ABSTRACT

HOSSAIN, MD. SAHADAT. Mechanics of Compressibility and Strength of Solid Waste in Bioreactor Landfills (Under the direction of Prof. Mohammed A. Gabr)

Bioreactor landfills are operated to enhance refuse decomposition, gas production, and waste stabilization. A major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. While there are significant economic advantages to the operation of landfills as a bioreactor, our understanding of the mechanics governing accelerated waste degradation and its impact on waste geotechnical properties is limited. As such, there is a need to explain and quantify such impact on compressibility and shear strength parameters; these parameters are needed for the three design phases of landfill construction, operation, and post-closure.

The overall objective of the research was to develop an understanding of change in refuse compressibility and strength during accelerated waste decomposition in landfills operated as bioreactors. An experimental program was performed to provide data on parameters describing MSW compressibility and strength properties as a function of the state of decomposition, gas generation, and physical characteristics of waste particles. The research links the measured parameters to the physical and biological changes that take place as waste decomposition is accelerated. The research provides data on the significance of using relatively small equipment and shredded waste relative to field-estimated properties. The research develops a model of waste settlement that considers the effect of high moisture content and time-dependent property changes on waste compressibility. This research also develops a model for shear stress-displacement behavior of MSW in bioreactor landfills.

Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The reactors were destructively sampled to obtain refuse at various states of decomposition, based on the reactor's methane production rate curve. In addition, the state of decomposition was quantified by measurement of the concentrations of cellulose (C), hemicellulose (H), and lignin (L), and (C+H)/L ratio. Reactors were sampled at each

of four time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, and early and late in the decelerated methane production phase.

The experimental program was performed using oedometer and direct shear tests to determine the compressibility parameters and shear strength parameters and illustrate the effect of shredding and equipment size on compressibility and strength parameters for refuse (at different degrees of degradation). The extent of degradation was documented by gas production rates as well as (C+H)/L ratios.

Oedometer test conducted on 63.5 mm, 100mm, 200mm diameter equipment with constant R, specimen to equipment size ratio, indicate that compressibility parameters are dependent on R. Compressibility parameters are similar with constant R even though the equipment size varies. Shredding of MSW affects mainly initial compression as observed from the test results on same equipment with variable R. For example, initial compression for MSW in 200mm equipment is 31% and 35% for R =0.34 and 0.17, respectively. Creep and biological strain rate of MSW is not affected by shredding. The variation of the magnitude of biological indices with varied R is minimal. The shear strength is affected by shredding as the light-weight reinforcing materials are shredded into smaller pieces during specimen preparation. The measured shearing angles are 31° and 27° for R=0.50 and 0.25, respectively. The larger components in the specimen act as better reinforcing element than shredded smaller components during the shear test.

Compressibility increased with increasing gas production as solid-to-gas conversion took place. Testing results indicated a correlation between the coefficient of primary compression (Cc) and (C+H)/L ratio. The coefficient of primary compression (Cc) for all samples showed an increasing trend with decreasing (C+H)/L. Results indicated the creep index (C_{α}) to be independent of the state of waste decomposition. The creep index range was 0.02 to 0.03 for traditional and bioreactor samples in various states of decomposition. The magnitude of the biological indices varied with the state of decomposition and yielded the highest values (C_{β}=0.19) when samples were actively decomposing and had substantial methane potential remaining.

The amount of plastic, a non-degradable waste component, within test sample remains the same where as the paper content decreases with degradation as their structure matrix breaks down. The experimental results found that with degradation of degradable

material, percentages of plastic content increases and contributes to decrease in friction angle. Accordingly, testing results indicated a correlation between strength parameters and (C+H)/L ratio. For example, measured shearing angle for bioreactor samples decreased from 32 ^{o} to 24 ^{o} as (C+H)/L ratio decreased from 1.29 to 0.25. The predicted shear behavior by the developed constitutive model for shear stress displacement was matched with the experimental results.

Settlement prediction using a developed model considered all the aspects of biological decomposition, creep and matrix stiffness change as decomposition takes place with time. Seven field case studies show that the model predicts landfill settlement quite well including the biological decomposition component.

MECHANICS OF COMPRESSIBILITY AND STRENGTH OF SOLID WASTE IN BIOREACTOR LANDFILLS

by

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TABLE OF CONTENTS

	Page No.
LIST OF TABLES	vii
LIST OF FIGURES	ix
INTRODUCTION	
Background	1
Problem Statement	2
Research Objective	3
Contributions to the State of Art	3
Scope of the Report	4
LITERATURE REVIEW	
Gas Phases and Biological Effect	5
Properties of Municipal Solid Waste	7
Physical Properties of Municipal Solid Waste	7
Classification	8
Composition	8
Moisture Content	9
Organic Content	10
Unit Weight	10
Specific Gravity	12
pH	13
Grain Size Distribution	13
Hydraulic Conductivity	13
Engineering Properties of Municipal Solid Waste	14
Review of Compressibility and Shear Strength	14
Waste Compressibility Parameters	14
Waste Compressibility Model	17
Conventional Compressibility Model	17
Power Creep and Hyperbolic Model	21
Biological Model	24
Shear Strength	29
Shear Strength Parameters of MSW	29
Change in Shear Strength with Decomposition	30
Increase in Strength with Displacement	31
References	33
Tables	41
Figures	48
THE EFFECT OF SHREDDING AND EQUIPMENT SIZE ON MEASURED COMPRESSIBILITY AND STRENGTH PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION	
Abstract	61
Introduction	62

Experimental Design 64
Preparation of Fresh and Decomposed Refuse 65
Oedometer Tests 66
Direct Shear Tests 66
Results 67
Refuse Decomposition 67
Compressibility Parameters 67
Shear Strength Parameters 70
Reliability of Data 71
Summary and Conclusions 71
References 73
Tables 76
Figures 80

COMPRESSIBILITY PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION
Abstract 88
Introduction 89
Refuse Biodegradation and Gas Production 91
Experimental Design 93
Preparation of Fresh and Decomposed Refuse 93
Oedometer Tests 94
Results 95
Refuse decomposition 95
Compressibility Parameters 96
Coefficient of Primary Compression 98
Effect of Shredding 99
Summary and Conclusions 99
References 101
Tables 105
Figures 108

PREDICTION OF MUNICIPAL SOLID WASTE LANDFILL SETTLEMENT WITH LEACHATE RECIRCULATION
Abstract 117
Introduction 117
Background 119
Proposed Compressibility Model 121
Compressibility Parameters 124
Experimental Design 124
Model Parameters 125
Model Validation 126
Results of Model Predictions 130
Summary and Conclusions 131
References 133
Tables 136
Figures 139

SHEAR STRENGTH PARAMETERS AND MODEL OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION AND DEGRADATION
Abstract 145
Introduction 146
Shear Strength Parameters: Past Work 146
Refuse Biodegradation and Gas Production 148
Experimental Design 149
Preparation of Fresh and Decomposed Refuse 150
Direct Shear Tests 151
Results 151
Refuse Decomposition 151
Shear Strength Parameters of Major Constituents 152
Mobilized Strength Incompatibility 153
Decrease in Strength with Decomposition 153
Increase in Shear Strength with Displacement 155
Non-Linear Failure Envelope 155
Model 156
Model Parameters 157
Samples at Advanced Stage of Decomposition 157
Samples at Initial Decomposition Stage, Fresh Paper and Plastics 158
Calibration of Model 158
Summary and Conclusions 158
References 160
Tables 163
Figures 164

SUMMARY AND CONCLUSIONS 180

LIST OF TABLES

Page No.

LITERATURE REVIEW

1	Composition and methane potential of municipal refuse by chemical constituents	42
2	MSW- components as weight percentage for different cities	42
3	Typical municipal waste components as fill materials	43
4	Composition of municipal refuse by component	43
5	Comparison of waste characteristics from different countries	44
6	Moisture content in the landfill	44
7	Range of unit weight of uncompacted and compacted refuse components	45
8	Lightest and heaviest combinations of refuse constituents	46
9	Summary of determination of hydraulic conductivity of domestic Waste	47

THE EFFECT OF SHREDDING AND EQUIPMENT SIZE ON MEASURED COMPRESSIBILITY AND STRENGTH PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION

1	Tests to evaluate the effect of shredding and equipment size on measured laboratory parameters	76
2	Description of the Sample Reactors and Their Gas Production Record	77
3	Compressibility parameters for bioreactor samples for different equipment size and variable R	78
4	Shear strength and compressibility parameters of bioreactor samples from repeatability tests	79

COMPRESSIBILITY PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION

1	Number of tests for measuring compressibility parameters	105

2 Description of the sampled reactors and their gas production record 106

3 Compressibility parameters for bioreactor and traditional samples 107

PREDICTION OF MUNICIPAL SOLID WASTE LANDFILL SETTLEMENT WITH LEACHATE RECIRCULATION

1 Description of the sampled reactors and their gas production record 136

2 Compressibility parameters for bioreactor and traditional samples 137

3 Model Parameters for Settlement Prediction 138

SHEAR STRENGTH PARAMETERS AND MODEL OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION AND DEGRADATION

1 Number of tests for measuring shear strength parameters 163

2 Description of the sampled reactors and their gas production record 163

LIST OF FIGURES

Page No.

LITERATURE REVIEW

1	Methane Gas Production as a Function of Time	48
2	Classification System Suggested by Landva and Clark (1990)	49
3	Variation of Moisture Content, Liquid Limit, Plastic Limit with Depth (Gabr and Valero, 1995)	50
4	Summary of Observed Trend in Leachate Recycle (Barlaz, 1990)	50
5	Grain Size Distribution by Dry and Wet Testing (Gabr and Valero, 1995)	51
6	Time Progression of the Specific MSW Subsidence in a Large Diameter Drained Column Test (Gandolla et al 1995)	51
7	Compressibility Properties as Measured from Conventional and Unconventional Tests (Gabr and Valero, 1995)	52
8	Relative Height as a Function of a) Applied Pressure b) The Log of the Applied Pressure (Rao, 1977)	53
9	Rheological Model (Edil et al, 1990)	54
10	Evaluation of Gibson and Lo Parameters (Valero, 1994)	54
11	Settlement Model (Bjarngard & Edgars, 1990)	55
12	Evaluation of Power Creep Parameters	56
13	Evaluation of Rate Process Creep Parameters	57
14	Typical Landfill Bacteria Growth Curve (Valero, 1994)	58
15	Shear Stress vs Shear Displacement Curve (Edincliler et.al., 1996)	59

THE EFFECT OF SHREDDING AND EQUIPMENT SIZE ON MEASURED COMPRESSIBILITY AND STRENGTH PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION

1	Percentage Distribution of Individual Components in MSW for Equipement Size and Shredding Effect	80

2	Rate of Methane Production for Bioreactor and Traditional Samples	81
3	Variation of pH with Time for Bioreactor and Traditional Samples	81
4a	Comparison of waste compressibility using different size equipment diameter. R, Specimen to equipment size ratio = 0.5	82
4b	Comparison of waste compressibility using different size equipment diameter. R, Specimen to equipment size ratio = 0.5	82
5a	Comparison of waste compressibility using different R, specimen to equipment ratio. Equipment size =200 mm	83
5b	Comparison of waste compressibility using different R, specimen to equipment ratio. Equipment size =200 mm	83
6	Comparison of waste compressibility using different R, specimen to equipment ratio. Equipment size =300 mm	84
7	Comparison of Shear Strength Parameters using Different R, Specimen to Equipement Ratio	85
8	Compressive Strain vs Log Pressure for the Shredded /Un-shredded Samples. Sample B3 is from this study and the other three samples are from Landva and Clark.	85
9	Repeatability test for compressibility parameters on samples from the same reactor	86
10	Repeatability test for shear strength parameters on samples from the same reactor	86

COMPRESSIBILITY PARAMETERS OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION

1	Methane production rate for a landfill that receives 286,000 metric ton/yr for 20 years. With reference to eqn. 2, Lo = 170 L/kg, the default value used for NSPS guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 and enhanced decomposition in a bioreactor (k = 0.15).	108
2	Rate of Methane Production for Bioreactors	109

3	Rate of Methane Production for Traditional Reactors	109
4	Variation of pH with Time for Bioreactors	110
5	Variation of pH with Time for Traditional Reactors	110
6	1-D Oedometer Test Results for Bioreactor Samples	111
7	1-D Oedometer Test Results for Traditional Samples	111
8	1-D Oedometer Test Results for Bioreactor Samples (Degradation Inhibited)	112
9	Void Ratio vs Log Pressure for the Bioreactor Samples	113
10	Void Ratio vs Log Pressure for the Traditional Samples	113
11	Compression Index Cc as a Function of (C+H)/L Ratio	114
12	Primary Compression Parameter as a Function of Initial Void Ratio	115
13	Compressive Strain vs Log Pressure for the Shredded /Un-shredded Samples. Sample B3 is from this study and the other three samples are from Landva and Clark.	115

PREDICTION OF MUNICIPAL SOLID WASTE LANDFILL SETTLEMENT WITH LEACHATE RECIRCULATION

1	Phase Diagram as a Function of Degradation Phase	139
2	Compressibility Parameters for Bioreactor Samples	140
3	Compressibility Plot for Bioreactor Sample	141
4	Time Factor Determination for the Compressibility Model	141
5	Time Factor t_3 for Yolo County Landfill (One Year Waste)	142
6	Comparison of Predicted and Observed Field Settlement for Bioreactor Landfills	143

SHEAR STRENGTH PARAMETERS AND MODEL OF MUNICIPAL SOLID WASTE WITH LEACHATE RECIRCULATION AND DEGRADATION

1	Methane production rate for a landfill that receives 286,000 metric ton/yr for 20 years. With reference to eqn. 2, Lo = 170 L/kg, the default value used for NSPS guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 and enhanced decomposition in a bioreactor (k = 0.15).	164

2	Rate of Methane Production for Bioreactors and Traditional Samples	165
3	Variation of pH with Time for Bioreactors and traditional samples	165
4	Direct Shear Test Data for Plastics	166
5	Direct Shear Test Data for Fresh Paper	166
6	Shear strength parameters for fresh paper and plastics at 10 mm displacement	167
7	Direct Shear Test Data for Degraded Paper, Textile and Organics	167
8	Direct Shear Test Data for Samples at (C+H)/L=0.73	168
9	Direct Shear Test Data for MSW Samples (Bowders, 2002)	168
10	Direct Shear Test Data for Samples at (C+H)/L=1.29	169
11	Shearing Angle for MSW at 10 mm Displacement	169
12	Comparison of Shear Strength Parameters with Existing Results	170
13	Effective Shear Strength Parameters for Municipal Solid Waste	171
14	Repeatability test for shear strength parameters on samples from the same reactor	172
15	Mobilized Friction Angle with Displacement for Paper and Plastics	172
16	Comparison of mobilized friction angle with existing results	173
17	Non-linear failure envelope for MSW	173
18	Schematic Diagram of Shear Stress – Displacement Behavior of MSW	174
19	Variation of Model Pararmeters against Normal Stress	175
20	Variation of Model Pararmeters against Normal Stress	176
21	Variation of Model Pararmeters against Normal Stress	177
22	Model Verification using Experimental Results	178
23	Comparison of Predicted and Measured Shear Stress Displacement	179

INTRODUCTION

Background

In 1998, 217 million tons of municipal solid waste (MSW) was generated in the U.S., with approximately 55% of this waste buried in landfills (U. S. EPA, 1999). While portions of this waste are recycled and composted (28%), and converted to energy (17%), landfills will remain a significant aspect of MSW management for the foreseeable future. There have been substantial changes in the design and operation of landfills over the past twenty years. First, state and federal regulations now require that landfills be constructed with low permeability liners and leachate collection systems. These systems are intended to isolate waste from the environment and to insure that contaminated water is collected and treated prior to its release. Furthermore, low permeability covers must now be installed once a landfill has reached its permitted capacity to minimize long-term leachate production.

A second major change occurred concerning the operation of landfills. Though first suggested in the mid 1970s (Pohland, 1975), the concept of operating a landfill as a bioreactor has recently received increased attention (Pacey et al., 1999). A bioreactor landfill is operated to enhance refuse decomposition, gas production, and waste stabilization. A major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. There are several benefits associated with the operation of landfills as bioreactors including (1) more rapid settlement which results in increased effective refuse density and air space, (2) in-situ leachate treatment, (3) increased gas production which can improve the economics of energy recovery, and (4) ultimately the rapid stabilization of a landfill to a more environmentally benign state (Reinhart and Townsend, 1998). As a result of these benefits, there has been a significant increase in the number of landfills that are being operated with leachate recycle and discussions of bioreactor landfills have dominated waste industry conferences for at least the past two years.

The advantages of bioreactor landfills, refuse decomposition, and factors that affect the decomposition rate are generally well documented (Barlaz et al., 1990). However, the design and operation of landfills as bioreactors raise some concerns. First, as described in the Literature Review, the physical properties of MSW are expected to

change with the increasing moisture content. These changes must be considered during the design phase to ensure slope and cover stability. Second, the enhanced rate of waste decomposition can result in an enhanced rate of waste settlement as refuse solids are converted to landfill gas (CH_4 and CO_2). Third, the shear strength of the waste will vary with time, as the cellulose plus hemicellulose to lignin ratio decreases. Materials such as paper and textiles can initially provide reinforcement action to increase waste slopes stability. However, as these materials degrade, the density of the buried waste increases coupled with the possible reduction in waste shear strength.

Having these changes occur over a relatively short time can affect the design philosophy of landfills as well as operating practices as waste exhibits a highly compressible skeleton depending on its degradation phase. This was demonstrated through a recent comparison of traditional and bioreactor landfills. The comparison was conducted on 0.25 acre, 12 m (40 ft) deep test cells at the Yolo County, CA landfill. After 3 years, settlement was measured to be 2% and 16% in the traditional and bioreactor cells, respectively, (Mehta et al. 2002).

Problem Statement

While there are significant economic advantages to the operation of landfills as bioreactor, our understanding of the mechanics governing accelerated waste degradation and its impact on waste geotechnical properties is limited. As such, there is a need to explain and quantify such impact on compressibility and shear strength design parameters. Unfortunately, there are difficulties in performing these tests on MSW materials due to the heterogeneity and wide range of particle sizes. To test refuse using conventional laboratory techniques requires shredding or exclusion of large waste pieces. Having no data to evaluate the effect of waste shredding, or sorting, on the measured properties hinders the engineers' ability to utilize measured data within a realm of reason. This leaves the professional community and the regulatory agencies with some uncertainty regarding the design and permitting of bioreactor landfills.

Research Objectives

The overall objective of the research is to develop an understanding of change in refuse compressibility and strength during accelerated waste decomposition in landfills operated as bioreactors. An experimental program was completed to provide data on parameters describing MSW compressibility and strength properties as a function of the state of decomposition and associated changes in waste density and physical characteristics of waste particles. The research links the measured parameters to the physical and biological changes that take place as waste decomposition is accelerated. The research also provides data on the significance of using relatively small equipment and shredded waste relative to field-estimated properties. Specific objectives are to:

1. Investigate the effect of equipment size on measured waste compressibility and shear strength as degradation takes place and the chemical composition of the waste changes. This includes characterizing the effect of initial physical particle size on waste compressibility and strength parameters.
2. Investigate the dominant mode of waste compressibility at different stages of waste decomposition.
3. Measure and define time-dependent waste compressibility as a function of the cellulose plus hemicellulose to lignin ratio as well as gas production. Compressibility components due to the overburden weight of the waste, creep, and biodegradation will be characterized.
4. Develop a model of waste settlement that considers the effect of high moisture content and material a time-dependent property changes on waste compressibility.
5. Develop general behavior patterns and a model describing refuse shear strength as a function of stress state and gas generation rates taking into account the state of waste decomposition. In addition, define changes in strength properties with degree of decomposition.

