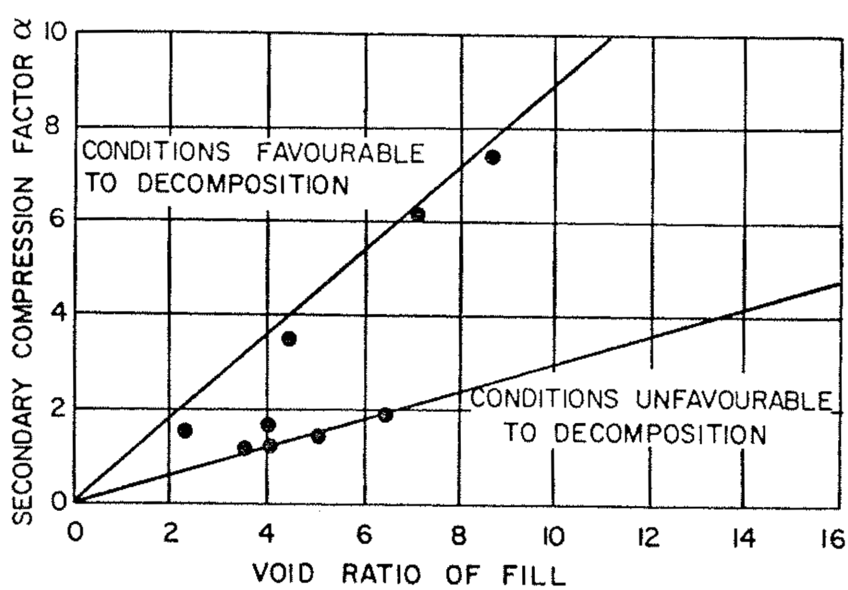

Figure 4 Secondary compression of waste fills

simulate landfill behaviour. From this, the various laboratory produced parameters were derived and matching was attempted. Failure of this first technique led to the second technique which was a simple back calculation of the necessary parameters for each theory from the field observations. Using this latter technique Rao concluded that the Gibson and Lo (1961) analysis best modelled settlement in a refuse landfill. The poor correlation between the predicted and the observed field behaviour using the laboratory derived parameters was explained in terms of load ratio, load duration and load intensity effects as well as contrasting environments between the field and laboratory settings. Other causes of differences not cited include level of saturation, placement methods and aging effects. While Rao had aged the samples, it is doubtful that a suitable match would be achieved. It is the author's opinion that Rao's conclusion that "the settlements of refuse landfills are best modelled by Gibson and Lo's theory", is based on only circumstantial evidence. Given another site, an entirely different analysis may have given a better correlation. Therefore, because of this low level of confidence the author will not detail the Gibson and Lo theory.

Zimmerman (1972) developed a mathematical model for settlement of milled refuse. In a later work printed in 1977, with Chen and Franklin, Zimmerman and Chen combined their work and performed laboratory experiments to investigate its accuracy. Briefly, the model encompasses saturation effects, compressibility changes, behavior of materials with void ratios greater than one, permeability varying with time, finite strains and bio-chemical decomposition. Formulation of this model relied heavily on input derived from observations of peat which was described as being similar to milled refuse. For more detail the reader is referred to the dissertation by Zimmerman (1972). From the preceding laboratory work, it was established that, for fully saturated conditions, good agreement was found between the laboratory and theoretical curves. What remains to be shown is whether the proposed laboratory technique accurately models a milled refuse landfill where unsaturated conditions may dominate.

Of the studies presented only those reported by Sowers and Tan may have any direct application to "sanitary" landfills. Rao investigated the responses of untreated waste without soil cover and Chen and Zimmerman directed their studies towards milled refuse. Collectively however, certain principles were established which are believed to be independent of the specific treatment and placement technique. Each of the principles or observations have been briefly mentioned as they applied to each approach to settlement analysis. Following is an expanded description of each principle.

1. Load Increment Ratio:

Depending on the value of the load increment, refuse can have diverse types of time deformation curves.

a. "For both raw and aged refuse, a large amount of secondary compression per unit of total compression is associated with a smaller load increment ratio." (Zimmerman, et al, 1977).

b. "A large rate of secondary settlement is associated with a large load increment ratio." (Zimmerman, et al, 1977)

c. For load increments close to 1 an almost linear percent compression versus log time curve is achieved in untreated refuse (Rao, 1974).

d. "For small load changes ($\Delta p/P \leq 0.5$), creep will dominate the predicted response while for large changes ($\Delta p/p \geq 1.0$), the pore pressure dissipation response will dominate. For intermediate cases, the response will be a composite of the two." (Zimmerman, 1972)

2. Age:

Aged refuse is more susceptible to greater secondary settlements than fresh refuse. However, Yen and Scanlon (1975) reported "the rate of settlement appears to decrease linearly, proportional to the logarithm of medium fill age.

3. Depth:

Settlement decreases with increasing depth of fill to a certain limit after which changes become insignificant. Yen and Scanlon (1975) attributes this to effects of aerobic decomposition. After roughly 30 metres only anaerobic decomposition is likely.

3.2 Influence of Natural Soil Components

Natural soils influence sanitary landfills in several ways. For example, from the foundation perspective, the choice of a fine-grained soil over a coarse-grained soil will determine the relative settlement attributable to the foundation soils under the weight of the sanitary landfill and settlement of the sanitary landfill under self weight. More important however is the suitability of the soil for controlling leachate migration.

Sanitary landfills should be constructed on carefully prepared fine grained soils with appropriate consideration given to the location of the groundwater table. Historically landfill or dumping sites have been chosen purely on the basis of economics, consequently, low wetlands were prime candidates for such use. In retrospect, many such sites have done irreparable damage to the environment. Several controversial sites still exist at major centres in Canada. In Vancouver, British Columbia one landfill has been constructed on a peat bog (Miller, 1980) and in Alberta, Edmonton's present landfill site is constructed in a depleted gravel pit. Attempts to prevent pollution of the North Saskatchewan River have been made at considerable expense (Frost et. al., 1974).

Results of a survey of landfill sites in the United States presented by Stone (1961) revealed 35 percent of waste disposal sites to be founded on clay, 34 percent on sand, 18 percent on sand and clay and 13 percent on other soil types. Seventy-nine percent of the sites were within 6.1 metres of the groundwater table and 27 percent were at, or within 1.5 metres of the groundwater table.

The choice of a fine or coarse grained soil for daily or finishing cover can also have a strong impact on the sanitary landfill. The primary purpose of soil cover is to control access of rodents and keep paper and other objects from being swept away by the wind. In this regard, almost any type of soil is adequate, however, if a choice exists to which type of soil is to be used, then the designer must decide whether to encourage or discourage decomposition in the sanitary landfill. Coarse grained soil will enable free access of water and permit gas movements while fine grained soils will behave just the opposite. Climate shares an equally important role and can govern the rate of decomposition to a large extent irrespective of the soil cover.

To illustrate how slow decomposition can occur, Stone (1975) described the excavation of one landfill in which recovered newspaper was still readable after 40 years. Eliassen (1942) and other authors reported similar finding in landfills which were 25 years old. If the designer is deliberately trying to prevent decomposition or leachate production, fine grained soils are most suited. Continual monitoring should be performed at such landfills to ensure dessication cracks are filled and to maintain positive drainage away from the fill.

Fine grained soils do not dictate the rate of decomposition. Active decomposition can be achieved by installing the appropriate plumbing. For example, Hanashima et. al. (1981) describe the design of a "semi-aerobic" landfill in Japan which utilizes leachate collection tubes both to collect leachates and circulate air through the landfill.

The influence of uniformly mixing soil with refuse have also been investigated (Committee on Sanitary Engineering Research, 1959). It was concluded that the marginally improved densities were greatly offset by the much lower capacity of the site to retain refuse.

3.3 Measures of the Degree of Stabilization

"Stabilization of sanitary landfills is the result of a complex act of physical, chemical and biological processes. In practice it is usually desirable to quantify the rate of stabilization and possibly predict the time required for landfill site management. A landfill is considered stabilized when the following criteria are met:

1. Maximum settlement has occurred;
2. Negligible gas production is occurring; and

3. Leachate does not constitute a pollution hazard (Leckie, 1979).

Monitoring of these criteria will yield information concerning the potential for further activities within the landfill.

3.3.1 Direct Methods

Throughout the life of a sanitary landfill, the environment within the landfill will undergo many changes. In an attempt to assess the effects of various trial treatments of sanitary landfills, many methods of establishing the stability of sanitary landfills have been devised. Although settlement magnitudes may be of primary interest, it is also prudent to gather as much information as possible on the state of decomposition. With the entire scope covered it is then possible to assess the potential for further settlements.

In terms of direct surveys, settlement monuments or platforms, elevation points and profiles are popular methods of evaluating settlements. Currently the Alberta Environment is also studying the prospect of evaluating settlements quantitatively via air photo interpretation methods.

While settlement magnitudes are site specific, it is of interest to note some of the recorded observations. It is important to realize, however, that the majority of reported studies have come from the United States and more specifically from the State of California hence, the relevance of the observed magnitudes to Alberta is difficult, if not impossible, to assess in light of the many complex variables involved. Furthermore, frequently the only recorded magnitudes and rates of settlement are under controlled environments which have little application in Alberta.

Settlement magnitudes are reported either in terms of direct movements of the landfill surface or in terms of volume reduction. This division has developed from an initial interest in the most efficient method of reducing the volume of refuse rather than the magnitudes of surface settlement. Furthermore, surface settlements may be so erratic that there is little practical value in reporting them. In light of this, Table 4 presents calculated values of volume reduction.

Average initial volume reductions, relative to trucked volume, are calculated at 55 percent for the given table. In-place volume reduction, measured after two years, averages 12 percent of the original "in place" volume. These figures would indicate, in very rough terms, that given a depth of loose refuse equivalent to 6.1 metres would compact to 4 metres during placement and subsequent compaction. Two years later a further settlement in the order of 0.45 metres would occur. Stone (1961) reduced data presented by the American Society of Civil Engineers, Solid Wastes Research Committee in a separate survey conducted in the United States and found similar results to those presented by the

TABLE 4 SELECTED SANITARY LANDFILL DATA
(26th Report of Committee Sanitary Enginering Research, 1959)

City	Initial Percent Volume Reduction	Depth of Fill Per Lift (metres)	Cover Soil Depth (metres)	Percent In-Place Volume Reduction (2 years)
Berkeley, Calif.	50	3.05	0.46	-
Burbank, Calif.	52	0.91	0.23	1.5
Fresno, Calif.	56	4.75-8.23	1.22	-
Lodi, Calif.	73	3.66	0.61	-
Stockton, Calif.	52	5.49	0.61	-
Wetsonville, Calif.	54	4.88	0.01	-
L.A. County, Calif.	50 to 56	--	--	-
Montary Park, Cali.	23	6.10	0.31	10-25*
Mandan, N.D.	75	1.52-1.83	0.31-0.61	0-18
N.Y. City, N.Y.	50	--	--	33
Richmond, Vanc.	--	1.83-4.57	--	5.10
Seattle, Wash.	68	6.10	0.31	25
Average of 58 Cities	--	1.22-6.10	--	33

*AFTER FIVE YEARS SETTLEMENT

Committee on Sanitary Engineering Research. More precisely, Stone reported volume reduction magnitudes from approximately 70 percent of the surveyed sites, to fall between 50 and 66 percentof the inplace volume. However, the significance of these figures was somewhat diminished by the fact that no mention was made regarding how long after placement these volume reductions were noted.

3.3.2 Indirect Methods

Glover (1972) investigated the stabilization of sanitary landfills by injection grouting of fly ash. To assess the degree of stabilization of the reported landfill site he used several indirect methods. While these techniques indicate little concerning magnitudes of setttlement, they do offer a useful alternative for evaluating a sanitary landfill performance. The measured temperature, gas and leachate production all reflect the activity of decomposition underway within a given landfill.

Temperatures are a strong indicator of the presence of aerobic or anaerobic decomposition. The most effective means of obtaining the temperature data is to install thermistor strings, with the thermistors spaced closely in the top 3 metres becoming increasingly spaced with depth. If possible records of the fill and air temperature should be obtained hourly for the first 4 months (Fungeroli and Steiner, 1971) to allow a meaningful interpretation. As noted in Section 3.1.1, aerobic decomposition produces the greatest amount of heat and is most prevalent shortly after completion of construction when oxygen is abundant. Some of the reported temperature responses are presented in Table 5.