Contributions to the State of Art

The proposed work will provide a fundamental geotechnical characterization of waste in bioreactor landfills. Workshops held at two different national meetings (GRI Las Vegas meeting in December 2000 and Environmental Industries Association (EIA) San Diego meeting in February 2001) emphasized the lack of knowledge regarding

geotechnical properties of waste in bioreactor landfills. The research will have global impact as professional communities' worldwide search for strategies to extend the life span of existing landfills and operate new ones in the most cost-effective manner possible. As implementation of leachate recycle will lead to in more rapid waste decomposition, and the waste will be considerably wetter than is typical of conventional landfills. The lack of defined testing techniques to measure design properties and the lack of understanding of the mechanics governing compressibility and strength can have grave consequences. The specific contributions of the proposed research are:

1. Development of a fundamental understanding of factors governing refuse compressibility and strength as waste decomposes, linking gas generation, and chemical composition with geotechnical properties, which will enhance design and operating practices for bioreactor landfills,
2. Development of a simple model of bioreactor waste settlement that provides the professional community with a tool to study key scenarios during design, operation, and post-closure periods, and
3. Establishment of a model for waste strength as a function of the state of waste decomposition.

In general, the research result presented herein will advance rational design, operation, and regulation of MSW landfills.

Scope of the Report

Initially the objectives of the research are defined followed by literature review. The rest of the report is divided into four papers. The first paper discusses the shredding and equipment size effect on the measured compressibility and shear strength properties of waste. The second paper discusses compressibility parameters of MSW as a function of cellulose plus hemicellulose to lignin ratio. In this paper, waste decomposition has been linked with gas generation and compressibility parameters have been obtained at different decomposition stages. The third paper focuses on developing and validating the compressibility model considering the biological degradation aspects of MSW. Finally, the fourth paper discusses effect of degradation on the measured refuse shear strength and development of a constitutive model defining the shearing pattern for MSW. These papers are followed by summary and conclusion.

LITERATURE REVIEW

Gas Phases and Biological Effects

Biodegradability rate is a function of waste composition, waste nutrient level, the presence or absence of buffering agent and operational management practices. As degradation takes place, the solid mass is converted to gas, and void ratio increases, with consequent increase in the compressibility of waste. Accordingly, the settlement component due to biodegradation of solid waste can be related to landfill gas production and enhanced biodegradability with leachate recirculation.

In general, gas production is a function of waste composition. Waste composition can be performed by visual or chemical methods. Cellulose and hemicellulose comprise 45-60% of the dry weight of MSW and are its major biodegradable constituents (Barlaz et al., 1989). The decomposition of these compounds to methane (CH_4) and carbon dioxide (CO_2) in landfills is well documented and their decomposition contributes to the long-term settlement and stability of landfills (Barlaz et al., 1990; Pohland and Harper, 1986; Bookter and Ham, 1982). The conversion of cellulose and hemicellulose to CH_4 and CO_2 is carried out by three groups of anaerobic bacteria working together; (1) the hydrolytic and fermentative bacteria, (2) the acetogenic bacteria and (3) the methanogens (Zehnder 1982). This process proceeds efficiently over a relatively narrow pH range around neutral. Table 1 (Barlaz, 1990) shows the chemical composition and methane potential of typical residential municipal solid waste The data in Table 1 indicate that about 60% of the total solid composition are cellulose and hemicellulose. These two constituents are responsible for 90% of methane production in the landfill.

Methane potential was calculated assuming 100% conversion of the degradable constituents to gas i.e. carbon dioxide and methane. For cellulose, conversion reaction was given by Barlaz (1990) as:

Equation (1) $(C_6 H_{10} O_5)_n + n H_2 O \xrightarrow{\text{Bacteria}} 3n CH_4 + 3 n CO_2$

Cellulose Monomer

As cellulose and hemicellulose will be surrounded by lignin, they will not fully decompose due to the inhibitory affect of lignin. There are five phases of gas production,

with the initial phase (phase 0) is taken as the fresh refuse before biological and chemical reactions take place. The four phases of waste were characterized as follows (Barlaz, 1990):

Phase 1: Aerobic Phase – During this phase oxygen present in the voids will be consumed for the CO_2 production and this will continue until all the oxygen is consumed. In aerobic phase leachate strength is relatively low and the gas produced are mainly CO_2 and N_2 with no methane production. The solid with gas potential remains almost same as the fresh refuse (may be 5-10% decomposition of solids) because this phase continues for a short period of time.

Phase 2: Anaerobic Acid Phase – In anaerobic phase carboxylic acids accumulate and pH decreases. The gas produced is still mainly CO_2 with little methane production at the end of the phase. As transition to phase 3 takes place, the pH starts to increase and carboxylic acid accumulation goes down with the measurable production of the methane. Cellulose and hemicellulose starts to decompose in this phase. The decomposition of solid is estimated to be between 15-20% based on laboratory data. The acid phase explains the time lag between the refuse burial and the onset of methane production.

Phase 3: Accelerated Methane Production Phase – An increasing rate of methane production, increase in pH, decrease in carboxylic acid concentration, methane concentration of 50-60% marks the onset of this phase. Due to decrease in accumulation of carboxylic acid, pH increases significantly. Some additional solids decomposition occurs in this phase but much of the methane is due to depletion of carboxylic acids accumulated in phase 2.

Phase 4: Decelerated Methane Production Phase – The rate of methane production decreases but the methane and carbon dioxide concentrations remains same as previous phase, 60% and 40% respectively. The rate of cellulose and hemicellulose decomposition is maximum in this stage. In the earlier phases refuse decomposition leads to the accumulation of carboxylic acid whereas in fourth phase the rate of polymer hydrolysis exceeds the other phases and no accumulation of carboxylic acids are observed. Solid decomposition is 50-70% in this phase depending on the methane production and operational management practices.

Gas production from landfills is typically modeled using a first order decomposition rate such as that in the US EPA Landgem Model (1998).

Equation (2) $G = WL_0ke^{-kt}$

G is annual methane generation for a specific year t (ft^3 CH_4/yr);

W is the mass of waste buried annually (tons/yr)

L_o is the methane potential (ft^3 CH_4/ton of waste):

t is time after initial waste placement (yr);

k is the first order decay rate constant (1/yr)

Methane production rates calculated from equation 2 for traditional and bioreactor landfills are presented in Fig. 1. It should be noted that the decay rate for a biroeactor landfill has not been verified and is used here to represent accelerated decomposition.

Properties of MSW

One of the major challenges for the geotechnical engineers is to determine the soil properties with the variation of material content within them. Quantification of engineering properties is extremely important. Environmental geotechnics deal with soil as well as different kind of waste materials contained within them. The reliable knowledge of geotechnical properties of these waste materials is required for the evaluation and prediction of actual behavior of landfill. Determination of Municipal Solid Waste properties is extremely difficult as stated by Manassero et.al (1997) due to the following reasons:

1. It is difficult to obtain samples of relevant size to be representative of in situ condition,
2. There are no generally accepted sampling procedure for waste materials,
3. The properties of waste materials changes drastically with time,
4. The level of training and education of the personnel on site is not high enough to deal with all necessary basic interpretation and understanding of the measurements, and,
5. Municipal solid waste is inherently heterogeneous and variable among different geographical locations, (Table 2)

Physical Properties Municipal Solid Waste

Although proper waste characteristics and adequate model to predict behavior, are required, few authors have tried to determine waste properties. Landva and Clark (1990),

Gabr and Valero (1995), Manassero et.al (1997) have determined compressibility, degradability and other characteristics of MSW. In general, waste are commonly divided into two types (ETC8, 1993):

- Soil-like waste defined as granular waste (for example fly ash and bottom ash), for which conventional soil mechanics testing and soil mechanics theory to a large extent is applicable. In case of MSW this models are far from realistic.
- Other waste for which engineering properties should be defined as case by case.

Classification

Considering the biodegradability of the waste materials, the classification system suggested by Landva and Clark (1990) are shown in Fig. 2. The materials classified as ON,IN,ID may contain large void-forming object which affect the engineering characteristics of the waste fill. According to the authors, the classification system along with visual inspection should be supplemented with water content, specific gravity, organic content and particle size distribution. Sowers (1968, 1972) discussed the major components of the waste materials, which affect the bearing capacity of soil greatly (Table 3).

Composition

Barlaz (1990) showed the refuse composition on the basis of visual inspection, which is shown in Table 4. It should be noted that at different time of the year, the material in the waste varies. Geographical location also plays a very important role in the composition of the landfill.

Westake (1994, Table 5), Manassero et. al (1997, Table 2) showed comparative data among the different countries and different parts of the world. These complex and variable nature of waste composition make it difficult to predict or generalize the waste properties in a particular landfill. Chemical composition of the MSW has been published, and they are an important constituent to characterize the compressibility of waste fill. Barlaz (1990) indicated that the cellulose and hemicellulose fraction accounts for 91% of its methane potential (Table 1).

Moisture Content

For the purposes of characterizing the amount and distribution of liquids within an MSW landfill, mechanisms of moisture retention within the waste mass was classified as follows (Zornberg et. al. 1999):

1. moisture within the waste particles (i.e. within intraparticle voids)
2. moisture between particles (i.e., within interparticle voids), held by capillary stress
3. moisture between particles, retained by low hydraulic conductivity

There is generally limited information regarding the in situ moisture distribution with depth in MSW landfill. The moisture content of the solid waste (w) can be defined as the wet weight (w_w) or dry weight (w_d) method. The following two equations are used for the calculation of moisture content:

Equation 3(a) $w_w = (w_o - w_1)/ w_o$

or

Equation 3(b) $w_d = (w_o - w_1) / w_1$

where,

w_o = initial weight of sample,

w_1 = weight of sample after drying

Zornberg et. al. (1999) presented the relationship between the volumetric moisture content, θ and gravimetric moisture content w_w. In situ volumetric moisture content is the ratio between the volume of liquid and total control volume ($\theta = Vw/V$)

Equation 4 $\theta = (\gamma_d/\gamma_w).w_w$

where,

γ_d = bulk dry unit weight of porous material

γ_w = unit weight of water

w_w = gravimetric moisture content

In data collected from San Gabriel Valley landfill (Zornberg et. al. 1999), the average gravimetric moisture content is reported to be 28% and do not show a

significantly increasing trend with the depth. But the volumetric moisture content increases with depth.

Huitric (1981) and Tchobanouglous (1993) reported that for most of the domestic landfill in the USA, the moisture content varies from 15% to 40% depending on the composition of the waste, season of the year, the natural humidity and weather condition particularly rain. The moisture content for different authors is presented in Table 6.

Blight et.al. (1992) showed that water content in the waste at a depth of 3-5m increased by a factor of two between the period of 1988 and 1990. This was due to the unseasonal precipitation. Gabr and Valero (1995) presented results from the test made at the Pioneer Crossing Landfill, Pennsylvania. The authors showed that the water content can be 30% near the surface and as high as 130 % at greater depth closer to the ground water table (Fig 3). The general trend is increase in moisture content and liquid limit with depth as waste decomposition is increased. An opposite is reported by Columbus et.al (1995) from the Ano Liossa Landfill in Greece. Upto 15m depth the water content is more than 60% but decrease with depth to less than 40%.

Organic Contents

The organic content in a landfill affects the compressibility characteristics of the waste. Barlaz (1990) , Landva and Clark (1990), Gifford et.al (1990) showed that the organic content ranges from 5 to 75 % with the major constituents being cellulose and hemicellulose. The organic content, cellulose and hemicellose, is higher at surface level and low at a deeper depth (Barlaz, 1988). The author suggested that due to the complete decomposition at the deeper depth, the cellulose content is lower. Landva and Clark (1990) showed that with increasing organic content, water content also increases and surface area increase due to the breakdown of particles. Wall and Zeiss (1995) reported that with the increasing organic content, the compression index increased. Therefore the organic content in the waste material should play a vital role for the development of compressibility model.

Unit Weight

The unit weight of landfill materials varies widely due to variations in the waste constituents, state of decomposition, degree of control during placement (such as thickness of daily cover or its absence), amount of compaction, total depth of landfill, the

depth from which the sample is taken, amount of water or lechate present etc. Domestic waste usually weights higher than industrial waste. Table 7 (Oweis and Khera, 1998) shows the range of uncompacted and compacted municipal solid waste components. Fassete (1994) reported that unit weights ranged from 3-8 kN/m^3 for uncompacted waste, 5-9 kN/m^3 for moderately compacted waste and 10-11 kN/m^3 for well-compacted waste.

Zornberg et.al. (1999) completed a field investigation for the total unit weight profile of the waste for the San Gabriel Valley in Log Angeles County, California. The total unit weight ranged from 10 kN/m^3 to 15 kN/m^3 between 3m and 55m below the landfill surface. The upper 3m and lower 3m showed higher unit weights of the waste.

Landva and Clark (1990) proposed a unit weight determination method, which takes into account the intraparticle and interparticle void, porosity and degree of saturation. In general the average dry unit weight of the constituents is (Landva and Clark, 1990):

Equation 5 $$\gamma_c = \frac{1}{\sum_1^n \frac{w_i}{w_c} . \frac{1}{\gamma_i}}$$

where: γ_i = unit weight of solid portion of an individual constituent i

$\frac{w_i}{w_c}$ = weight of constituent I as a fraction of the total weight w_c of the constituents

n = number of constituents

When exposed to water, the unit weight of the constituents absorbing water would increase. A new average unit weight of the constituents would be as follows (Landva and Clark, 1990):

Equation 6 $$\gamma_c{}' = \gamma_c \left[1 + \sum_1^n \frac{w_i}{w_c} . \frac{\Delta\gamma_i}{\gamma_i} \right]$$

where: $\Delta\gamma_i$ = increase in unit weight of constituent i

all others are same as equation 5

Using the typical composition of a landfill and using equation 6, Landva and Clark (1990) determined the possible range of unit weight for the lightest and heaviest

combination given in Table 8. The lightest combination yields 3.6 kN/m^3 and the heaviest combination yields 16.4 kN/m^3. It was emphasized that these are the average unit weights of the constituents, not the unit weight of the waste aggregate. The unit weight of the waste aggregate could be determined if the porosity and void ration for the same material is known as well as the degree of saturation. Overall range given by the authors is 6.8 to 16.2 kN/m^3.

Exact means of determining unit weight in-situ are not known. Landva and Clark used the excavation method. They measured the depth and width of the excavation and weighted the excavated materials. Then they oven-dried the material in pottery klin. In the end, they reported the in situ unit weight to be 6.2 to 16.8 kN/m^3. Table 8 shows that, the very high variability in the municipal waste can be expected. This is a complicating factor for determining the influence of self-weight on the settlement of waste.

Gabr and Valero (1995) determined the compacted unit weight and optimum moisture content through compaction tests. The maximum dry weight density was 9.3 kN/m^3 and optimum moisture content was 31%. The variation of the measured unit weight with increasing moisture content was similar to that observed in soil. Full saturation was achieved at approximately 70% water content with a unit weight of 8 kN/m^3. A unit weight of 12 kN/m^{3}was estimated from the zero air void curves at moisture content of 31%.

Specific Gravity

Sowers (1972) suggested that precise determination of specific gravity may be not justified considering the complex nature of waste. Landva and Clark (1990) mentioned that the waste contains both intraparticle voids and interparticle voids. The determination of specific gravity is possible for the saturated intraparticle voids and dry intraparticle voids. The typical values for the waste materials are hardly available. Gabr and Valero (1994) determined the specific gravity of the waste using fine fraction (<200 sieve). The specific gravity was determined to be 2.0 with a variance of 0.0032 using entire waste grain size distribution, and 2.4 for the fine-grained part of the waste. The lower value was estimated due to the presence of decomposed organic matter, which has a specific gravity of 1.

pH

Barlaz (1990) reports that the pH of the refuse in the anaerobic acid phase remained between 5.7 to 6.2. The microbial population, gas production and chemical constituent's data are presented in Fig. 4. This, in fact, is four phase characterization of refuse decomposition. Therefore the pH is a very good indication for the decomposition grade.

Grain Size Distribution

Wastes are classified as a) soil like and b) other waste. Soil mechanics concepts are difficult to apply for waste. One of the basic approaches to identify the waste is to run a gradation test (Jesserberg, 1994) for the various portions of the material. The interesting observation is that the tendency to increase in fine grain materials with aging. Two-particle size determinations of waste cuttings from 14.5m to 19.2m depth were performed by Gabr and Valero (1995). For the shallow depth, the specimens were oven dried and mechanical sieve analysis was conducted. For 19m depth, the specimens were washed through each sieve used in the test. Hydrometer analyses were conducted for materials passing through the No. 200 sieve. Fig. 5 shows the results of both the mechanical and hydrometer test results. Specimen from shallower depth indicated coarser particle distribution. The difference in grain distribution may be due to the higher degree of decomposition of the deeper sample, the conglomeration of the particles in dry sample as well as the difference in dry and wet sieve method. Grain size distribution is very helpful for the classification of waste. According to Landva and Clark (1990) at least a partial grain size distribution can also be helpful.

Hydraulic Conductivity of waste

New solid waste facilities are required to install liner and leachate control and collection system. Proper assessment of hydraulic conductivity of waste is an important parameter because of the potential impact related to the uncontrolled leachate and stability problem. Table 9 gives a summary of reported hydraulic conductivity of waste determined by different methods. These values are influenced by degree of decomposition, aging, sample depth etc.

Engineering Properties of Municipal Solid Waste

The determination of the engineering properties of waste is a difficult task. For fine-grained soil like waste, mechanical properties like shear strength, compressibility, swelling and shrinkage behavior can be determined by using the conventional geotechnical test methods. But for the mixed and coarse-grained waste the conventional method is not appropriate for determination of mechanical properties. Most of the waste mechanical properties and compressibility are determined from estimation, back calculation or laboratory/ field-testing.

Review of Compressibility and Shear Strength

There is a dearth of data on the physicochemical and biological effects of leachate recirculation on the compressibility and strength properties of MSW. As waste decomposition is enhanced through leachate recirculation, there are gaps in the literature regarding (1) changes in waste properties with time and stress level, (2) methods for evaluation of the magnitude and rate of settlement as a function of moisture content, (3) the impact of leachate recycle on waste strength and above-grade slope stability, and (4) the configuration of stable and cost-effective "interim" and final cover designs to meet the objective of operating and then closing a bioreactor landfill.

Waste Compressibility Parameters

The compressibility properties of waste are of special importance when designing the interim and final closure covers for solid waste landfills. The variability of the waste properties has been highlighted in the previous sections and such variability is expected to affect cover stability as decomposition takes place. Factors affecting changes in waste compressibility include physiochemical and biological changes and decomposition of the waste, distortion and reorientation of the refuse, erosion of the fine material into large void due to the nature of the waste and long term creep process.

It was established that MSW settles substantially under its own weight as well as under external loads. Sowers (1972) estimated that waste settles 10 - 30% of its original height under its own weight within one to two years of burial. This is also confirmed by test results suggested by Gandolla (1995, Fig. 6). The magnitude of settlement decreases over time and with increasing depth below the surface of the fill. However, past research did not systematically characterize the change in waste compressibility as a function of

degradation, as current regulations call for entombing and fossilizing the waste material by minimizing moisture infiltration. Unlike soil, the landfill experiences differential settlement causing a lot off damage in the structures and developments over the landfill (Sowers, 1968 & 1972, Edil et.al 1990, Ling H.I, 1999). Dodt et.al, (1987) measured differential settlement in the order of 1 inch vertically for every 10 feet horizontally during vertical expansion of an existing landfill. Sowers (1968) explains large, relatively hard inclusion such as appliances or boulders are responsible for such differential settlement. Sowers (1972) showed that waste settlement was similar to that of peat with large initial consolidation and substantial secondary compression. Rao (1977) indicated that a settlement time curve from waste specimens might vary from those for typical clay soils but is similar to those from organic soils and peat.

Since waste exhibit a highly compressible skeleton, primary and secondary consolidation occur simultaneously. It is difficult to identify the magnitude of primary settlement as well as time taken for the settlement. The primary settlement of waste may take place shortly after fill placement, within a few months. The determination of secondary settlement is a major concern because a large reduction of volume occurs due to waste decomposition through biological and chemical process (Ling et.al.,1999). The decomposition process is complicated by many factors such as the type of materials, moisture content, temperature and so forth. For aerobic moist conditions above the water table, secondary compression is three times as great as for anaerobic conditions below a stagnant water table (Sowers, 1968).

Based on the mechanism proposed by Sowers, the factors affecting the magnitude of settlement are many and are influenced by each other (Edil et.al, 1990). They include:

1. initial domestic waste density or void ratio;
2. content of the decomposable materials in the waste;
3. fill height;
4. stress history (treatment during and after placement);
5. leachate level and fluctuation;
6. environmental factors (such as moisture content, temperature and gases present to generated within the landfill).

For analysis of load-induced settlement, methods derived from soil mechanics concepts include using elastic approaches, or e-log p from consolidation testing method (Sowers, 1973). Landva and Clark (1990), Gabr and Valero (1995) have conducted some of the conventional and unconventional test and the results are plotted in Figure 7. These results show the very high compressibility of waste. Typical values of Compression Ratio, CR, is in the range of 0.2 to 0.5 depending on the stress level whereas rate of compression index, $C\alpha e$ was found to be in the range of 0.2% to 3%. It also appeared that $C\alpha e$ increased with increasing organic content. Gabr and Valero (1995) conducted small scale compression test (conventional equipment) on old waste samples (15 to 30 years old). The CR was found to be 0.15 to 0.22 and $C\alpha e$ ranged between 0.8 to 0.9%. The compression index were between 0.4 and 0.8 for a void ratio of 1.0 to 3.0, the secondary compression index ranged from 0.03 to 0.09 and appeared less dependent on void ratio and more dependent on microbial activity conditions.

Coumoulous (1999) evaluated secondary settlement data from 13 landfill case studies and showed a range of the secondary compression coefficient from 0.02-0.07. Sharma (1999) also studied old landfills (10-15 years old) and found secondary compression coefficients to be between 0.02 and 0.07. In comparison, El Fadel and Al-Rashed (1998) analyzed 1576 days of settlement data from the Mountain View landfill test cell that was operated with leachate recycle and computed a secondary compression coefficient of 0.1-0.32. These values are five times the values obtained by Sharma (1999) and Coumoulous (1999).

Earth Tech Consultants (1999) studied several landfills for evaluation of the secondary compression coefficient. The computed values ranged from 0.02 to 0.088, 0.006 to 0.035, and 0.18 to 0.26 for the Atlantic Landfill, Central Landfill, and Crow-wing Landfill, respectively. Crow-wing landfill was one of the few landfills operated as a bioreactor. The secondary coefficient in this case was relatively higher than values computed from traditional landfills and matched El-Fadel and Al-Rashed's data from the Mountain View Landfill bioreactor cell. Unfortunately, none of the reported work correlated compressibility coefficients with the chemical composition of the waste.

Waste Compressibility Model

Most settlement models applied to solid waste were developed for inorganic soils or peat and were not necessarily developed considering leachate recirculation. The models used for refuse were typically developed using one of the following approaches:

1) Based on traditional methods for clay settlement using consolidation data,
2) based on rheological simulation in which the soil, waste skeleton, was replaced by Hookean spring and dashpots,
3) based on correlation with field and laboratory test data and application of rate process theory or
4) A combination of the above three approaches.

These approaches provide a convenient, familiar, and relatively simple methods to evaluate and model waste compressibility. However, in the case of bioreactor landfills, time-dependent settlement will be due to compressibility of the waste matrix as manifested by changes in waste stiffness with decomposition as well as waste density. Waste settlement will include creep and biological components due to the heterogeneous nature of waste particles, and accelerated cellulose and hemicellulose biodegradation, respectively, as leachate is recycled. On a conceptual level, the compressibility of waste can be viewed as due to mechanistic (layer weights), creep (rearrangement of waste particles as physiochemical changes takes place) and biological (increase in void space and compressibility as solid-to-gas conversion takes place).

Conventional Compressibility Model

The most frequently applied model is Sowers (1968) model. The model is simplified one-dimensional compressibility model with an empirical term to account for time dependent secondary compression effects. The equation, which represents the model, is as follows:

Equation 8 $$\Delta H = \frac{C_c.H}{1+e_o}.\log\left(\frac{\sigma_o' + \Delta\sigma}{\sigma_o'}\right) + \frac{\alpha H}{1+e_o}.\log\left(\frac{t}{t_p}\right)$$

Where: ΔH = vertical settlement

C_c = mpression index

H = initial thickness of the layer under consideration (before compression)

e_o = initial void ratio

σ'_o = initial effective vertical stress acting at the middle of the layer

$\Delta\sigma$ = change in effective vertical stress

α = secondary compression factor (gradient of void ratio log time curve)

t_p = time at the end of primary consolidation

t = any time of interest > t_p

Either laboratory consolidation tests or field settlement data can be used for the construction of void ratio versus log pressure curve, and void ration versus log time curve, on order to estimate Cc and α. As with soils, the compression index is the average slope of the void ratio versus log pressure curve, in the applicable stress range, while the slope of void ratio versus logarithmic time beyond 100 percent "primary consolidation" defines the secondary compression factor. Alternatively Sowers (1973) showed that C_c and α are related to the initial void ratio, e_o in the following manner:

Equation 9 $C_c = p.e_o$

Equation 10 $\alpha = s.\ e_o$

Where: p = 0.15 for fills with low organic content,

= 0.55 for fills with high organic content

s = 0.03 for conditions unfavorable to dacay

= 0.09 for conditions favorable to decay,

all the terms are as equation 8

Therefore, if organic content, conditions for decomposition, and initial void ratio are known, the Cc and α can be determined. According to Sowers (1973) the laboratory consolidation test data can not be used for the waste due to heterogeneity and large particle size. The author suggested that field test data should be used for the model parameters. Furthermore the initial void ratio determination for the waste is also a very difficult task.

Rao et.al (1977) developed a model to predict the total settlement of the waste as a function of load neglecting the time affect on the settlement. This model is not very popular as the waste settlement continues for a very long period of time due to the

biodegradability of the waste. According to the authors the conventional void ratio log pressure curve cannot be used for the waste as there is no way of computing reliable void ratio. To estimate the total settlement, Rao (1977) used the following equation:

Equation 11 (a) $$S = H_o \frac{\frac{\Delta H}{H_i}}{\frac{H_o}{H_i}}$$ (considering Fig. 8.a)

where: S = settlement

H_o = existing thickness of refuse

H_o/H_i = relative height corresponding to the existing overburden pressure σ_o

$\Delta H/H_i$ = change in relative height corresponding to the stress increment $\Delta\sigma$

Equation 11 (b) $$S = H_o \frac{C_s}{\left(H_o / H_i\right)} \log \frac{\sigma_o + \Delta\sigma}{\sigma_o}$$ (considering Fig. 8.b)

The rheological model proposed by Gibson and Lo (1961) for the long term secondary compression of soils was found to be useful in predicting settlements of peat Representation of the rheological model is shown in Fig. 9 (Edil et.al, 1990) and it represents the one-dimensional compression of refuse fill. The applied stress may be self-weight or load imposed on the landfill. When a stress increment $\Delta\sigma$, acts on the model, Hookean spring, with a spring constant a, compress instantaneously. This is same as primary compression. The compression of lower spring with a constant b parallel to dashpot (viscosity of λ/b) is retarded by Newtonian (linear) dashpot. This is analogous to the continuous process of secondary compression. After a long time the load will be taken by the two springs. The equation in this case is as follows (Gibson and Lo, 1961):

Equation 12 $$S(t) = H \in (t) = H.\Delta\sigma\left\{a + b(1 - \exp\left[-(\lambda / b)t\right]\right\}$$

Where:

S = settlement

H = initial height of refuse

ε = strain (settlement divided by the layer thickness i.e., S/H)

$\Delta\sigma$ = compressive stress

a = primary compressibility parameter

b = secondary compressibility parameter

λ/b = rate of secondary compression

t = time since the load application

To evaluate the parameters a, b and λ/b, Lo et.al (1976) show that the equation can be expressed as follows also:

Equation 13 $$\log\left(\frac{\partial \in}{\partial t}\right) = \log(\Delta\sigma.\lambda) - 0.434.\frac{\lambda}{b}.t$$

Where: $\partial\varepsilon/\partial t$ = strain rate in secondary range, other terms are as same as equation 12

A plot of logarithmic strain rate versus time (Fig. 10) produces the straight line described by the equation after dissipation of pore water pressure. The parameters b and λ can be obtained from the slope and intercept and a may be evaluated by substituting a known strain at a particular time into equation 12.

This model also assumes classical Terzaghi's assumptions of consolidation and suffers some theoretical inadequacies. Additionally parameter variation analysis performed by Lo showed a value to be mildly nonlinear with time and λ to be strongly non-linear with time. Edit et.al (1990) pointed out that as average strain rate increases, so does the rate of secondary compression. The same was also observed for peat soil and indicates that the dashpot is essentially non-linear in the model. The implication is that the parameters obtained from a given field test on refuse should be extrapolated with much care for settlement prediction at another fill with different applied stress.

Bjarngard and Edgers (1990) and Fassette et.al (1994) compiled available MSW landfill data, evaluated the data, and proposed two models for the prediction of settlements in landfills. The model proposed by Bjarngard and Edgers (1990) is presented below (Fig.11):

Equation 14 $$\frac{\Delta H}{H} = CR\log\frac{P_o + \Delta p}{P_o} + C\alpha_1\log\frac{t_2}{t_1} + C\alpha_2\log\frac{t_3}{t_2}$$

Where:

ΔH = settlement

H = initial thickness of waste layer

$\Delta H/H$ = vertical strain (normalized settlement)

Po = Initial average vertical effective stress

ΔP = average induced vertical stress increment

t_1 = time (days) for completion of "initial" compression as in Fig. 11

t_2 = time (days) for completion of "intermediate"compression as in Fig. 11

t_3 = period of time (days) for prediction of settlement as in Fig. 11

CR = compression ratio

$C_{\alpha 1}$ = intermediate secondary compression index

$C_{\alpha 2}$ = long term secondary compression index

Fassett et.al (1994) model is same as the previous model except the two secondary compression indices for intermediate and long term are combined into one denoted as Cα. Equation 15 $\frac{\Delta H}{H} = CR \log \frac{P_o + \Delta p}{P_o} + C_\alpha \log \frac{t_f}{t_i}$

Where: $t_f = t_3$ & $t_i = t_1$ as in equation 14

$C_{\alpha 2} = C_{\alpha 2} = C_\alpha$ as in equation 14 , all other terms are same as equation 14

Bjarngard indicated that short term settlement versus vertical stress generally exhibits a linear behavior. On the other hand, Fassett et al (1994) indicated that strain versus log vertical stress is often non-linear. These models are expressed in terms of effective stress. Since the waste mass is generally in moist state, the use of total stress for the prediction of settlement would be appropriate as well. The initial vertical stress is extremely important for the prediction of settlement and therefore site specific unit weight data are required rather than being assumed.

Power Creep and Hyperbolic Model

Edil et. al (1990) investigated the power creep model for time dependent settlement prediction under constant stress. This model has been extensively used for the transient creep behavior of many engineering materials. The time dependent settlement can be expressed as:

Equation 16 $$S(t) = H.\in t = H.\Delta\sigma.m.\left(t/t_r\right)^n$$

where: S = settlement

H = initial height of refuse

$\Delta\sigma$ = compressive stress

m = reference compressibility

n = rate of compression

t = elapsed time since loading

t_r = reference unit time to make time dimensionless

The logarithmic strain versus logarithmic time method is used for the evaluation of m and n. the logarithmic strain versus logarithmic time graph (Fig. 12 & 13) is plotted using the laboratory or field test data. The slope of the line is used as n value whereas the intercept is the value for m. The reference compressibility m shows no discernible pattern with respect to placement condition of the refuse. Rate of compression n indicates some pattern with respect to age and placement conditions of the refuse (Edil et.al, 1990). These model parameters lack physical meaning.

Ling et. al. (1998) combined the logarithmic function and power function and proposed new empirical relationship for the settlement prediction of waste. A hyperbolic model is also proposed as an improved tool for the time-settlement relationships and to predict the final settlement as well. Logarithmic function (Yen and Scanlon, 1975) is used to determine the settlement using the following equation:

Equation 17 (a) $$\rho = \frac{dS}{dt} = m - n.\log t$$

where m and n = positive empirical constants.

t = time

ρ = settlement rate

This is known as ρ-log t, or logarithmic function.

Power function has been used by Edil et al (1990) for the settlement prediction with time as follows:

Equation 17(b) $$\rho = \frac{dS}{dt} = \frac{p}{t^q}$$

Where p, q = positive empirical constants.

ρ = the settlement rate at unit time

Since the logarithmic function and power function express strain rate-time relationship, they can be integrated with respect to time to predict settlement.

Equation 17(c) $S = [m - n(\log t - 1)]t$

Equation 17(d) $S = \frac{p}{1-q} t^{1-q}$

The settlement may be expressed directly using log t and power functions as follows:

Equation 18 $S = m' + n' . \log t$

Equation 19 $S = p' . t^{q'}$

Ling et.al. (1998) model gives negative settlement for very large times. This indicates that the landfill undergoes expansion which is physically impossible. The logarithmic function does not allow a maximum time to be defined such that the final settlement will be determined when settlement rate approaches to zero. A solution does not exist for settlement rate equal to zero.

Hyperbolic function (Ling et. al. 1998) has been used successfully for the settlement of embankment on soft clay. For the prediction of MSW settlement, the following expression was used:

Equation 20 $S = \frac{t}{1/\rho_o + t/S_{ult}}$

Where t = difference between time of interest and time of starting measurement

= ti – to

S = difference between settlement at time ti and that measured at time to

= Si – So

ρ_o = initial rate of settlement (at t = to)

S_{ult} = ultimate settlement (i.e. at t = α)

It is likely that the final settlement will be 80% - 95% of ultimate settlement. The time taken to reach 95% settlement is calculated as $t_f = 19S_{ult}/\rho_o$. This model is useful when there is a change in loading condition such as waste recharging. The hyperbolic

model (Ling et.al., 1998) gave better prediction of long term settlement over log t and power functions.

Biological Model

By considering approximately 25 case studies, Edgars et al (1992) developed a refuse settlement model which takes into consideration the microbiological process within the landfill. Edgars et.al (1992) observed that several fills which were initially modeled successfully by rate process had experienced a marked increase in compressive strain rate after extended period, some of which did not experience direct exposure to oxygen as in Sowers (1972) case. According to them, this increase was due to rapid biological decomposition corresponding to the exponential growth phase of microorganism in the fill. They also suggested that the long time lag phase, years in some cases, is a result mass transfer limitations and mixed microbial populations within the landfill. Based on these observations, Edgars et al proposed modeling landfill settlement as a creep rate process until a critical time where biological decay must be accounted for. Equation 21a and 21b express compression due to structural creep as linear and non linear functions of logarithmic time, respectively. These equations were originally proposed by Singh and Mitchell (1968) to model creep deformation of soil. Singh and Mitchel suggested testing two identical samples at different creep stress levels to evaluate A and α. However, Edgars et al (1992) indicated that all parameter may be evaluated from a single set of time-settlement data.

Equation 21a $\in = \in_1 + A.e^{\alpha D}.t_1.\ln\left(\frac{t}{t_1}\right)$; when m=1

Equation 21b $\in = \in_1 + \frac{A.e^{\alpha D}}{1-m}.t_1.\left\{ \ln\left(\frac{t}{t_1}\right)^{1-m} - 1 \right\}$; when m=1

Where: ε = compressive vertical strain

t = elapsed time

ε_1=known strain at time t_1

D =stress level

A= creep parameter reflecting composition structure and stress history

α = creep parameter indicating stress intensity effect on creep rate

m= creep parameter controlling strain rate decrease with time

To determine the parameters, a plot of logarithmic of strain rates versus logarithmic of time, as shown in Fig. 13 must be constructed. The slope of best fit line through the data points where strain rate is decreasing yields m while the intercept at t_1 represents the quantity $A.e^{\alpha D}$.

Equation 22 predicts compression due to biological decay. Edgars et al based this on the growth cycle of the microbial population within a landfill as in Fig 14.

Equation 22 $\in_{bio} = B\left[e^{\beta(t-t_k)} - 1\right]$

Where: ε_{bio} = compressive vertical strain due to biological decomposition

β = average landfill microorganism growth rate

B = scale factor relating field settlement to growth kinetics

t = elapsed time

t_k = critical time at which strain rate increase due to biological activity

The equation was developed on the basis of the following assumptions:effects of decomposition are small until some critical time , t_k, (possibly corresponding to the lag phase), when strain rate increases, (ii) decomposition and associated gas production is characterized by exponential bacterial growth and (iii) strain due to decomposition is directly proportional to the number of bacteria present. This is the model, which considers the biological process into landfill settlement calculation. But there is no accurate method available to predict t_k.

Wall and Zeiss (1995) studied the ability of biological enhancement to reduce the time to reach biological stabilization of the waste to nondegradable matter and to determine the effects of biodegradation on settlement. The initial, primary and secondary compression was calculated using conventional (Sowers) models. The authors acknowledged the limitations of using the Sowers model but reasoned that Sowers model attributed secondary settlement of waste to the combination of mechanical secondary compression, physiochemical action and biochemical decay. The authors suggested that increased rate of degradation due to favorable biological conditions results in higher values for secondary compression index, and thus higher settlement rates.

Six cells were tested and monitored during the whole process of the test. Three of them were enhanced cells while three others were inactive cells. All cells were monitored for gas composition and volume, leachate pH and total organic carbon, and refuse settlement. In order to calculate rate constants, first order kinetics were used on carbon mass balance data.