In Table 5 it is apparent that temperatures in some sanitary landfills may exceed the ambient air temperature by as much as 33°C. In most sanitary landfills Pohland (1975) anticipated a general pattern. High temperature will prevail at the outset for a period of approximately 1 week and then will show a slow decline. After some poorly defined length of time, the temperatures will take a suddent drop and continue to decline slowly. Even after a period of years the air-fill temperature differences will not close. Pohland (1975) has devoted some study to this effect and attributes this pattern to changing microbial population with changing gas and pH levels within the landfill.

Monitoring the rate of gas production and the composition of the gases will yield data concerning the composition of the refuse, the water content and the age of the refuse. Glover (1972) presents a detailed account of these relations and hence these relations will not be persued here. However, it is to be noted that gas monitoring by itself is of marginal value, but, if gases are to be monitored as a safety precaution to check the migration of gases into neighbouring developments, then little extra effort is required to install a few additional monitoring instruments at the fill site.

TABLE 5 TYPICAL TEMPERATURE BEHAVIOUR REPORTED IN THE LITERATURE

Author	Time After Completion	Depth m	Refuse Temperature	Air Temperature
Glover, (1972)	7 days 2 months	1 1	71 60	
Glover, (1972)	24 hours		38	
Sowers, (1973)			33°C above ambient	
Committee on Sanitary Engineering Research, (1959)	1.5 years		29.4 - 50.0	11.1 - 17.2
Pohland, (1975)	1 week shorterm longterm		68 60 30	
Pohland, (1975)	"initially" longterm	1 - 2.13 1 - 2.3	50 - 70 25 - 40	10 - 20 10 - 20
Merz and Stone, (1962)	Maximum		49 - 42	
Merz and Stone, (1966)			87.7 (aerobic)	
Committee on Sanitary Engineering Research, (1958)			8.3°C above ambient	

A major problem facing the actual monitoring is anticipating the locations of greatest gas concentrations. The degree of sophistication used to predict gas migration ranges from finite element techniques (Hanashima et. al., 1981) to establishing iso-concentration lines via collecting field data (ASCE Manual, 1976). Techniques used to obtain this data include drilling small wells and using inverted gas capturing devices, installing synthetic tubes in the landfill or measurement by portable gas metres. In the laboratory the most effective tool in gas analysis is the gas Chromatograph.

A further measure of decomposition comes from the analysis of intermediate metabolic products of fermentation such as volatile fatty acids and alcohols. Glover (1972) was able to illustrate the effects of fly ash on accelerating anaerobic decomposition by correlating decomposition with volatile short chain fatty acids. Glover was also able to find good correlations between total organic carbon content in leachates and decomposition and suggested further studies be conducted to support this finding.

4. MINIMIZATION OF SETTLEMENTS

The practical application of any scientific solution to settlement prediction of sanitary landfills is not yet available. As discussed in Section 3.1.1.1, authors may have matched measured settlements with theoretical or empirical curves but none have successfully predicted what settlements would occur prior to measurement. The complexity of the interaction between variables and the large number of variables in a landfill of untreated waste defies practical solution.

This opinion is not meant to discourage construction. With the application of some of the treatments discussed in the foregoing sections and a joint effort on the part of the structural engineer to make the intended design flexible, settlements can be accommodated.

Settlements can be reduced in a variety of ways and at different stages in the development of the santiary landfill. The following sections present each of these techniques and their relevance to Alberta.

4.1 Initial Placement

Regardless of the geographical location of a sanitary landfill, compaction is an effective means of achieving volume reduction. Throughout the surveyed literature initial volume reductions of 50 percent are frequently quoted after compaction. The relative success achieved by this technique will depend largely on the composition, water content and compactive effort. Harris (1979) produced the moisture density curves shown in Figure 5, for milled refuse and found optimum water contents to range from 50 to 70 percent. While a direct application of these values to untreated wastes is not justified, the trend is indicative. Rao (1974) produced the moisture density curves for untreated wastes shown in Figure 6. Once again a trend was established, however, the actual results have little practical value. Earlier reports by Merz and Stone (1962) and Stone (1961) also indicated that the addition of water benefits compaction.

The most important issues, however, remain the control of gas and leachate within the landfill. Maximum methane generation develops at water contents in excess of the natural water content of the refuse and after the addition of a further volume of water, leachates will become "excessive". The water content at which these leachates will become excessive has been defined as the field capacity. This term refers to the maximum amount of liquid which the material can retain in the gravitational field without downward percolation (Harris 1979). For untreated wastes this water content may reach values of 113 percent for static conditions, however, during actual placement it is anticipated that the field capacity would be much lower because of the immediate disturbance of the compacting equipment.