Wall and Zeiss (1995) observed that during the first period of secondary settlement biodegradation has very little effect on the secondary settlement rates. To determine whether an effect of solids removal on settlement is probable, the percentage of carbon decomposed during the test period (250 days) and estimated five year predictions were compared to present and future secondary settlement and rates. The total mass of solids decomposed during the test period were 1% whereas the secondary settlement at the same period accounts for a deformation of 4%. That means decomposition does not have a significant effect on the rate of secondary settlement. At this time, either bridging between the refuse particles or creation of a skeleton of large objects or both may mask the contribution of decomposition to the settlement rate. Five years future predictions can be derived from settlement and biodegradation model. By using the first order model and the measured rate constants, the organic carbon mass loss in five years will be equal to:

Equation 23 $$C_o - C_t = C_o - C_{o.}e^{-k.t}$$

Where: C_o = initial carbon mass

C_t = carbon mass at time t

k = constant

The lost organic carbon mass indicates 5-8% of the total refuse. From their results, it is evident that settlement occurs at a faster rate than the decomposition initially then slows considerably. This predicts that decomposition will become increasingly significant over time.

This decomposition of mass at a lower rate initially can be related with Edgars et.al. model (1992) where they observed a lag period for the bacterial growth and the decomposition peaks at a faster rate. But they could not define or propose an accurate

tool for the determination of that lag period. Wall and Zeiss (1995) concluded that enhancing initial settlement with the addition of water can significantly increased the capacity of landfill. The research is limited over a short period and extrapolated results need to be verified over the period to link between the secondary compression and refuse decomposition.

Park and Lee (1997) presents a mathematical model that considers the decomposition process of biodegradable refuse from a geotechnical point of view and suggested the overall compressibility behavior of refuse including decomposition effect. The theoretical compressibility curve, which takes into account most of the characteristics of refuse deformation, proposed by Grisolia and Napoleoni (1995) were considered for the settlement analysis. This curve is divided into five stages: Phase I : the initial settlement stage, which shows large reduction in the macro porosity by arrangement of deformable materials, Phase II : the initial residual settlement stage; Phase III : the mechanical secondary settlement stage which may be caused by long term slipagges, reorientation of materials and deformation induced by decomposition of biodegradable elements; Phase IV : the decomposition completion stage, in which settlement due to decomposition has mostly completed; Phase V : the residual settlement stage, which is characterized by long term slippage's and reorientation of residual materials. Therefore the long term secondary settlement is due to the mechanical secondary compression and decomposition.

This can be expressed as:

Equation 24a $\Delta\varepsilon\,(t)_{\text{long-term}} = \Delta\varepsilon\,(t)_{\text{mec}} + \Delta\varepsilon\,(t)_{\text{dec}}$

Mechanical secondary compression ($\Delta\varepsilon_{\text{mec}}$) occurs due to long term slippages, reorientation of the particles and delayed compression of some refuse materials. This can be expressed as:

Equation 24b $$\Delta \in (t)_{mec} = C_{\alpha} Log\left[\left(t + \Delta t\right)/t\right]$$

Where C_{α} : the rate of secondary compression

Secondary compression due to decomposition ($\Delta\varepsilon_{\text{dec}}$) is a complex process that is developed by a mixed population of microorganism. The strain caused by the biodegradable solids at time t has been expressed as (Park and Lee) :

Equation 25 $\varepsilon(t)_{dec} = f(\varepsilon_{tot\text{-}dec}, k) = \varepsilon_{tot\text{-}dec}(1\text{-}e^{-kt})$

where: k : strain rate due to decomposition

$\varepsilon(0)_{dec} = \varepsilon_{tot\text{-}dec}$,total compression due to decomposition of biodegradable refuse.

The authors has applied this model for the aged refuse landfill and found that decomposition induced a considerable amount of compression in the overall settlement behavior. It was also found that the biological strain would be completed within 3-5 years. These results are contradicting the finding of Edgars et al (1992) and Wall and Zeiss (1995), who found that decomposition becomes significant after a lag time.

In summary, no models are available in literature which considers the effect of leachate recycling on compressibility of solid waste. Bjangard and Edgers (1990) compiled data from traditional landfills and proposed a model for the prediction of settlement. Fassett et al. (1994) later presented an extension of the 1990 model with the two secondary compression indices ($C_{\alpha 1}$ and $C_{\alpha 2}$) for intermediate and long-term compression combined into one term, denoted C_1. Models presented by Bjamgard and Edgers (1990) and Fassett et al. (1994) make assumptions similar to those in Terzaghi's model. Mitchell et al. (1995) and Wall and Zeiss (1995) discussed the use of Terzaghi's classical consolidation approach for prediction of waste settlement. Mitchell et al. (1995) recognized that the mechanistic-based behavior of MSW during the early phases of landfilling did not conform to Terzaghi's model. Wall and Zeiss stated that fresh refuse was normally not saturated and has a coefficient of permeability similar to that of sand and gravel such that liquid is readily expelled from the voids. Notwithstanding, Wall and Zeiss (1995) used Terzaghi's approach in analyzing measured settlement results from field test cells that were monitored for approximately 8 months. They were able to curve fit the measured data using a form of Terzaghi's model. El Fadel and Alrashed (1998) used the power Creep model and a one-dimensional consolidation model to analyze data from the Mountain View bioreactor test cells (tests by Emcon, 1982-1986) in which leachate recycle was one of the test parameters. The authors were able to curve fit the measured data using the Terzaghi's I -D approach although the fit was not possible without field measurements being known in advance. There is a lack of knowledge on the impact of biological changes on waste compressibility properties with time in landfills

with leachate recycle operation. With the exception of Mountain View Landfill data and the recently-started Yolo County test, past work reported in the literature did not document solids composition and gas generation potential in conjunction with compressibility or strength parameters. On the other hand, once an understanding of how compressibility parameters change with decomposition is achieved, a simple model can be developed to provide engineers and regulators with a needed analytical tool to estimate available air space, provide estimates of deformation associated with future vertical expansions/land use of landfills, and assist with the design of interim and final cover systems. Such a model should account for changes in material characteristics as a function of the waste biodegradation rate.

Shear Strength

In addition to settlement, the evaluation of waste shear strength is important for the design of waste slopes, covers, vertical expansions and future land use, as well as assessing the seismic stability of landfills. Traditionally, failures of waste slopes are not highly publicized, or published, although they are known to occur. One of few of cases reported in literature was by Stark et al (2000) in which they indicated that strain incompatibility and progressive failure can occur between MSW and underlying materials and lead to a reduction in mobilized shear strength and failure. A number of studies have been conducted on the shear strength of MSW, e.g. Landva and Clark (1986); Siegel et al. (1990); Singh and Murphy (1990); Gabr and Valero (1995); and Edincliler et al. (1996).

Shear Strength Parameters of MSW

Landva and Clark (1986) determined drained shear strength parameters for old refuse samples. They measured friction angles ranging from 38° to 42° and cohesion's (c) ranging from 16 to 19 kPa.

Landva and Clark (1986) also conducted direct shear test on fresh shredded refuse containing a large amount of plastic sheet waste. They found the friction angle of 24° and cohesion of 23 kPa. The low friction angle was attributed to sliding between plastic sheets.

Siegel et. al (1990) conducted direct shear test under consolidated drained condition on specimens of refuse 13 cm in diameter and 7.6 to 10.2 cm high. The

samples were collected from 4 to 25 m depth and each specimen having different composition. The friction angle were between 39 ^{o} and 53 ^{o}. The authors assumed cohesion to be zero.

Howland and Landva (1992) conducted direct shear test in a large shear box (43.2 cm x 27.9 cm) using 10 to 15 years old waste. The shearing rate was adjusted to maintain drained condition. They reported that the strength of MSW is primarily frictional in nature. From their tests, a friction angle of 33 ^{o} and cohesion of 17 kPa were obtained.

Gabr and Valero (1995) tested MSW 10 to 15 years old in direct shear using a circular 6.35 cm diameter and 2.3 cm thickness shear box. The specimen contained particles smaller than 6.3 mm and large particles were removed before the test. Friction angles ranging from 20 ^{o} to 39 ^{o} and cohesion ranging from 0 to 28 kPa were obtained. Gabr and Valero (1995) conducted consolidated undrained triaxial tests on MSW with and without measuring pore water pressure. They reported an average effective friction angle of 34 and effective cohesion of 17 kPa at an axial strain of 20%.

Thomas et.al. (2000) determined the in situ shear strength parameters for Torcy landfill in France using a direct shear box (LxL = 1000 x 1000 mm^2). The shearing angle for the waste was 29.6^{o} and cohesion 23.4 kPa at 180 mm shearing displacement. The authors found that the shearing strength is greatly influenced by the presence of plastics content in the sample. The shearing strength is less for the specimen with more plastic content. The also have shown the shearing displacement dependency of shear strength.

Pelky et.al (2001) determined the shear strength of municipal waste, collected from landfills across Canada, using 450 mm long by 305 mm wide shear box. They found the shear angles were between 26° and 35° and cohesion were between 0 to 50 kPa at peak shear strain.

Change in Shear Strength with Decomposition

Landva and Clark (1986) determined drained shear strength parameters for old refuse samples. They measured friction angles ranging from 38° to 42° and cohesion's (c) ranging from 16 to 19 kPa. The samples were subsequently stored in plastic containers for one year. Landva and Clark (1986) reported that specimens underwent decomposition during storage as was evidenced by gas generation and smell. When they evaluated the strength parameters again, they found the friction angle decreased to 33° with cohesion of

16 kPa. The authors believe that the reduction in strength was caused by decomposition, but they indicated more data must have been collected to confirm their hypothesis.

Van Impe (1998) summarized the available shear strength data and concluded that shear strength is higher for old refuse compared to fresh refuse. Pelky (2001) concluded that more data were required to contradict or verify the trend. The author had no systemic data of MSW shearing strength as a function of various stages of decomposition.

Increase in Strength with Displacement

Gabr and Valero (1995) tested 10 to 15 year old MSW in small direct shear box (6.4 cm diameter and a thickness of 2.3 cm) and found that shear strength kept increasing at horizontal displacement more than 10% of the specimen diameter.

Jones (1997) tested municipal solid waste samples (38% paper, 18% plastics and 17% textiles) and reported that mobilized friction angle increased from 7 ^{o} at 5 mm displacement to 25 ^{o} -30 ^{o} at 100 mm displacement for normal stress between 100 to 400 kPa.

Thomas et.al. (2000) determined the in situ shear strength parameters for Torcy landfill in France using a direct shear box (LxL = 1000 x 1000 mm^2). They found the shearing angle increases with the shearing displacement. The shearing angle for the waste was 9.2^{o} at 50 mm displacement and 29.6 ^{o} at 180 mm displacement.

Pelky et.al. (2001) reported mobilized friction angle for MSW sample collected from Blackfoot landfill increased from 5° at 5mm displacement to 29° at 100mm displacement for a normal stress of 496 kPa.

Similar to soils, the shear strength parameters normally used for waste characterization are cohesion and friction angle. A review of published literature yielded no data on the shear strength of waste from landfills specifically operated under high moisture conditions despite the significant influence of moisture on waste shear strength and, consequently, on the stability of slopes and cover systems. Gabr and Valero (1995) showed that a 15% increase in moisture resulted in a 50% decrease in waste cohesion. This decrease in strength was attributed to changes associated with the physical characteristics of waste particles as decomposition takes place. None of the existing literature has attempted to discern and explain changes in strength and stiffness characteristics as a function of the physical and chemical properties of the waste. Such

characterization is of utmost importance as landfills are operated to accelerate changes in the physical and chemical properties of the waste.

In summary, there is a limited understanding of the mechanisms affecting shear strength changes as a function of solids composition, moisture content, and waste density. In comparison to the literature on waste compressibility, the body of literature on strength contains no work that systematically documented shear strength as a function of waste decomposition. The change in waste strength is expected to vary as the (C + H)/L ratio decreases. Yield envelopes and factors controlling peak and residual strength as a function of stress level as well as the change in these values due to creep/stress relaxation need to explained and defined.

The lack of characterization persists despite several results yielding unusual shear stress shear displacement relationship of tested MSW. Figure 15 shows results by Edincliler et al. (1996) where, contrary to shapes obtained for soil, " two peaks" were observed. This type of relationship was also observed by Bowders (2002) as well as in this study as will be shown by data in the thesis.

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TABLES

Table 1: Composition and methane potential of municipal refuse by chemical constituents (Barlaz, 1990)

Chemical constituents	% Dry weight	% Methane potential
Cellulose	51.2	73.4
Hemicellulose	11.9	17.1
Protein	4.2	8.3
Lignin	15.2	0
Starch	0.5	0.7
Pectin	<3.0	-
Soluble sugars	0.35	0.5
Total volatile solids	78.6	

Table 2 :MSW-components as weight percentage for different cities (Manassero et.al 1997)

MSW	1	2	3	4	5	6	7	8	9	10
Metals	1	1	3	3	5	2	2.5	4	1	3
Paper /cardboard	25	5	12	3	22	10	31	19	2	16
Plastics	-	1	5	-	-	3	9.5	7	3	20
Leather/wood/rubber	7	1	-	7	3	6	4	4	1	-
Textiles	3	-	-	10	-	3	5	-	-	-
Putrescible materials	44	45	74	15	20	61	28	59	71	58
Glass	1	1	4	10	6	1	9	2	1	2
Others	19	46	2	22	46	14	11	5	21	1

1.Bangkok (Thailand), 2. Pekin (china), 3. Nairobi (Kenya), 4. Hongkong, 5. NewYork (USA), 6. Istanbul (Turkey), 7. Geneva (Switzerland), 8. Athens (Greece), 9. Cochabamba (Bolivia) and 10. Wollongong (Australia)

Table 3: Typical municipal waste componenets as fill materials (Sowers, 1972)

Material	Typical percentage	Characteristic as fill
1. Food waste	10-20	wet. Ferments and decays readily, compressible, weak
2. Paper, textiles	10-40	Dry to damp, decays and burns, compressible.
3. Garden refuse	10-20	Damp, ferments, decays and burns.
4. Plastics	1-2	Dry, compressible, decay resistant but may burn.
5. Hollow metal	5-15	Dry, corrodable and crushable
6. Massive metal	1	Dry, slightly corrodable, rigid
7. Rubber	5-10	Dry,resilient,compressible but uncrushable, decay resistant
8. Glass	5-15	Dry,crushable and compressible, decay resistant.
9. Wood	0-5	Dry,crushable and compressible, decays and burns, some interlocking strength.
10.Rubble	0-10	Damp, crushable, erodable, decay resistant.
11. Ashes,cinders etc	0-5	Damp, soil-like, compressible, active chemically and partially soluble

Table 4: Composition of municipal refuse by component (Barlaz, 1990)

Components 1970	Percent by wet weight (%)	Components 1986	Percent by wet weight (%)
Food	15	Food	7.9
Garden trimmimg	22	Yard	17.9
Paper, cardboard	44	Paper, paperboard	41
Plastics	3	Plastics	6.5
Textile, rubber,leather,wood	5	Textile, rubber,leather,wood	8.1
Glass	8	Glass	8.2
Tin cans, ferrous and non ferrous metal	9	Metal and ceramics	8.7
Dirt, ashes, brick	4	Miscellaneous, inorganic waste	1.6

Table 5: Comparison of waste characteristics from different countries (Westake, 1995)

(as % waste arising)

Waste	United Kingdom	Asian City	Middle East City
Vegetables	28	75	50
Papers	37	2	16
Metals	9	0.1	5
Glass	9	0.2	2
Textiles	3	3	3
Plastics	2	1	1
Miscellaneous	12	18.7	23
Weight person^{-1} day^{-1}	0.845 kg	0.415 kg	1.060 kg
Density kg m^{-3}	132	570	211

Table 6 Moisture Content in the Landfill

Authors	Moisture Content (%)
Sowers (1973)	10-50
Gifford (1990)	14-68
Landva and clark (1990)	15-125
Blight et al (1992)	10-100
Huitritic (1981)	15-40
Tchobanouglous et al (1993)	15-45
Coumoulos et.al (1995)	20-125
Gabr and Valero (1995)	30-130

Table 7: Range of unit weight of uncompacted and compacted refuse components (Oweis and Khera, 1998)

			Ratio of compacted to uncompacted weight	
Waste components	Uncompacted unit weight lb/ft^3 (kN/m^3)	Water content (%)	Normal compaction	Well compaction
Food waste	8-30 (1.2-4.7)	50-80	2.9	3.0
Paper and paperboard	2-8 (0.3-1.2)	4-10	4.5	6.2
Plastics	2-8 (0.3-1.2)	1-4	6.7	10
Textiles	2-6 (0.3-0.9)	6-15	5.6	6.7
Rubber and leather	6-16 (0.9-2.5)	1-12	3.3	3.3
Yard waste	4-14 (0.6-2.2)	30-80	4	5
Wood	8-20 (1.2-3.1)	15-40	3.3	3.3
Glass	10-30 (1.6-4.7)	1-4	.7	2.5
Metals	3-70 (0.5-11)	2-6	4.3	5.3
Ash, brick, dirt	2-60 (0.3-9.4)	6-12	1.2	1.3

Table 8: Lightest and heaviest combinations of refuse constituents (Landva and Clark, 1990)

Category	Lightest Combination		Heaviest Combination	
	% of total weight	Dry unit weight kN/m^3 (pcf)	% of total weight	Saturated unit weight, kN/m^3 (pcf)
Food waste	6	1.0(6.4)	-	-
Garden refuse	20	0.3(1.9)	-	-
Paper	55	0.4(2.5)	40	1.2(7.6)
Plastic and rubber	-	-	15	1.1(7.0)
Textiles	4	0.3(1.9)	-	-
Wood	15	0.45(2.9)	-	-
Metal	-	-	15	6.0(38.2)
Glass and ceramic	-	-	15	2.9(18.5)
Ash, brick, dirt	-	-	15	2.7(17.2)

Table 9 Summary of determination of hydraulic conductivity of domestic waste (Manassero et. al, 1997)

Source	Unit Weight, kN/m^3	Hydraulic conductivity, m/s	Method
Fungaroli et al, 1979	1.1- 4.0	10^{-5} to 2 x 10^{-4}	Lysimetres determination
Koriates et al. 1983	8.6	5 x 10^{-5} to 3.15x 10^{-5}	Laboratory test
Oweis and Khera, 1986	6.45	10^{-5}	Field data
Oweis et al, 1990	6.45 9.4-14 6.3-9.4	10^{-5} 1.5 x 10^{-6} 1.1 x 10^{-5}	Pumping test Falling head Field test Test pit
Landva and Clark, 1990	10.1-14.4	1 x 10^{-5} to 4 x 10^{-4}	Test pit
Gabr and Valero, 1995	-	10^{-7} to 10^{-5}	Laboratory test
Blengino et al, 1996	9-11	3 x 10^{-7} to 3 x 10^{-6}	Deep borehole, Falling head test
Manassero, 1990	8-10	1.5 x 10^{-5} to 2.6 x 10^{-4}	Pumping test
Beaven & Powrie, 1995	5-13	10^{-7} to 10^{-4}	Laboratory test
Brandl, 1990	11-14(roller compacted) 13-16(roller+DC)	2 x 10^{-5} to 7 x 10^{-6} 5 x 10^{-6} to 3 x 10^{-7}	Falling head field test Test pit
Brandl, 1994	9-12(pretreated)	2 x 10^{-5} to 1 x 10^{-6}	Laboratory test
Brandl, 1994	9-12(pretreated)	5 x 10^{-4} to 3 x 10^{-5}	Laboratory test
Brandl, 1994	13-17(very compacted)	2 x 10^{-6} to 3 x 10^{-8}	Laboratory test

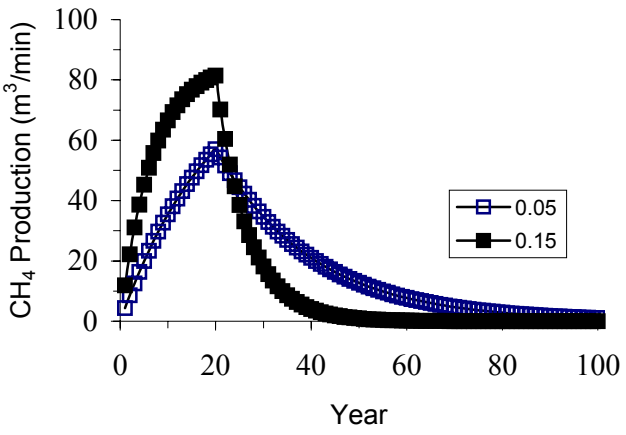

Figure 1. Methane production rate for a landfill that receives 286,000 metric ton/yr for 20 years. With reference to eqn. 2, Lo = 170 L/kg, the default value used for NSPS guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 and enhanced decomposition in a bioreactor (k = 0.15).

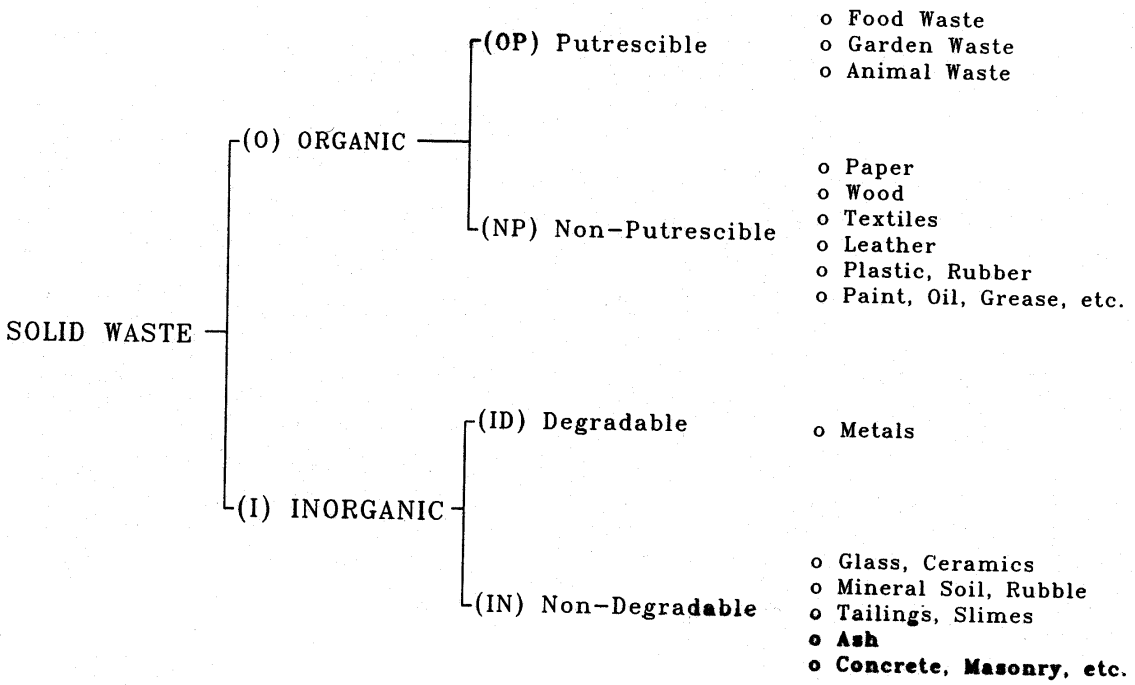

Figure 2 Classification System Suggested by Landva and Clark (1990)

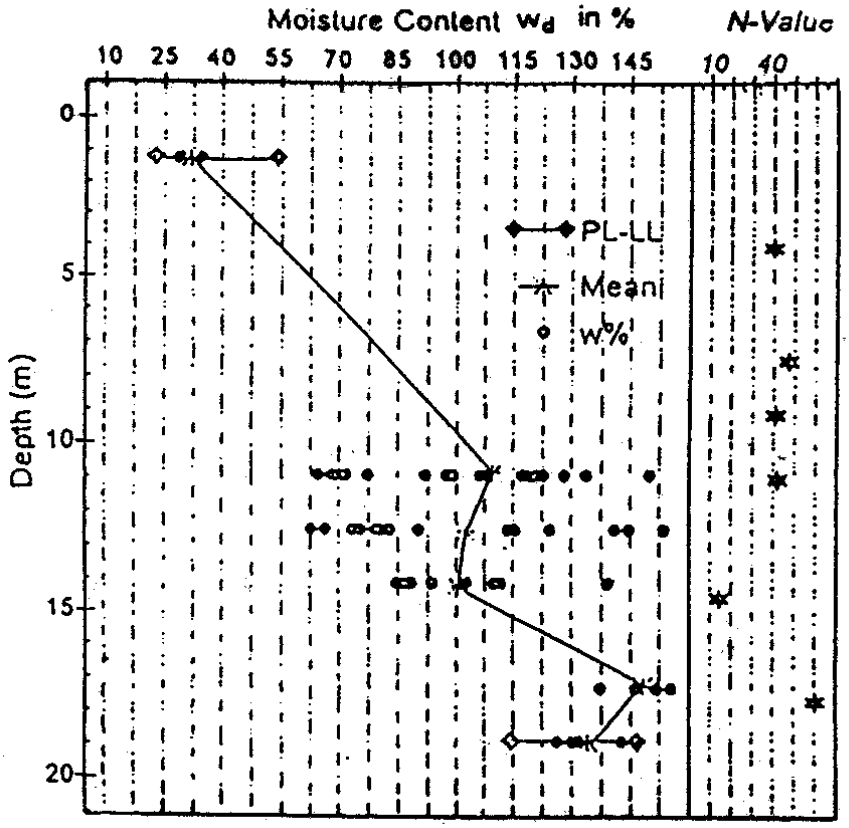

Figure 3 Variation of Moisture Content, Liquid Limit, Plastic Limit with Depth (Gabr and Valero, 1995)

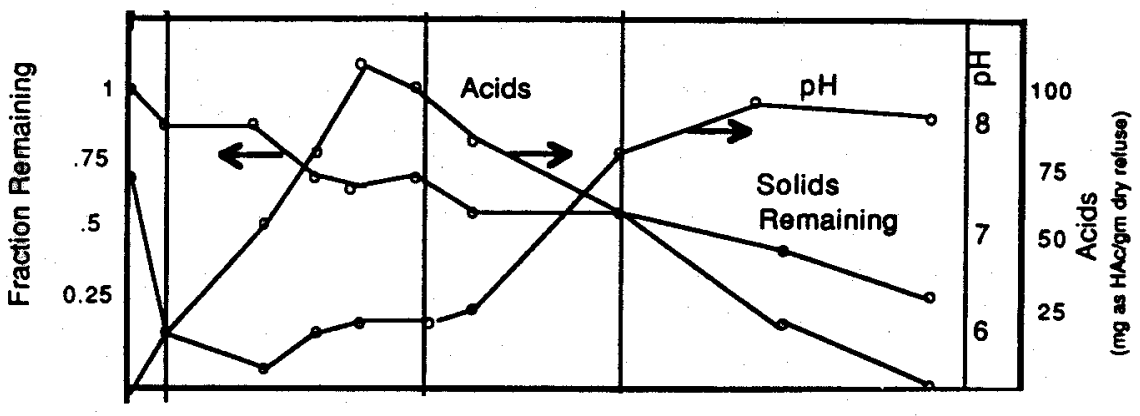

Figure 4 Summary of Observed Trend in Leachate Recycle (Barlaz, 1990)

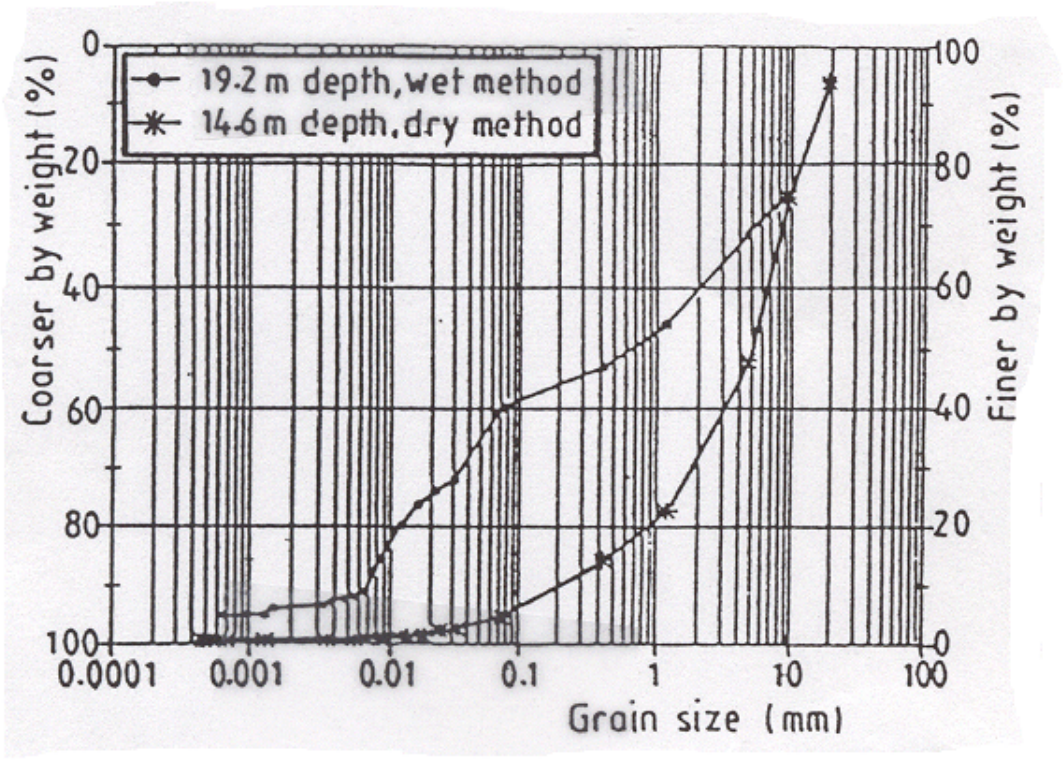

Figure 5. Grain Size Distribution by Dry and Wet Testing (Gabr and Valero, 1995)

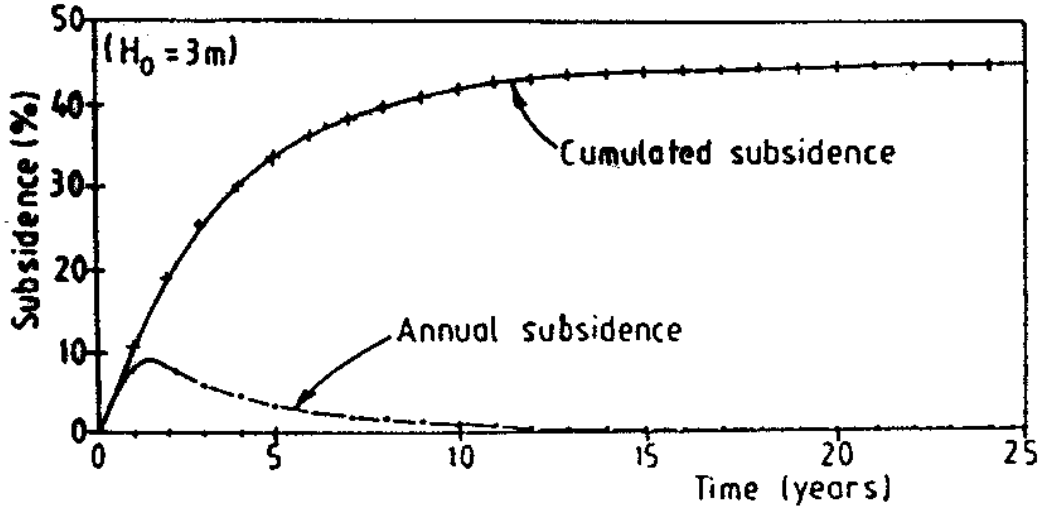

Figure 6. Time Progression of the Specific MSW Subsidence in a Large Diameter Drained Column Test

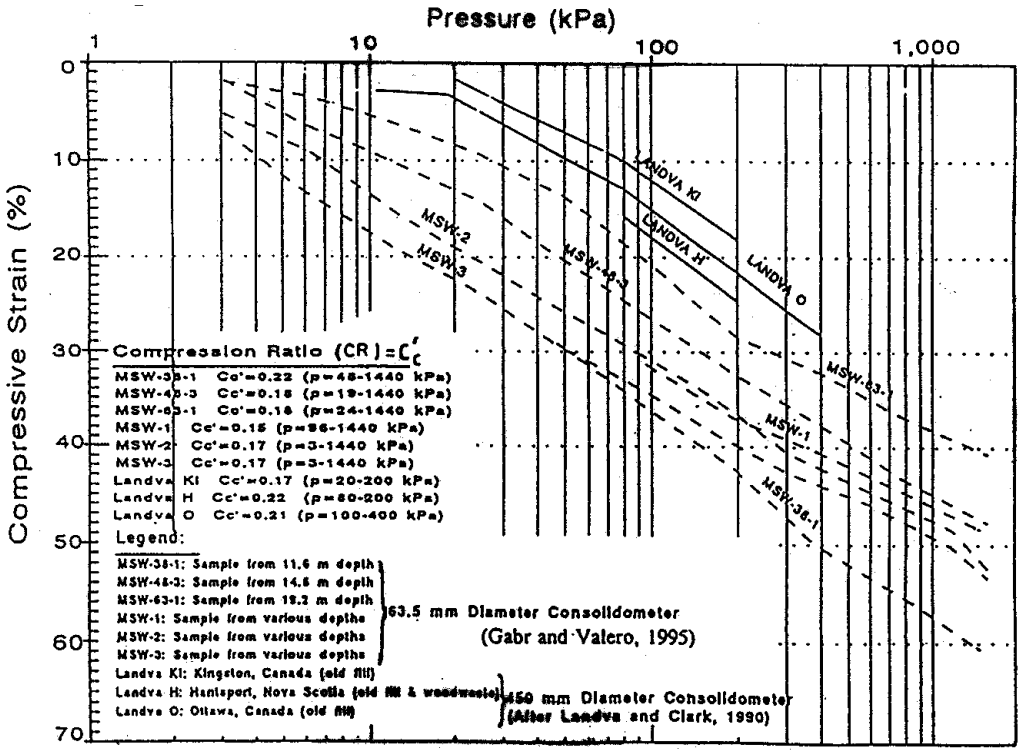

Figure 7. Compressibility Properties as Measured from Conventional and Unconventional Tests (Gabr and Valero, 1995)

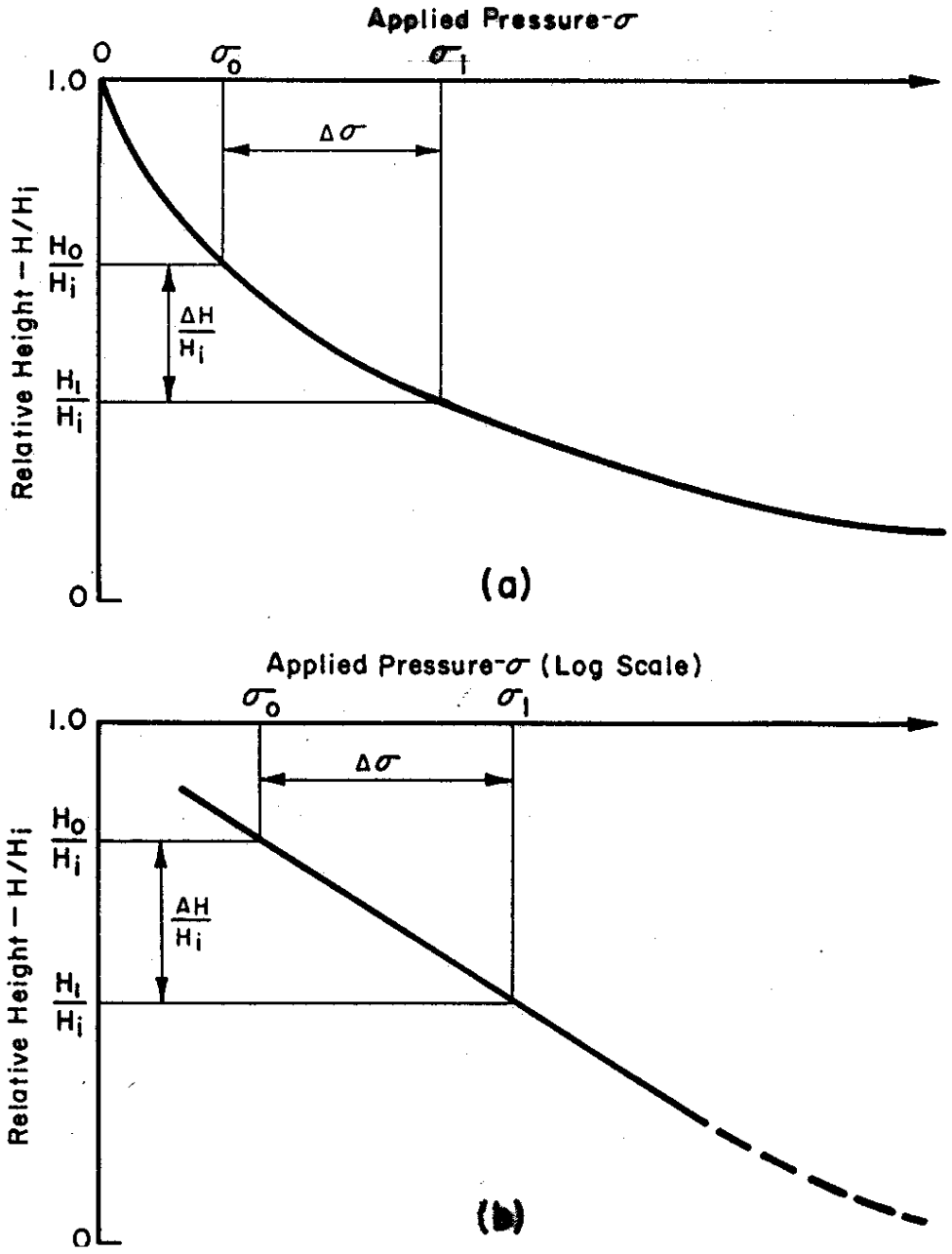

Figure 8. Relative Heights as a Function of a) Applied Pressure b) The log of the Applied Pressure (Rao, 1977)