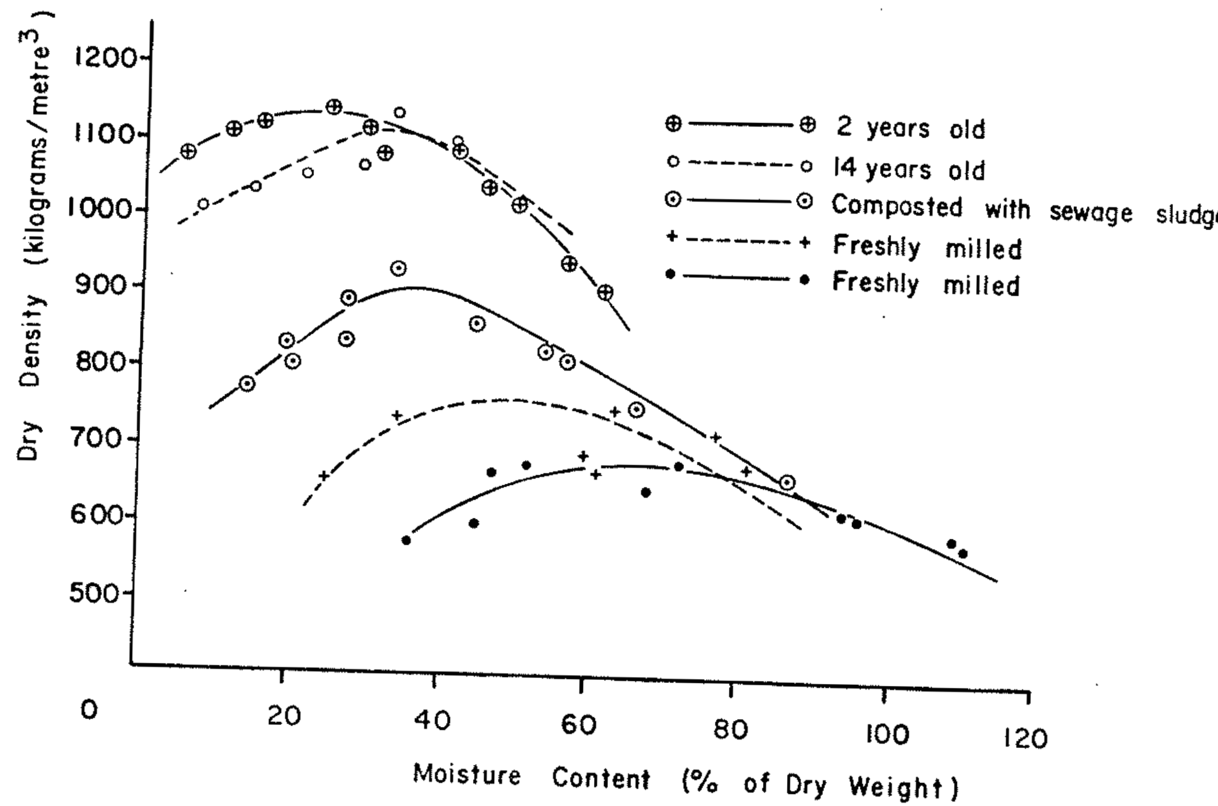

Figure 5 Compaction tests on milled refuse

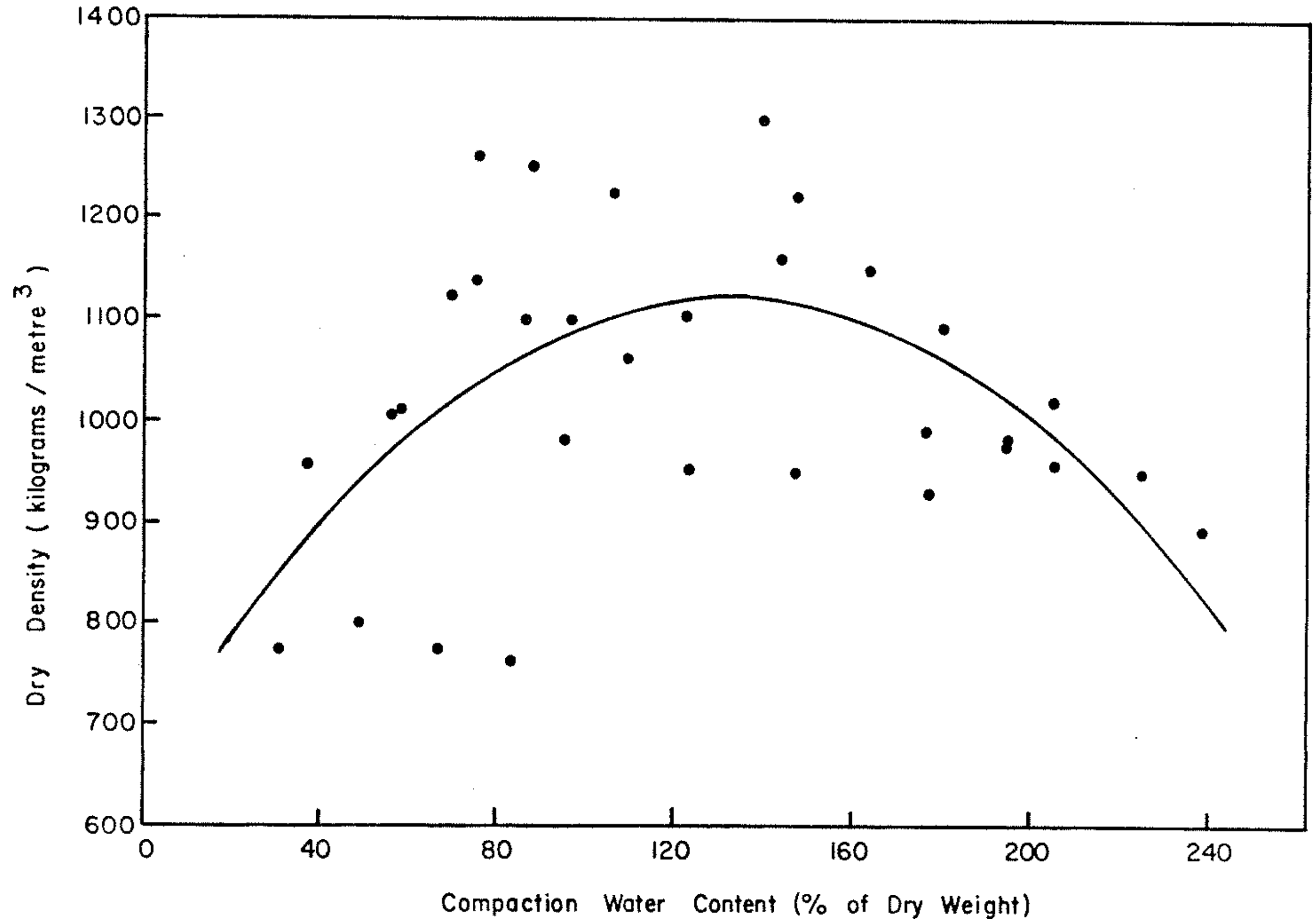

Figure 6 Typical moisture-density relationship for laboratory compacted refuse

Water content and the depth of lifts chosen for compaction will also control the size of equipment used or conversely, the available equipment will determine what water content and depth of lifts are to be used. Compaction equipment found at sanitary landfill sites varies. Among some of those found are specially designed sheepfoot compactors weighing 25 tonnes, 33 to 42 tonne rubber tired rollers and (most popular in Alberta) are D-8 size tractors (Caterpillar). If the water content is too high or as is more often the case, the lifts are too thick, bearing capacity failures can occur. The optimal lift thickness is usually in the order of 600 millimetres. Routine practice should be established at the outset to create some type of consistent compaction of the landfill during placement of the refuse.

4.2 In-Place Treatment

In-place treatments of entire sanitary landfills have become one of the major thrusts of study in more recent years. The construction of landfills for optimum aerobic decomposition (Stone, 1975) is discussed in Section 3.1 and can be considered as one of several options including direct water application, seeding with sewage sludge, fly ash injection and leachate recycling that can be used to treat landfill sites. Each of the last four options improve the anaerobic rate of decomposition. In Japan a combined approach has been taken called semi-aerobic landfilling. A brief description of this method has been presented in Section 3.2.

Practical applications of the aerobic method of construction in Alberta may not be cost effective because of the high labour input and, further, the general method described by Stone (1975) may be less effective in our seasonally harsh environment. Excavation of the cell requires the use of the trench method. This method is discouraged in colder climates because of the problems of separating the unfrozen and frozen portions of the soil fill for effective daily coverage of the refuse. Nonetheless, the excavation is formatted such that a small aerobic cell adjoins a much larger fill cell. Within the aerobic cell a system of gravel and pipes are installed to distribute the forced air through the refuse as illustrated in Figure 7. The large cell is used to receive the residue from the aerobic cell and is managed in the same manner as any sanitary landfill. Hence, the total operation consists of excavating the cells, installing the plumbing, placing the fresh municipal refuse in the aerobic cell, covering the refuse with a thin layer of compacted soil and applying the forced air to initiate the decomposition cycle. After 30 to 90 days (in California) the soil is removed and the residue transferred to the large adjacent fill cell where it is spread, compacted and covered with a lift of soil. The number of cycles which can be performed, depends upon the

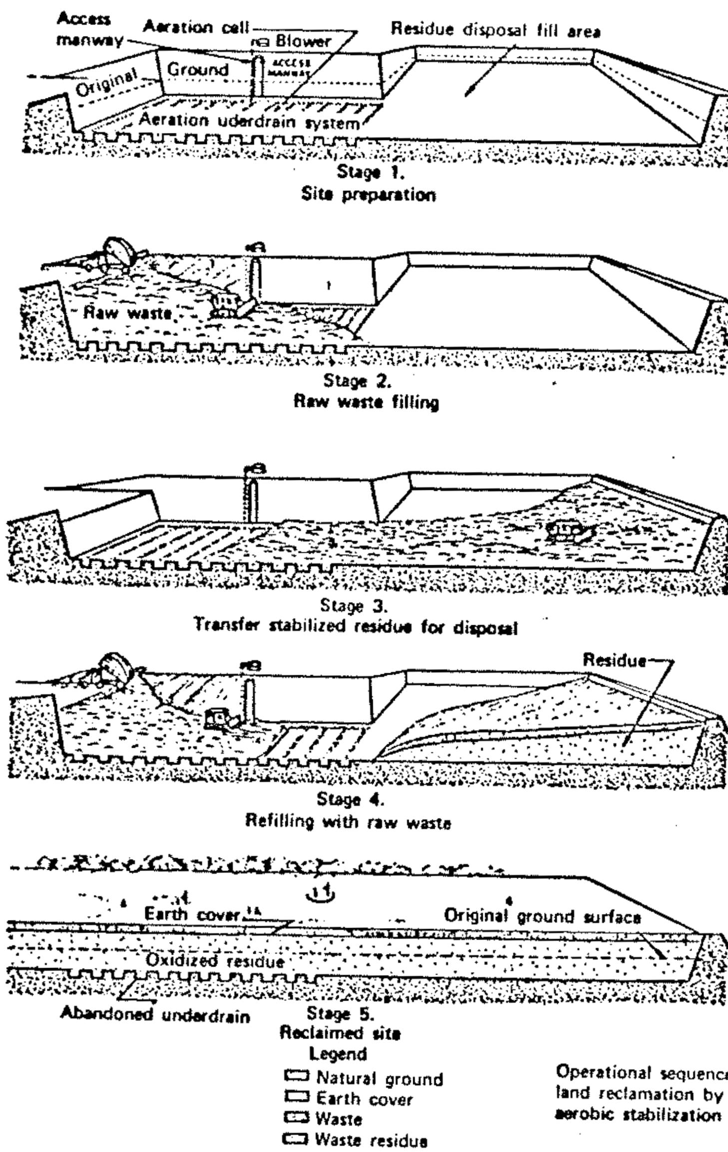

Figure 7 Operational sequence, land reclamation by aerobic stabilization

durability of the air distribution system. Stone's experimental cell was designed for 20 cycles before maintenance was required.

Acceleration of anaerobic decay relies on how favourable an environment can be created for the associated microrganisms. Pohland (1975) found the pH level within the landfill will strongly influence the rate of decay. Optimum anaerobic decomposition is reported to occur at pH levels between 6.8 and 7.2. The pH level is ultimately controlled by the presence of volatile acids, the alkalinity in the leachate and the carbon dioxide content of the gas evolved from the decomposing refuse.

From an investigation of the response of sanitary landfills to leachate recirculation, Pohland (1975) listed the advantages as follows:

1. It presents a more rapid development of an active anaerobic bacterial population of methane formers.
2. It increases the rate and predictability of biological stabilization of the readily available organic pollutants in the refuse and leachate.
3. It decreases the time required for stabilization.
4. It reduces the potential for environmental impairment.

While the emphasis in Pohland's report is on stabilizing leachates as defined in Section 3.3, it is this very aspect which will take precedence in any decision making process regarding sanitary landfill management. Therefore, the merit of this technique for increasing the rate of decomposition is that is addresses the leachate problem. The difficulty of applying this technique to Alberta again lies in the ability to design a distribution system which can endure winters but does not interfere with the overall operation.

Pohland's investigation of sanitary landfill stabilization also encompassed the recirculation of leachate with pH control and initial seeding of the landfill with sewage sludge. Results of both these techniques showed biological decay to accelerate such that biological stabilization was achieved in a period of months rather than years. This does not imply that settlements would decrease, only that the time in which the most erratic settlements take place would be reduced.