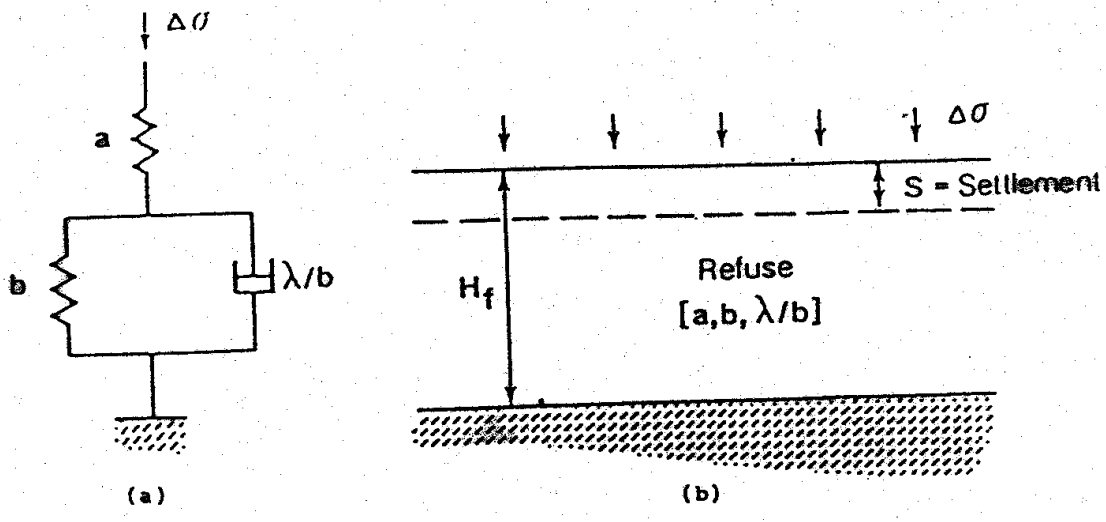

Figure 9. Rheological Model (Edil, et. Al., 1990)

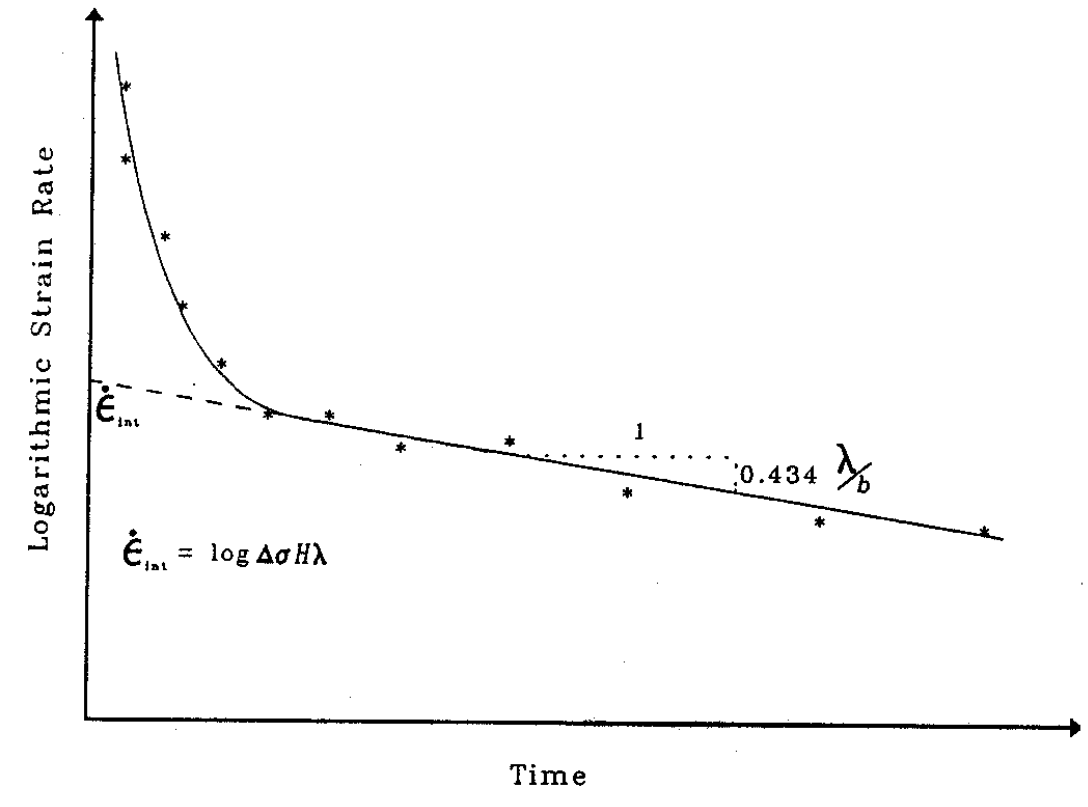

Figure 10. Evaluation of Gibson and Lo Parameter (Valero, 1994)

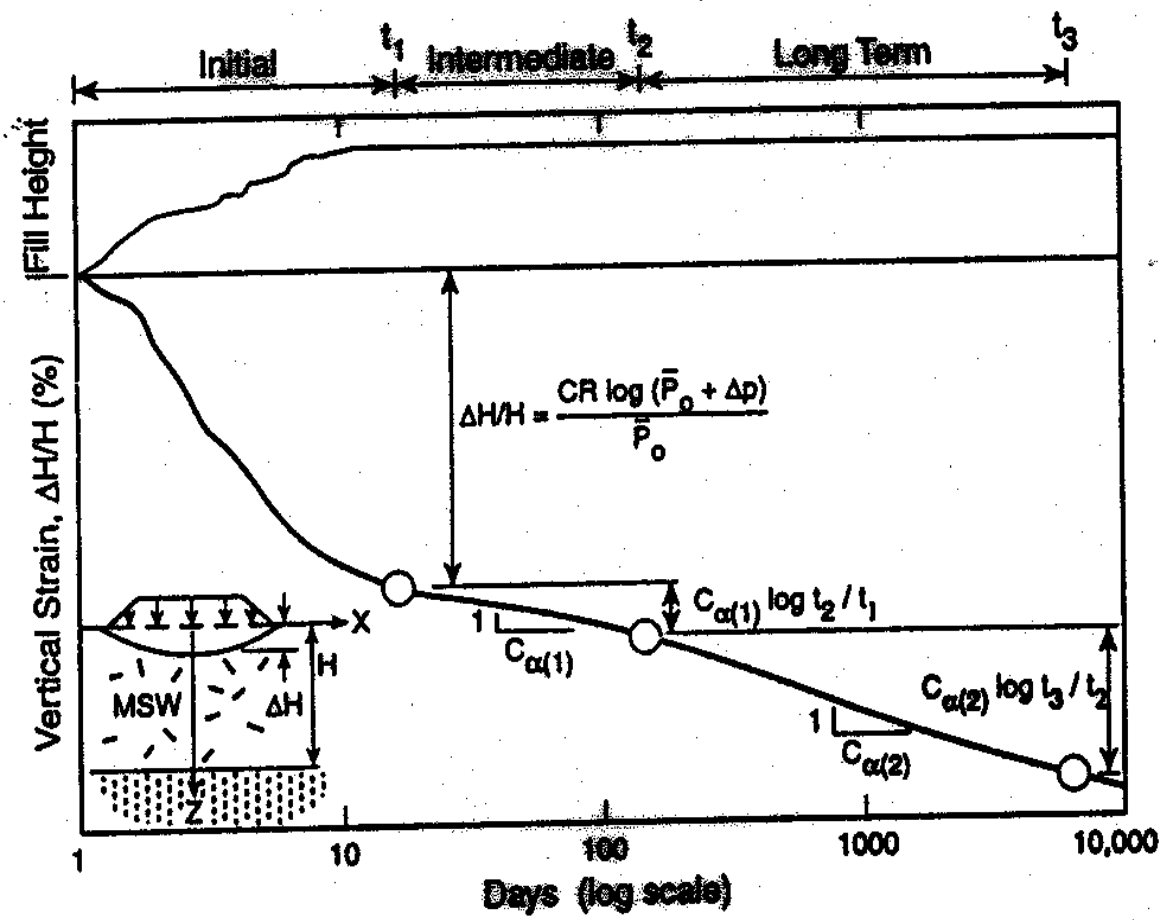

Figure 11. Settlement Model (Bjarngard and Edgars, 1990)

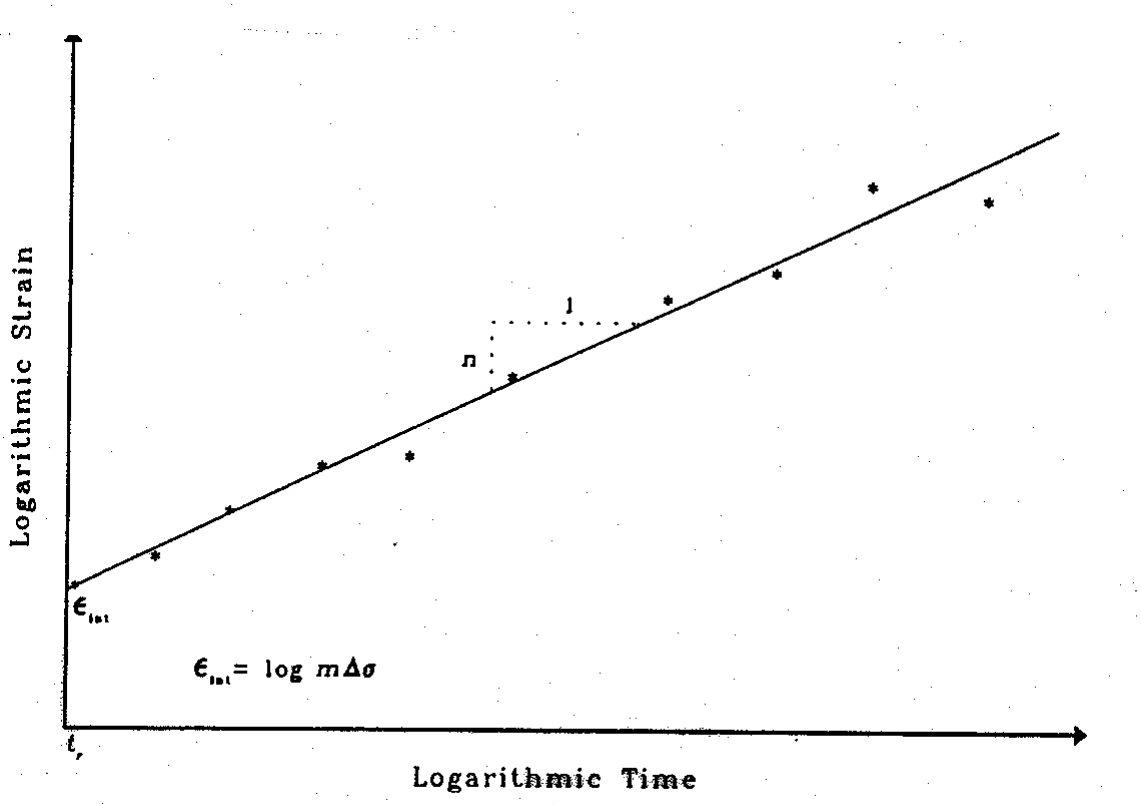

Figure 12. Evaluation of Power Creep Parameters

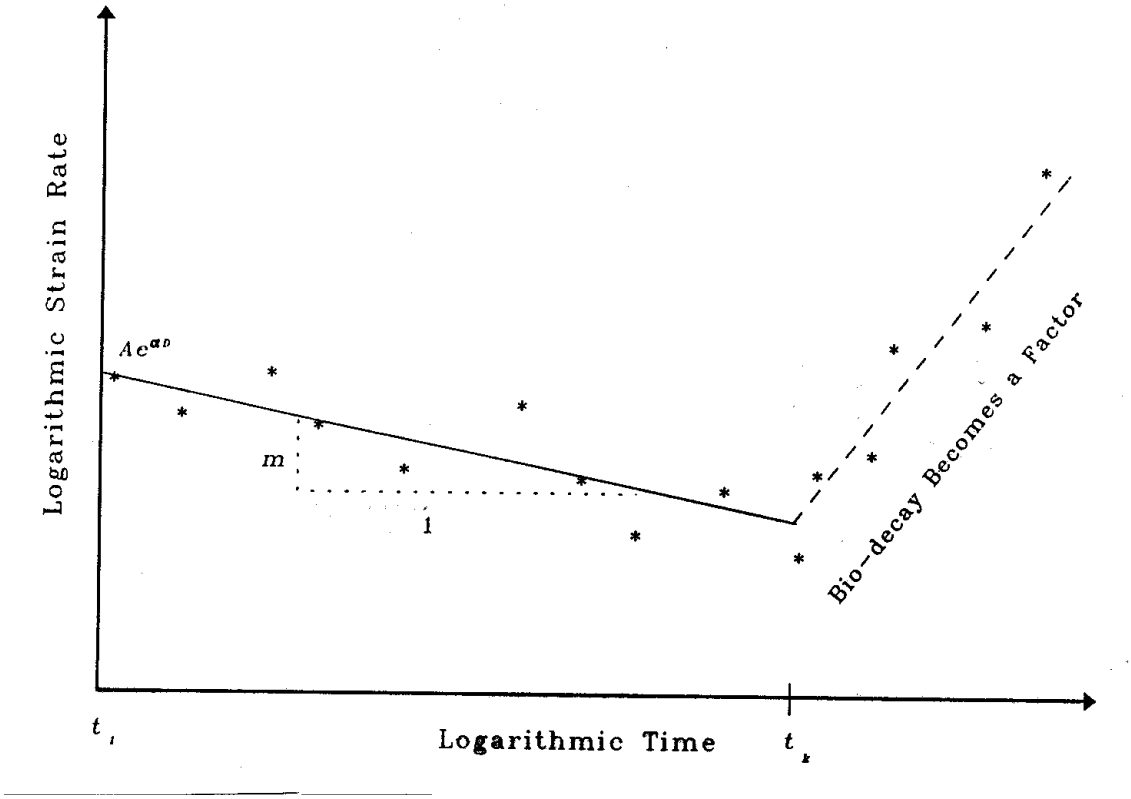

Figure 13 Evaluation of Rate Process Creep Parameters

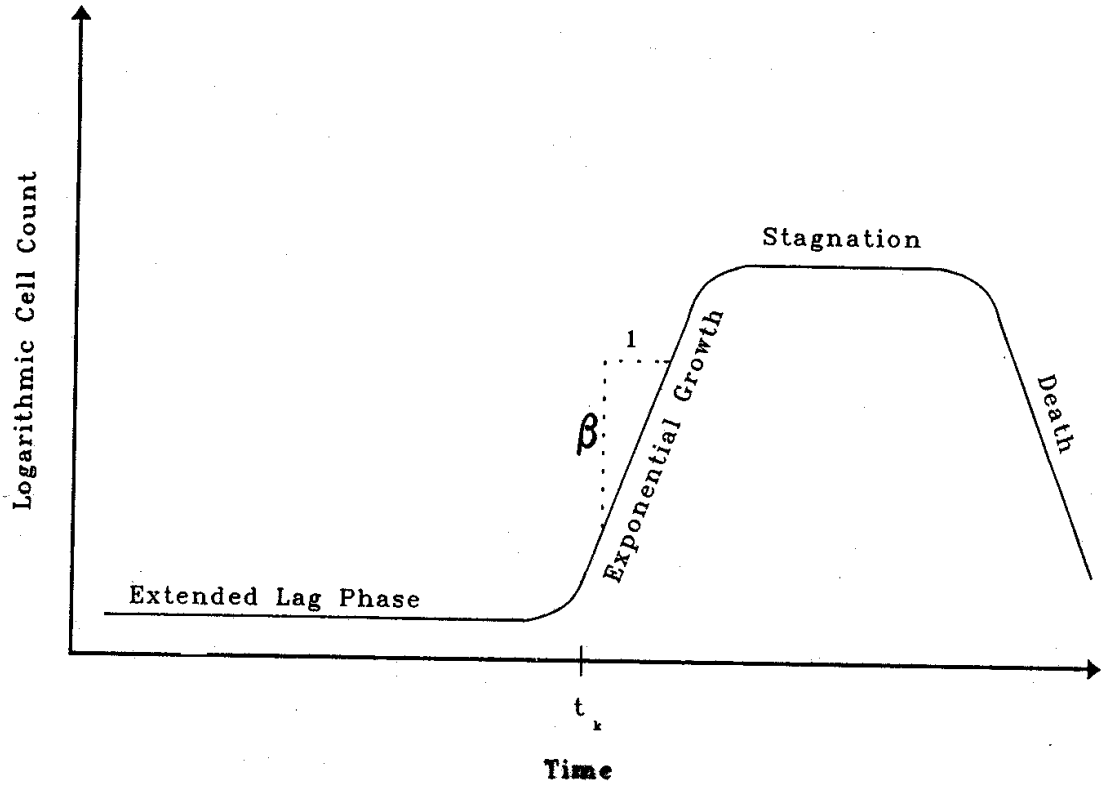

Figure 14. Typical Landfill Bacteria Growth Curve (Valero, 1994)

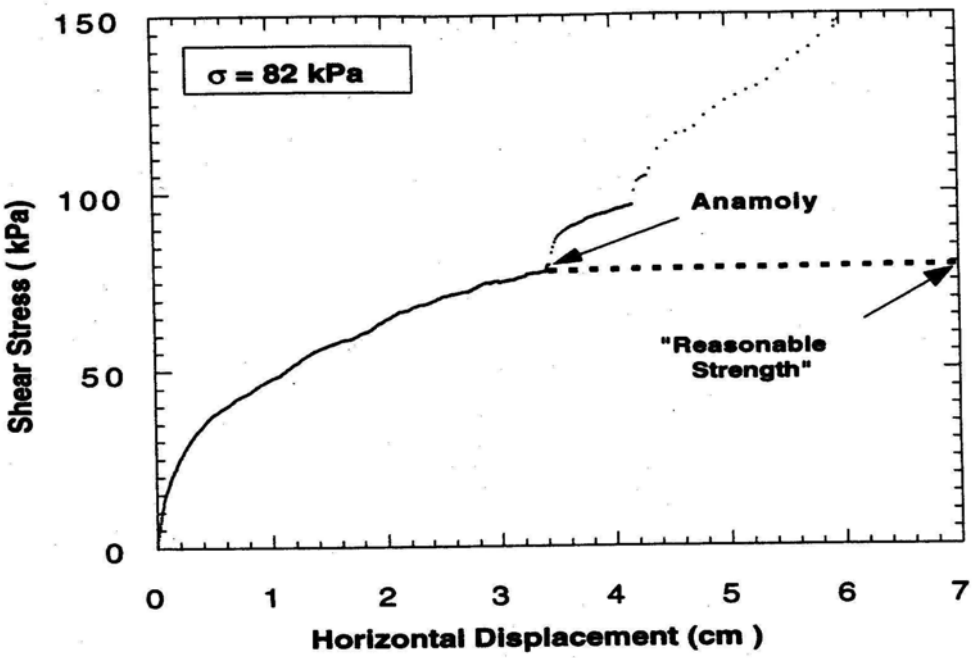

Figure 15. Shear Stress vs Horizontal Displacement Curve (Edincliler et.al., 1996)

The Effect of Shredding and Equipment Size on Measured Compressibility and Strength Parameters of Municipal Solid Waste with Leachate Recirculation

Paper to be submitted for review

The effect of Shredding and Equipment size on Measured Compressibility and Strength Parameters of Municipal Solid Waste with Leachate Recirculation

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ABSTRACT

Municipal Solid Waste (MSW) particles are usually larger than particles of sand, clay or organic soils and are processed and shredded before use in laboratory experiment using conventional soil testing equipment. It is important to understand the effect of shredding and equipment size on measured compressibility and shear strength characteristics. In this study, measured compressibility and shear strength parameters dependency on the ratio of waste particle size to equipment size, R, was investigated. For compressibility parameters, oedometer tests were performed on fresh and fully decomposed samples using devices that are 63.5 mm, 100mm, 200mm and 300 mm in diameter. Initially, oedometer tests were conducted using constant R with different equipment size, and, then oedometer tests were performed using variable R for same equipment size. In addition, direct shear test were performed for R=0.5 and R=0.25 using 100 mm (4 inch) shear boxes for the preliminary evaluation of the shredding effect on shear strength parameters. Oedometer test with constant R, specimen to equipment size ratio, indicate that compressibility parameters are dependent on R. Compressibility parameters are similar with constant R even though the equipment size varies. Shredding of MSW affects mainly initial compression as observed from the test results on same equipment with variable R. For example, initial compression for MSW in 200mm equipment is 31% and 35% for R =0.34 and 0.17, respectively. Creep and biological strain rate of MSW is not affected by shredding. The shear strength is affected by shredding as the light-weight reinforcing materials are shredded into smaller pieces during specimen preparation. The measured shearing angles are 31 ^{o} and 27 ^{o} for R=0.5 and 0.25, respectively. Based on the calculated parameters from experimental results, the

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co-efficient of variation for the materials collected from same reactors are small (3-5%). The results are accurate and can be repeated without significant variation.