When addressing the practical application of seeding landfills with sewage sludge or septic tank contents, one must not forget how difficult and objectionable this method is for those directly involved. It is in this respect that the method finds its greatest drawbacks and hence is not persued enthusiastically.

Grouting of sanitary landfills is usually applied only in localized areas. However, where coal ash is produced in greater quantities than can be consumed by other users of coal ash, a surplus develops. Investigators have attempted to dispose of this surplus by mixing the coal ash with lime or cement and injecting this grout into sanitary landfill (Rao, 1974). From a limited number of studies, the applications seem to offer some promise. Some of the reported characteristics of the grouting process are:

1. Given up to 3 years, some coal ash grouts, depending on their exact composition, may develop strengths of up to 2.4 MPa.
2. The grout can be mixed to an optimal viscosity which will allow thorough penetration of the landfill mass.
3. The application of the grout involves pressure which will compact the refuse.

This latter observation has prompted further studies into compaction grouting as a unique technique. Graf (1969) and Brown and Warner (1973) describe the various techniques associated with compaction grouting and their limitations in practice (Rao 1974).

Glover (1972) investigated the effects of fly ash injection on decomposition of the landfill material. The results of his work showed that, despite the high pH level of fly ash when combined with refuse in the environment of a sanitary landfill, the buffering capacity of the landfill will reduce the pH level to within acceptable limits for active anaerobic decomposition. In fact, where flyash contents exceed 40 percent, the rate of decomposition is actually higher than found in most untreated landfills.

4.3 Localized Treatments

Preloading is perhaps the most effective means of improving foundations for embankments or structures. Other techniques which have been proposed include grouting as discussed in Section 4.2, compacting as discussed in Section 3.1, prerolling and vibration.

Chang and Hannon (1976) compared preloading and prerolling of a high embankment foundation located on 5.4 to 6.1 metres of poorly decomposed refuse in San Diego. The age of the refuse was estimated to be 7 to 10 years. The major part of the experiment consisted of prerolling a section with 25 passes of a 42 tonne roller followed by the construction of a 3 metre embankment. The most significant results were:

1. Total settlements amounted to 420 millimetres after 476 days.
2. Twenty-five percent of the total settlements were achieved by prerolling.
3. Eighty-five percent of the prerolling settlements could be realized after only 10 passes of the roller.
4. Fifty-five percent of the total surcharge settlements occurred prior to completion of the 3 metre embankment.
5. Thirty percent of the total surcharge settlements were completed after 30 days following the end of construction of the surcharge embankment.

Hence, the superiority of preloading over prerolling was clearly established by this experiment. Preloading has

5. FOUNDATION DESIGN

While a sanitary landfill may be monitored for settlements under its own weight, the ultimate interest of the designer will be in the settlement performance of those structures constructed on the sanitary landfill and of their adjoining utilities. Sowers (1968) presented a relatively thorough report devoted to this subject. Bell (1977) also reported some case histories of structures constructed on refuse landfills. From these and other works produced from the United States, it is difficult and rather impractical to compare each set of results to the Alberta environment. Further, there is seldom enough detail in each report to permit such a comparison. Nonetheless, on the basis of the available experience, the following general design approaches will minimize settlements and avoid bearing capacity failures of structures built on reclaimed landfill sites.

5.1 Footing and Raft Foundations

Continuous footings and raft foundations are acceptable under circumstances where the intended structures are relatively light. Allowable bearing capacities of 24 to 38 kPa and additional structural reinforcement will minimize settlements and enable the structural foundation to bridge small voids which may develop (Sowers, 1968).

A second approach suggested by Sowers (1968) is to construct a blanket of competent material above the existing soil cover. The depth of this blanket must be sufficient to provide a base thickness equal to approximately 1.5 times the width of the footing, as well as frost protection cover. This will eliminate punching shear and contain the potential rotational or general shear failure planes within the new fill thereby avoiding this mode of failure. Unfortunately, the addition of this blanket of soil will also activate large settlements, hence, the blanket should be constructed two or more years in advance to minimize total settlements.

Depths of soil cover required for frost protection in Alberta can be particularly detrimental because of the proportionate settlements they cause. One potential solution lies in the application of insulation. Provided the insulation would not be attacked by any of the various landfill by-products, the depth of soil cover could be reduced by greater than 50 percent of the required fill height.

5.2 Pile Foundations

Where it is desirable to construct heavily loaded structures pile foundations bearing on suitable natural undisturbed soil underlying the landfill are likely to be the most feasible. Some of the impediments to pile foundations include the corrosive environment, the possibility of encountering large resistant objects during placement and reduced pile capacities caused by downdrag of the fill as it settles.

In light of these restrictions, it would appear that one solution might be to prebore at each of the chosen pile locations to locate any immovable objects and then to drive oversize precast concrete piles. In this manner corrosion may be compensated for without risk to the integrity of the foundation. Preplanning of sanitary landfills could significantly reduce the risks described and make pile foundations a safer solution.

5.3 Other Design Considerations

Within the context of settlement considerations, landscaping of finished sites must be approached with caution. The popular use of small mounds and other load imposing landscaping features adjacent to the structure may be enough to initiate harmful settlements.

Settlements of structures may not be the only source of settlement related failures. Incidences of sewerlines sagging and plugging, or settling and reversing the direction of flow have been recorded (Sowers 1968). Again the solution lies in extensive preplanning of sanitary landfills for future development. Alternatively the utilities might be constructed with pile support, however, this is an expensive procedure.

A further consideration for foundations on sanitary landfill sites is that of gas migration. Vents and careful sealing procedures are among some of the solutions detailed by MacFarlane (1970).

6. TECHNIQUES FOR DEVELOPMENT

6.1 Milled Refuse

Many of the problems associated with sanitary landfills can be alleviated by shredding or milling the refuse. The behaviour of municipal solid waste subsequent to shredding has attracted growing interest and has been developed to such an extent that it no longer is regarded by researchers as an intermediate process to sanitary landfills but as a separate and unique waste disposal method. In the United States the Federal Environmental Protection Agency has recognized this view and has adopted a different approach to handling shredded refuse.

In Edmonton, Alberta, shredding was used before 1972 (Frost et. al., 1974). However, as was common then, shredding refuse was only regarded as a step towards a more efficient means of transporting refuse long distances. Reportedly, milling refuse can reduce the delivered volume by 50 percent and hence this is where the savings were realized.