INTRODUCTION

Municipal solid waste (MSW) is highly heterogeneous in nature and particles in MSW are usually larger than particles of sand, clay or organic soils. In many situations, MSW components are processed and shredded before use in laboratory experiment using conventional soil testing equipment. Laboratory testing of samples made from shredded refuse is easier and less expensive than testing "virgin" samples. However, shredding the material may affect the target property to be measured. The need to perform geotechnical testing of MSW on a regular basis is rising as closed landfills are frequently considered for land development and for future vertical extension of existing landfill. Therefore, it is important to understand the effect of shredding and equipment size on measured compressibility and shear strength characteristics. The measured laboratory values need to be explained in relation to field-estimate values.

There is no conventional or standard equipment size for the laboratory testing of MSW. Two major constraints commonly dictating equipment size in this case are the heterogeneity and physical size of waste particles. Oedometers utilized in past work ranged from 63 mm (Gabr and Valero, 1995) to 600 mm diameter in size (Landava et al 2000). The maximum particle size in specimen for Gabr and Valero was 6.3 mm, sample to equipment ratio, R=0.10. Gabr and Valero found the vertical strain versus stress plotted in a logarithm scale are similar to the results obtained from 600mm, 450mm size equipment. Landva (2000) shredded sample constituents larger than 150 mm (Sample to Equipment ratio, R = 0.25). Jessberger and Kockel (1993) used a 1.0m diameter compression cell to test 15 years old untreated domestic waste with R = 1 (assuming, the maximum particle size for unshredded sample can be as large as cell size). .

Landva and Clark (1990) used 434 x 287 mm direct shear test box on unshredded samples with R=1 (assuming, the maximum particle size for unshredded sample can be as large as cell size). Pelky et.al (2001) used 450 x 305 mm direct shear box for measuring shear strength parameters of aged waste and fresh shredded paper. Gabr and Valero (1995) used 63 mm diameter direct shear box for shear strength of 15 to 30 years old samples collected from a landfill in Pennsylvania. Seigel et. al (1990) conducted direct

shear test using 130 mm diameter and 76 to 102 mm thick specimen. In general, there was no rational basis for selecting a specific equipment size or ratio of the particle size to equipment size. Edincliler et. al (1996) tested sample for shear strength on 300 mm diameter and 1.5m x 1.5 m direct shear box. Particles larger than 50 mm were removed from the 300 mm shear box (R=1/6). The main sample component before and after removing the 50 mm particles varies significantly. According to Edincliler et. al (1996), the shear strength obtained from laboratory was lower than the strength obtained from the field, because many reinforcing elements were removed from the specimen for testing in the small-scale equipment.

The effect of shredding and equipment size, relative to waste particle size has not been investigated. The effect of equipment size, relative to waste particle size, on measured properties needs to be investigated and correlated to field-evaluated values. Compressibility and shear strength dependency, of MSW, on decomposition had been presented by Hossain and Gabr (2002). In this study, measured compressibility and shear strength dependency on the ratio R, of the waste particle size to equipment size, will be investigated.

The objective of this study is to characterize the effect of equipment size, relative to the waste particle size, and shredding on measured compressibility and shear strength properties of municipal solid waste for bioreactor landfills. It is hypothesized that certain R-values will produce parameters than can be used to discern field values in a systematic manner. If the hypothesis of compressibility results dependency on R ratio is valid, similar stress-strain responses should be obtained from different size equipment, at constant R. Samples, prepared in 4-liter (~1 gal) reactors, were used for this purpose. The degree of decomposition was characterized through gas generation rates and the cellulose plus hemicellulose to lignin ratio. For compressibility parameters, oedometer tests were performed on fresh and fully decomposed samples using devices that are 63.5 mm, 100mm, 200mm and 300 mm in diameter. Initially, oedometer tests were conducted using constant R with different equipment size, and, then tests were performed using variable R for same equipment size. Time-dependent stress-strain relationships were evaluated from the oedometer testing. In addition, direct shear test were performed for R=0.5 and R=0.25 using 100 mm (4 inch) shear boxes (due to limited equipment

availability) for the preliminary evaluation of the shredding effect on shear strength parameters. Each direct shear test was conducted under three normal stress levels of 50 kPa, 100 kPa, and 150 kPa to represent a range of waste heights typically encountered in the field. The strength parameters obtained from laboratory test were compared to field data reported by Edincliler at al (1996) to evaluate the significance of testing conditions on the proposed measurements as outlined above. Finally three oedometer tests and nine direct shear tests were conducted on samples collected from same reactors to check the repeatability of the heterogeneous MSW. The measured laboratory values and backfigured field values were co-related and effect of shredding and equipment size is discerned.

EXPERIMENTAL DESIGN

Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The reactors were destructively sampled to obtain refuse at various states of decomposition based on the reactor's methane production rate curve. In addition, the state of decomposition was quantified by measurement of the concentrations of cellulose, hemicellulose and lignin (Hossain et. al, 2002). Reactors were sampled at each of four time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, early and late in the decelerated methane production phase, respectively. One-dimensional oedometer tests were then performed on waste specimens using different size equipment and R value. The compressibility parameters including initial compression, coefficient of primary compression, and creep and biological indices ($C_{\alpha i}$ and $C_{\beta i}$) were measured and compared. In addition, direct shear testing were performed for the evaluation of shear strength parameters with R values of 0.5 and 0.25. However, direct shear testing were only conducted using 100 mm (4 inch) shear boxes due to limited equipment availability.

Table 1 provides details of the testing program for the effect of equipment size (Constant R but different equipment size) and shredding (constant equipment size but different R) on measured compressibility and strength parameters. The tests are generally

conducted in duplicates. Three oedometer tests and six direct shear tests were conducted to evaluate the repeatability test of MSW parameters.

Preparation of Fresh and Decomposed Refuse

Solid waste representative of residential refuse was collected from a transfer station in Wake County, NC. Approximately 900 kg (2000 pounds) was shredded to about 10 mm x 20 mm pieces. The shredded refuse was then mixed and sequentially quartered until each pile contained 40-50 kg. Twenty piles were collected in separate plastic bags and stored at 4^0C until used in the experimental program.

Eight 4-L reactors were filled with refuse to prepare samples at different stages of decomposition for compressibility testing. Reactors T1-T4 were operated under conditions designed to simulate a traditional landfill and will be referred to as "traditional" samples. Sufficient moisture was added to adjust the moisture content to 55% (wet wt. basis). Reactors B1-B4 were operated under conditions designed to simulate a bioreactor including, (1) the addition of sufficient moisture to induce leachate production, (2) leachate recirculation and (3) the addition of an inoculum of anaerobically digested sewage sludge. The leachate was neutralized with KOH as necessary and recycled six days a week. All reactors were incubated in a room maintained at 37 to 41^0 C.

Gas was collected in five-layer gas-bags and the volume was measured by pumping into a calibrated carboy using water displacement. Gas concentrations (CO_2 and CH_4) were measured using a GOW-MAC gas chromatograph (Bound Brook, NJ) equipped with a thermal conductivity detector and a CTR1 column (Alltech, Deerfield, IL).

Reactors were destructively sampled based on their methane production rate curve. The contents were thoroughly mixed and a sub-sample was removed for composition analysis. The sub-sample was first dried to constant weight at 75°C and then ground in a Wiley mill to pass a 1 mm screen. Cellulose (C) and hemicellulose (H) concentrations were analyzed by acid hydrolysis followed by HPLC analysis of the hydrolyzed sugars (Wang et al., 1994). Lignin (L) was determined from the combustible (550°C) fraction of the material that remained after the acid hydrolysis. The remaining refuse was used in the direct shear tests without drying.

OEDOMETER TESTS

Remolded waste specimens, generated in the laboratory scale reactors, were compacted directly into a circular oedometer with a wooden dowel. Maximum particle lengths were decided on the basis of R (equipment to maximum specimen size ratio). Particles with a length no greater than half the diameter, one quarter of the diameter and one sixth of the diameter of test cell was included and therefore test specimen consisted of different particle size (Figure 1) based on the equipment size. The tests were conducted on specimen using 63.5 mm, 100 mm, 200 mm and 300 mm diameter by 19.2 mm, 25.4 mm, 51mm and 102 mm thick samples, respectively. Tests were performed in conformance with ASTM Test Method (D2435-90). The testing program is shown in Table 1. For determination of the primary compression ratio (Cc), the rapid loading method described by ASTM D2435-90 was adopted. The long-term compressibility behavior was determined by running the tests for 30-70 days under a constant stress of 95 kN/m^2. Testing conditions did not eliminate refuse biodegradation during the testing period. Settlement strains associated with primary, creep, and biological effects were measured.

DIRECT SHEAR TEST

Remolded specimens (collected from the reactors) were compacted directly into a circular 100-mm diameter and 50 mm thick direct shear box with a wooden dowel. Maximum particle of length equal to half the diameter of test cell (R=0.5) were included and therefore test specimen consisted of particle size equal to and smaller than 50 mm. For a second set of tests, particles of length equal to one quarter of the test cell diameter (R=0.25) were used. The two sets of test were conducted to compare the specimen size effect on the measured shear strength. During the testing, a strain rate was calculated based on consolidation of the specimen under normal stress as recommended by Head (1982). The strain rate used for the direct shear testing was 0.03 mm/ min. The sample were consolidated under normal load for 24 hours and sheared at the same normal load. Tests were performed in conformance with ASTM Test Method for Direct Shear Tests of Soils Under Consolidated Drained conditions (D 3080-90). The tests were strain controlled and readings were taken at particular strain interval. The testing program and sample description are presented in Table 1.

RESULTS

The methane production characteristics and solids composition of test samples used for measurement of shear strength parameters are described in the first part of this section. Then the effect of shredding of test samples and equipment size effect, on the measurements of compressibility and shear strength, are presented in this paper.

Refuse Decomposition

Methane production rates and volume for the bioreactor and traditional samples are presented Figure 2 and Table 2. Comparing results from traditional and bioreactor samples, the more rapid increase in the methane production rate and leachate pH (Figure 3) illustrates the enhancement of refuse decomposition when reactors are operated with leachate recycle and neutralization. The anaerobic sewage sludge seed and the external neutralization of the leachate reduced the time span of the anaerobic acid phase of decomposition.

Bioreactor systems were destructively sampled on days 24, 53, 84 and 127. As illustrated by the methane production and pH data in Table 2, the day 24 sample was in the anaerobic acid phase, the day 53 sample was in the accelerated methane production phase, and the day 84 and day 127 samples were in the decelerated methane production phase.

The composition of solids removed from each reactor at the end of the monitoring period is presented in Table 2. The (C+H)/L ratio in the bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower decrease in this ratio in the traditional landfill samples. These results were consistent with the low methane production volume (0-13.8 L) for the traditional samples. In general, the (C+H)/L ratios of traditional samples are higher than those of the bioreactor samples at the same time point. While bioreactor samples had completed all phases of degradation, the traditional samples were still in early Phase 3.

COMPRESSIBILITY PARAMETERS

A summary of test results obtained from the oedometer tests for bioreactor samples are presented in Table 3. Samples were tested at different states of decomposition as quantified by the cellulose plus hemicellulose to lignin ratio, (C+H)/L. Decomposed samples in the bioreactor simulations were tested at (C+H)/L ratios of 1.29,

0.71, 0.38 and 0.25. Samples, at (C+H)/L=1.29, were tested using 63.5 mm, 100mm and 200 mm diameter oedometer for a maximum particle size to equipment size ratio, R = 0.5 (Figure 4a). Compressibility with time was at a relatively constant rate, which is indicative of creep mechanics while the specimen was in the acid phase. The creep index for all diameter oedometer cell was estimated to be 0.030. After approximately 10000 min, the slope of the strain-time plot slightly increased indicating biological degradation. Biological indices were estimated to be 0.050 from 63.5mm and 200mm diameter equipment. The primary settlement strains, indicative of the induced immediate compression due to the placement of 95 kN/m^2 load, are relatively close for all equipment and estimated to range between 25.5% to 27%. At R=0.5, the reinforcement effect of waste components with respect to different equipment size are similar, producing relatively equal or close compressibility parameters. These results indicate the dependency of measured compressibility parameters on R (specimen to equipment size ratio) rather than on size of equipment itself. Another set of tests were conducted for a constant specimen to equipment size ratio, R = 0.5, for samples at (C+H)/L=0.38, advanced decomposition state. The test results (Figure 4b), for all equipment size, show a similar trend, with creep and biological index estimated to be 0.03 and 0.22, respectively. The primary settlement strains are estimated to be between 31.5% to 33.5% due to placement of 95 kN/m^2 load. This reaffirms the dependency of compressibility parameters on R, specimen to equipment size ratio.

Waste settlement using different R (0.34 and 0.17), and constant equipment size, 200mm, is presented in Figure 5a and 5b. Initial compression for R=0.17 is 7-15% more than initial compression in R=0.34. The same trend is observed for 300 mm equipment using different R (0.30 and 0.14) as shown in Figure 6. Initial compression for R=0.14 is 10-15% more than initial compression in R=0.30. One explanation for the increased compressibility of the samples in R=0.17 for 200mm and R=0.14 in 300 mm equipment size are that removal of larger size reinforcing material, including plastics, textiles and paper reduced the reinforcement effect, yielding to higher initial compression during the test. The creep and biological components of settlement for 200 mm equipment are quite similar to those measured using equipment sizes of 63.5mm and 100mm, with constant and variable R. The rate of strain increase with time under constant load does not seem to

be greatly affected by shredding as values of C_α and C_β obtained for shredded samples using different size equipment and variable R are equal. The shredding of MSW and equipment size mainly affected initial compression.

The secondary compressibility parameters, obtained from laboratory tests, for bioreactor samples are consistent with those back-calculated from field data provided by Edgar and Noble (1992), El Fadel and Al-Rashid (1998) and Earth Tech Consultants (2001). Edgers and Noble (1992) found that creep coefficients varied from 0.01 to 0.04 (average 0.025) and biological coefficients varied from 0.02 to 0.5 (average 0.1). El Fadel and Al-Rashed (1998) reported creep coefficients of 0.015 - 0.035 and biological coefficients of 0.1 - 0.32 for the Mountain View CA Landfill (bioreactor test cell). Earth Tech Consultants (2001) reported biological coefficient values of 0.18 - 0.26 for the Crow Wing County, MN bioreactor landfill.

To compare the effect of shredding on initial compression and coefficient of primary compression, compressibility results from Landva and Clark (1990) for three samples excavated from Kinston, Ottawa and Hantsport landfills, as well as test sample at (C+H)/L=0.38 from this research were plotted (Fig. 7). Sample at (C+H)/L=0.38, as indicated by its gas production trend, and pH value was in an advanced stage of decomposition. In Fig. 7, this sample is compared to results from compressibility testing of 10-15 year old Kinston (KI), Ottawa (O) and Hantsport (H) landfill samples. Bookter and Ham (1982) reported that 20-30 years old landfill refuse with significant decomposition has a C/L (Cellulose to Lignin ratio, used for determining degree of decomposition) ratio of 0.16-0.24. It is assumed that these three samples have undergone significant decomposition and are comparable to sample at (C+H)/L=0.38. Landva and Clark used 470 mm cells and unshredded samples. The measured coefficients for primary compression were 0.17, 0.22, 0.21 and 0.37 for the Kinston, Ottawa, Hantsport and (C+H)/L=0.38 samples, respectively. The respective compressive strains at a 100 kPa load are 12%, 15%, 18% and 37%. The cell size for the unshredded samples tested by Landva and Clark (1990) was approximately 7.5 times larger than the cell used in this research (470 mm versus 63 mm). The specimen size in 470 mm equipment is not known. However, it can be hypothesized that due to reinforcement effect of unshredded

specimen, the primary compression and co-efficient of primary compression are lower in 470 mm than 63.5 mm equipment (R=0.5).

SHEAR STRENGTH PARAMETERS

Similar to soils, the shear strength parameters normally used for waste characterization are cohesion and friction angle. According to Howland and Landva (1992) MSW is mainly frictional in nature. The shear strength has been presented in this paper as shearing angle only. Samples, at (C+H)/L=1.29, representative of fresh waste, were tested for shear strength using 100mm diameter direct shear box for specimen to equipment size ratio, R = 0.5 and R=0.25. The friction angle were estimated to be 32° and 27° for R=0.5 and R=0.25, respectively (Figure 8). The sample, at (C+H)/L=1.29, is at early stage of decomposition with the presence of fresh to slightly degraded paper. The friction angle for fresh paper is 33° while tested at R=0.5 (i.e. maximum size of paper is 50mm). At R=0.25, maximum size of MSW were 25 mm including paper. The smaller size (25 mm) paper and other reinforcing materials, including plastics, textiles has less reinforcement effect, than larger particles (50 mm), and therefore, the lower friction angle. Edincliler et. al (1996) tested a sample for shear strength on 300 mm diameter and 1.5m x 1.5 m direct shear box. Particles larger than 50 mm were removed from the 300 mm shear box (R=1/6). The main component of MSW before and after removing the 50 mm particles varies significantly. According to Edincliler et. al (1996), the shear strength obtained from lab is lower than the strength obtained from the field, since many reinforcing element are removed from the specimen for testing in the small-scale equipment. The friction angle obtained from fresh unshredded MSW was 42°. According to Edincliler et. al (1996) unprocessed MSW have high shear strength due to the boundary effect and processing is required before performing test. Pelky et. al. (2001) performed direct shear test using 450 mm long by 305 mm wide shear box. They found the range of friction angle between 26° to 35° for unshredded MSW. This result is comparable to the results obtained from shredded specimen in this research. The shredding will reduce size of MSW components as well as the reinforcement effect of the light-weight materials contributing to lower shear strength compared to unshredded specimen. Following the same logic, shear strength for R=0.5 should be more than shear

strength for R=0.25. The limited experimental results presented in this paper validate this hypothesis.