More recently, several more advantages have become apparent. Those which are easily recognized include reduced odors, low fire potential, elimination of rodent and insect problems and elimination of blowing paper. Of greater engineering significance, is the all-weather trafficability of the shredded refuse, the reduced need for soil cover, the increased decomposition rate and the much improved predictive possibilities.

Milling is widely used throughout Scandinavia and the British Isles and hence their experience is relevant to Alberta. Some of the research work performed on milled refuse included the investigation of compactability, with and without vibration (Ham et. al. 1978; Harris 1978), consolidation (Chan et. al. 1977) and effects of seeding (Hartz, 1973). In addition, the composition effects, the environmental effects and the site effects referred to in the context of sanitary landfills are equally applicable to milled refuse. The properties of milled refuse can similarly be correlated with untreated refuse. The major difference between the two types of refuse is the relative homogeneity of milled refuse as opposed to the heterogeneity of treated refuse and the much more active nature of decomposition likely to be found in a milled refuse landfill as opposed to a sanitary landfill.

Homogeneity is a general term which ecompasses a very wide range of responses. Both milled and untreated refuse have been shown to compact better with moisture control and vibration, however, milled refuse compacts to higher densities and with much improved predictive capabilities. Figures 5 and 6 illustrate this observation. Rao (1977) shows a scatter of results which defies a simple evaluation, however, the results presented by Harris shows plots which rank in consistency with many mineral soil "moisture density" relationships. The actual increase in density is predicted to be in the order to 15 percent. While this does not appear significant, this reduced volume combined with the savings in soil cover can improve the capacity of a landfill site by as much as 30% (Ham et al, 1973). Other savings are realized with respect to machinery maintenance which is an economic consideration often neglected. Objects which cannot be shredded must be treated separately and disposed of in a specially allotted area of the landfill site.

As discussed in Section 3.1.5, the most significant approaches to understanding refuse settlements have been developed in the context of milled refuse. Further, the best correlations between measured and predicted refuse response, on laboratory scale, have also been achieved with milled refuse. With further research, it appears that a complete correlation between theory, laboratory testing and field observations may be as possible as that for soils. It is further speculated that only such agreement in all areas of study is possible with milled refuse.

Hartz and Carlson (1973) have reported the Scandinavian practice of "multning". This practice is simply an application of some of those treatments for rapid decomposition mentioned in Section 4.2. The major difference is that milled refuse is treated much more easily than untreated wastes in sanitary landfills both before reaching the site and after placement. This convenience is partially a result of the fact that milled refuse landfills do not require soil cover. In addition, it may be easier to adjust moisture contents uniformly at the milling plant than at the site. Figures 8, 9 and 10 present some of the observations made by Hartz and Carlson (1973).

It is believed that milling refuse could be a major improvement to the municipal waste landfill system already in use in Alberta. Advantages of uniformity, improved decomposition characteristics and greater predictability are among those already described. Field observations to support this conclusion are available in the form of the Scandinavian experience. The relationships between milled refuse landfill and the leachate by-products remains to be investigated. If the milled refuse landfill is compatible with the environment then it would make both good engineering sense and likely good economic sense to persue this approach.

6.2 Baled Refuse

Baling of refuse is "accomplished by compressing solid waste in mechanical device to reduce the volume and obtain a dense bale suitable for transportation and landfilling (Stone and Kahle, 1977). While the author does not see an application for this system in the highly populated areas of Alberta, there does appear to be advantages in using it in the rural communities. It is suggested that since

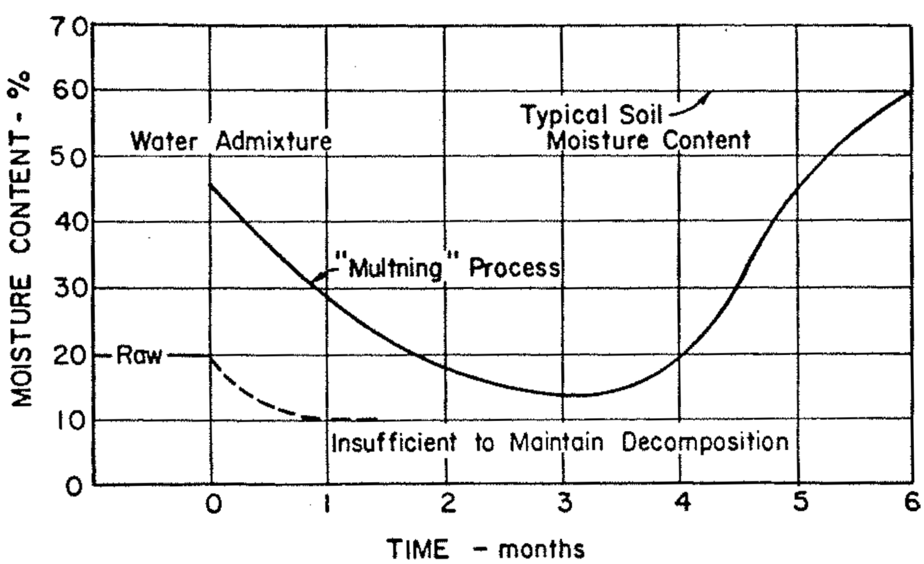

Figure 8 Moisture content as percent of total sample weight in the landfill.

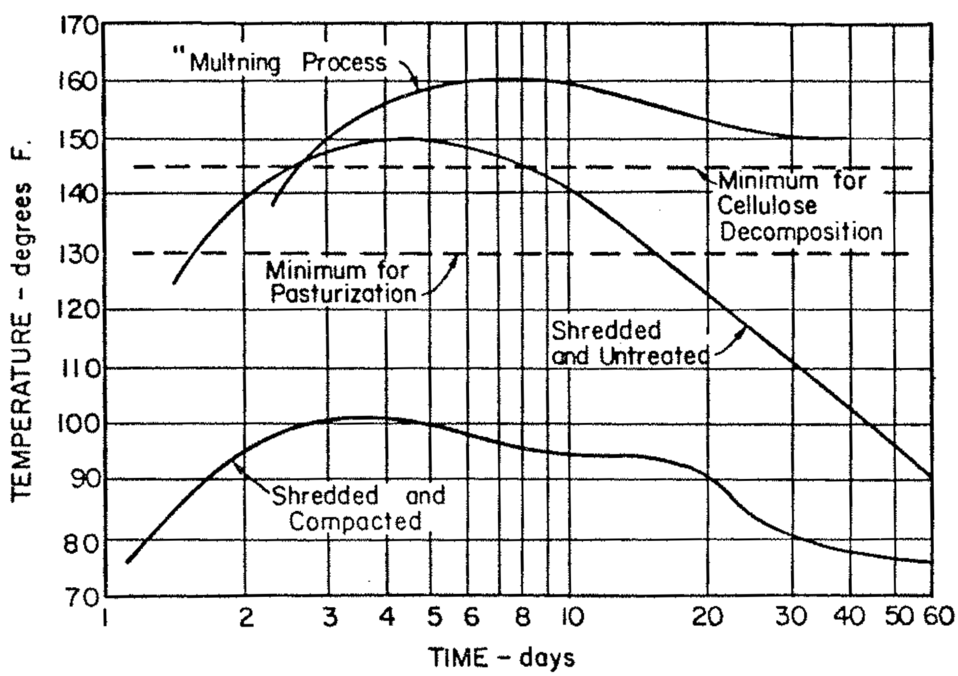

Figure 9 High temperatures of "multning"process accelerates decomposition.

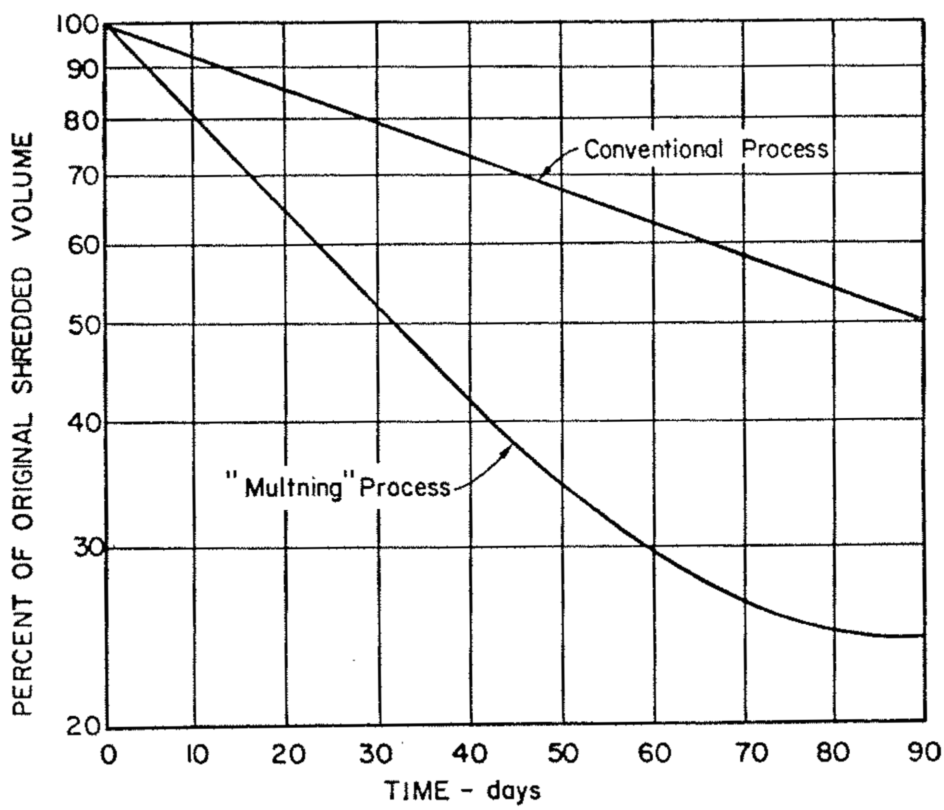

Figure 10 Rate of volume reduction is compared with the conventional process

development of structures on the proposed central rural sanitary landfills in Alberta (see Section 1.3) may not be as high a priority as efficient disposal of the wastes, baling could lead to a more economic and efficient method of waste management.

If each community or small group of communities had an appropriate sized baler, refuse could be disposed of, baled and trucked to the central landfill site efficiently. Furthermore, at the central landfill site a lower capital cost is necessary simply to stack bales and maintain a low volume of refuse which cannot be baled.

Properly prepared bales such as milled refuse need only minimal soil cover. Maximum densities can be achieved by baling with little additional treatment and when stacked with a little care the finished landfill can be just as dense and likely denser than a standard sanitary landfill. Following completion of experimental landfills using bales, expansions rather than settlements have been reported (Stone and Kahle, 1977) for monitoring periods as long as 1 year. From the standpoint of vertical movements, initial expansion is fast however subsequent movements are shown to occur at a very slow rate and for a longer period of time.

Therefore, it is suggested that this technique be considered a research program particularly for isolated communities or communities where bedrock is close to the ground surface and little soil cover is readily available. The study (Stone and Kahle, 1977) may be helpful for purposes of comparison even though their study is founded on work performed in California.

6.3 Recycling

Recycling is obviously the most desirable means of handling refuse from an environmental perspective. Alberta is already reported to be a leader in Canada in this regard (Environment 1978). Therefore continued research in this aspect must be maintained as a top priority.

7. CONCLUSIONS AND RECOMMENDATIONS

Throughout the text of this report various inconsistencies in the literature have been cited and conclusions drawn regarding the relevance of various techniques to Alberta. In summary the following points should be emphasized.

1. Future studies should exercise care in the choice of descriptions for solid wastes and adopt a consistent classification scheme for solid waste composition.
2. For purposes of quantitatively describing refuse it is recommended that the loss of mass on combusion be incorporated among the more commonly used indices of water content, dry unit weight and bulk unit weight.
3. Investigations should be directed toward the use of milled refuse landfills. If economic, and if leachate considerations are satisfied, then this method of refuse managmeent is believed to offer distinct advantages over the sanitary landfill method.
4. Other techniques which appear suitable to the Alberta environment, and hence should be persued on an experimental scale, include the semi-aerobic landfill construction methods and the leachate recycling.
5. Baling should be considered as an alternative to landfill construction in some of the more remote areas of Alberta.
6. Recycling must be continually promoted.

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