REPEATABILITY OF DATA

MSW is extremely heterogeneous in nature. The variation of MSW samples used in this testing program within the same sample preparation reactor can be significant. Arguably, the test results conducted on samples from same reactor are supposed to vary at same degree. Table 4 and Figure 9 presents the compressibility test results of MSW samples collected from same reactors. The rate of initial strain (creep) and long term strain (biological) are rather similar for all three tests, 0.04 and 0.02, respectively. Initial compression ranged between 31.5% and 34.5%. The standard deviation and coefficient of variation for initial compression are 1.53 and 5 %, respectively. Figure 10 presents the direct shear test results on samples collected from same reactor. The obtained friction angles for the three tests are 28.2 ^{o}, 27.2 ^{o} and 26.5 ^{o}. The standard deviation and coefficient of variation for friction angle are 0.85 and 3%, respectively. Figure 9 & 10, clearly indicates that the tests are precise with experimental error yielding coefficient of variation on the order of 3-5% and they can be repeated.

SUMMARY AND CONCLUSIONS

Work in this paper utilized data from laboratory oedometer and direct shear tests to illustrate shredding and equipment size effect on compressibility and strength parameters for refuse at different degrees of degradation. The extent of degradation was documented by gas production rates as well as (C+H)/L ratios. Twelve one-dimensional oedometer tests were run for 30-70 days under a constant stress of 95 kN/m^2. Six direct shear test were conducted under three normal stress levels of 50 kPa to 150 kPa to represent a range of waste heights typically encountered in the field. Finally three oedometer tests and nine direct shear tests were conducted on samples collected from same reactors to check the repeatability of highly heterogeneous MSW. Based on the results obtained in this study, the following conclusions are advanced:

1. Oedometer test conducted on 63.5 mm, 100mm, 200mm diameter equipment with constant R, specimen to equipment size ratio, indicate that compressibility parameters are dependent on R. Compressibility parameters are similar with constant R even though the equipment size varies. Shredding of MSW affects mainly initial

compression as observed from the test results on same equipment with variable R. For example, initial compression for MSW in 200mm equipment is 31% and 35% for R =0.34 and 0.17, respectively.

2. Creep and biological strain rate of MSW is not affected by shredding. The magnitude of the biological indices varied with the state of decomposition and yielded the highest values when samples were actively decomposing but their variation with varied R and same equipment is minimal.
3. The shear strength is affected by shredding as the light-weight reinforcing materials are shredded into smaller pieces during specimen preparation. The measured friction angles are 31 ^{o} and 27 ^{o} for max particle size in specimen of 50mm and 25 mm, respectively. The larger components in the specimen act as better reinforcing element than shredded smaller components during the shear test.
4. Based on the calculated parameters from experimental results, the co-efficient of variation for the materials collected from same reactors are small (3-5%). The results are accurate and can be repeated without significant variation.

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Table 1 Tests to Evaluate the Effect of Shredding and Equipment Size on Measured Laboratory Parameters

	Compressibility Testing		Direct Shear Testing	
Equipment Size (mm)	R values =1/2	Variable R value	R values =1/2	Variable R value
63.5	6	-	-	-
100	4	-	3	3 test at R=1/4
200	4	3 test at R=1/6	-	-
300	1	1 test at R=1/4	-	-

* C_c = Co-efficient of primary compression

Table 2 Description of the Sampled Reactors and Their Gas Production Record

Sample Identification[a]	Day Sampled[b]	Cumulative Methane Production (L)	% Cellulose (C)	% Hemi-Cellulose (H)	%Lignin (L)	(C+H)/L
Fresh Refuse	n/a	n/a	41.91	8.47	19.96	2.52
B1	24	0.5	32.79	6.55	30.53	1.29
B2	53	70.5	21.87	4.95	38.08	0.71
B3	84	102.2	13.48	3.94	46.26	0.38
B4	127	53.5	11.88	2.29	56.44	0.25
T1	27	0	37.32	8.10	19.17	2.37
T2	56	0.7	27.45	6.03	26.06	1.29
T3	91	3.0	29.40	6.25	19.88	1.79
T4	130	13.8	16.92	3.88	28.47	0.73

a. B and T designate bioreactor and traditional samples, respectively

b. Traditional reactors were filled with MSW 3 days before bioreactors ;

n/a - not applicable

Table 3 Compressibility Parameters for Bioreactor Samples for Different Equipment Size and Variable R

Equipment Size (mm) & R	(C+H)/L	Primary Compression (%)	C_c	C_α	C_β
63.5 – R=0.5	1.29	26	-	0.030	0.050
100 – R=0.5	1.29	27	-	0.030	0.020
200 – R=0.34	1.29	27	-	0.030	0.040
63.5 – R=0.5	0.38	33	-	0.030	0.020
100 – R=0.5	0.38	31.5	-	0.030	0.020
200 – R=0.34	0.38	33	-	0.030	0.020
63.5– R=1.0	1.29	27	-	0.030	0.030
63.5 – R=0.5	0.73	30	-	0.030	0.190
100 – R=0.25	1.29	25.5	-	0.030	0.020
100 – R=0.25	0.38	33	-	0.030	0.020
200 – R=0.17	1.29	28.5	-	0.030	0.025
200 – R=0.34 & 0.17	0.73	29 & 33	-	0.030	0.055
63.5 (test 1)	0.38	31.5	-	0.040	0.022
63.5 (test 2)	0.38	33.5	-	0.040	0.022
63.5 (test 3)	0.38	34.5	-	0.030	0.022

Table 4 Shear Strength and Compressibility Parameters of Bioreactor Samples for Repeatability Test

Equipment Size (mm)	(C+H)/L	Shear Angle (deg)	Initial Compression (%)	Standard Deviation	Coefficient of Variation (%)
DS-100 (test 1)	0.73	28.2	-	0.85	3
DS-100 (test 2)	0.73	27.2	-		
DS-100 (test 3)	0.73	26.5	-		
C-100 (test 1)	0.38	-	28.2	1.53	5
C-100 (test 2)	0.38	-	27.2		
C-100 (test 3)	0.38	-	26.5		

* DS-Direct Shear, C-Compreesibility

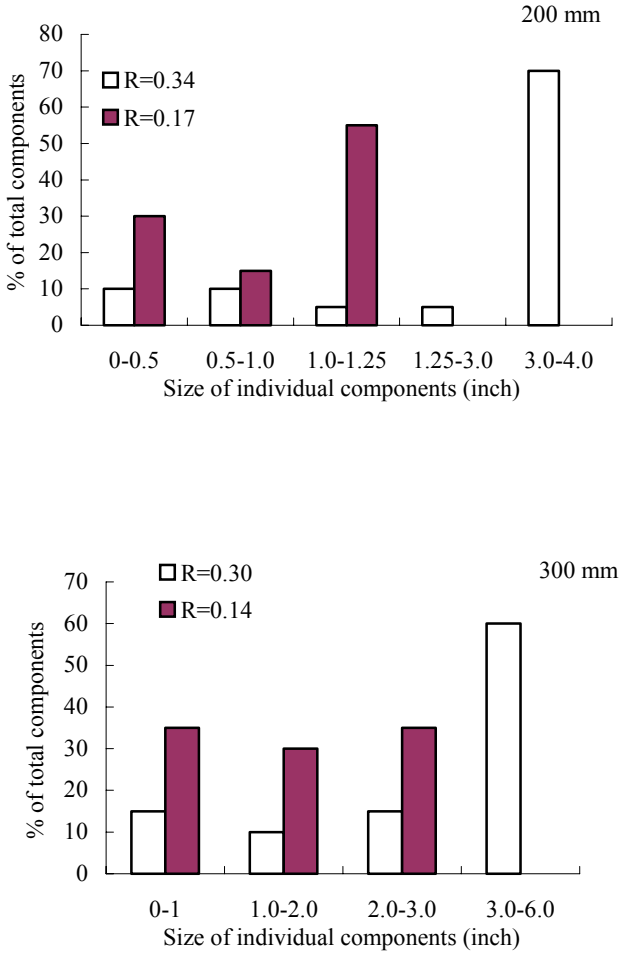

Figure 1. Percentage Distribution of Individual Components in MSW for Equipement Size and Shredding Effect

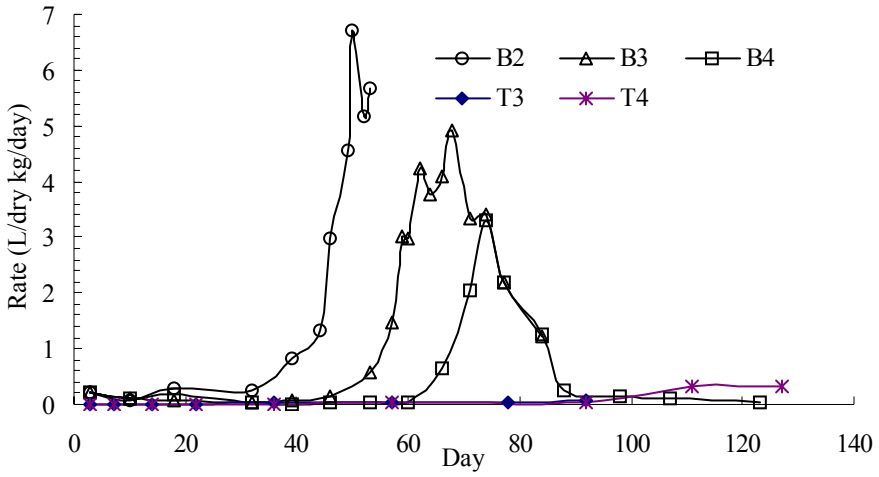

Figure 2. Rate of Methane Production for Bioreactor and Traditional Samples

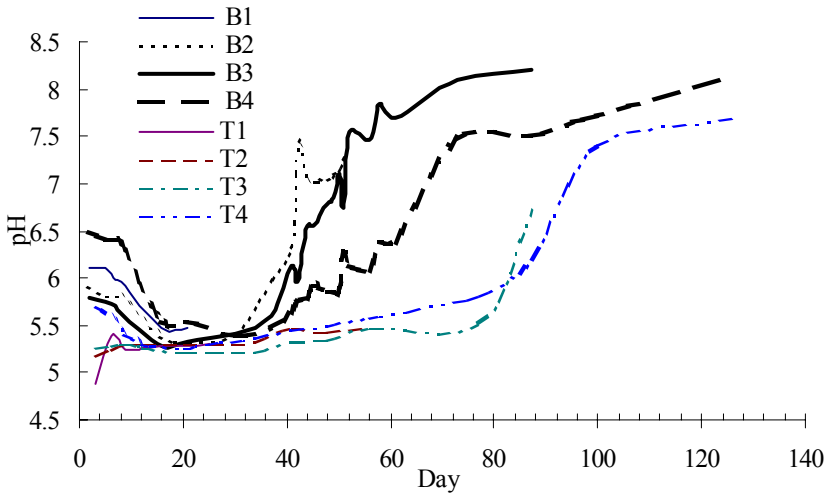

Figure 3. Variation of pH with Time for Bioreactor and Traditional Samples

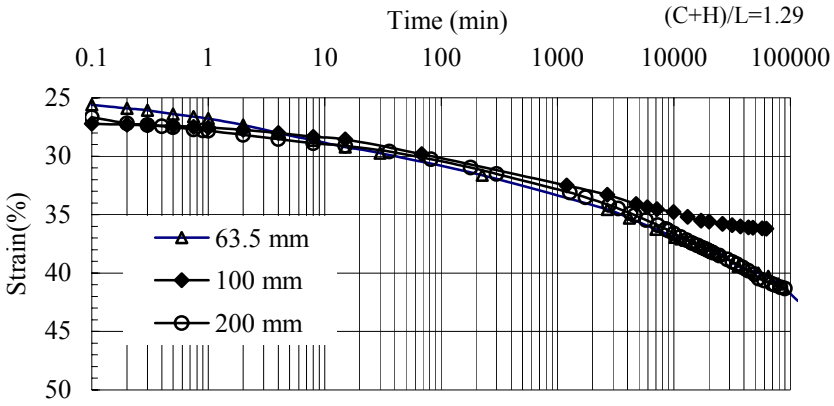

Figure 4a. Comparison of Waste Compressibility Using Different Size Equipement Diameter R, Specimen to Equipement Size Ratio = 0.5

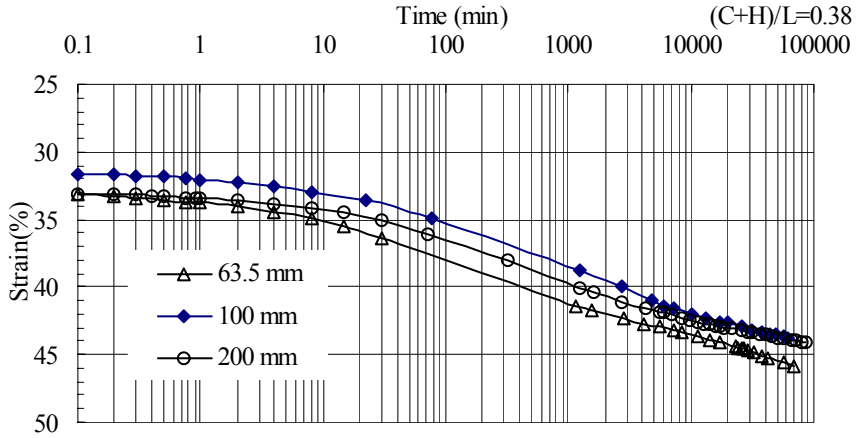

Figure 4b. Comparison of Waste Compressibility Using Different Size Equipement Diameter R, Specimen to Equipement Size Ratio = 0.5

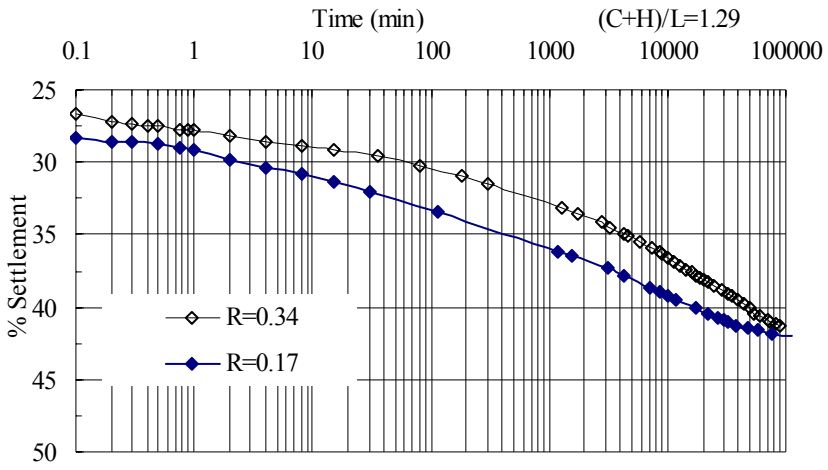

Figure 5a. Comparison of Waste Compressibility Using Different R, Specimen to Equipment Ratio . Equipment Size = 200 mm diameter

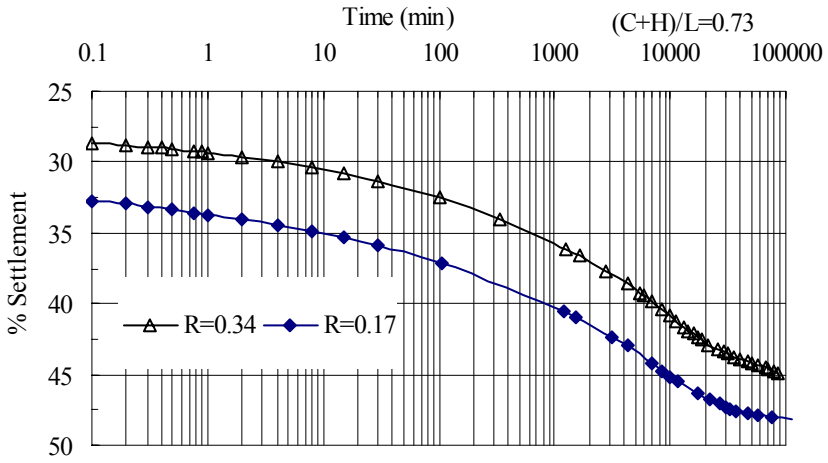

Figure 5b. Comparison of Waste Compressibility Using Different R, Specimen to Equipment Ratio . Equipment Size = 200 mm diameter

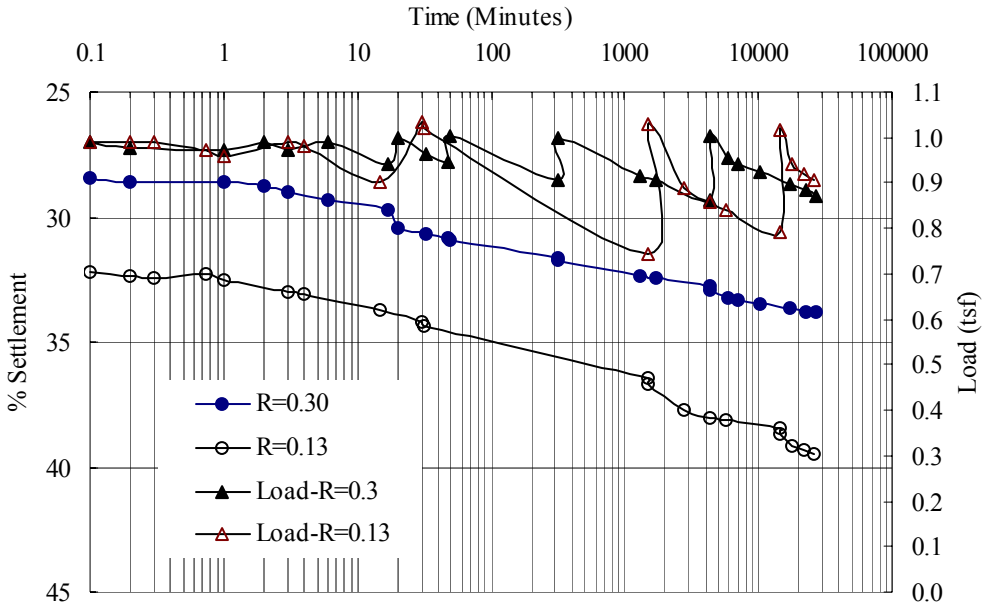

Figure 6. Comparison of Waste Compressibility Using Different R, Specimen to Equipment Ratio . Equipment Size = 300 mm diameter

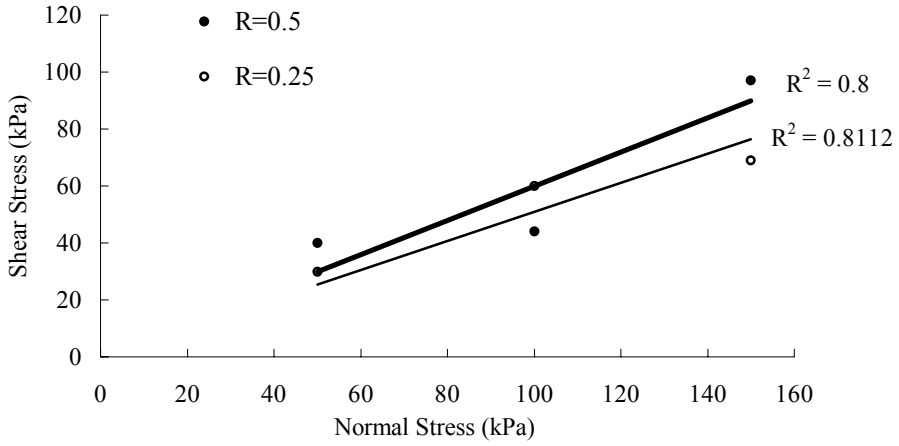

Figure 7. Comparison of Shear Strength Parameters using Different R, Specimen to Equipement Ratio

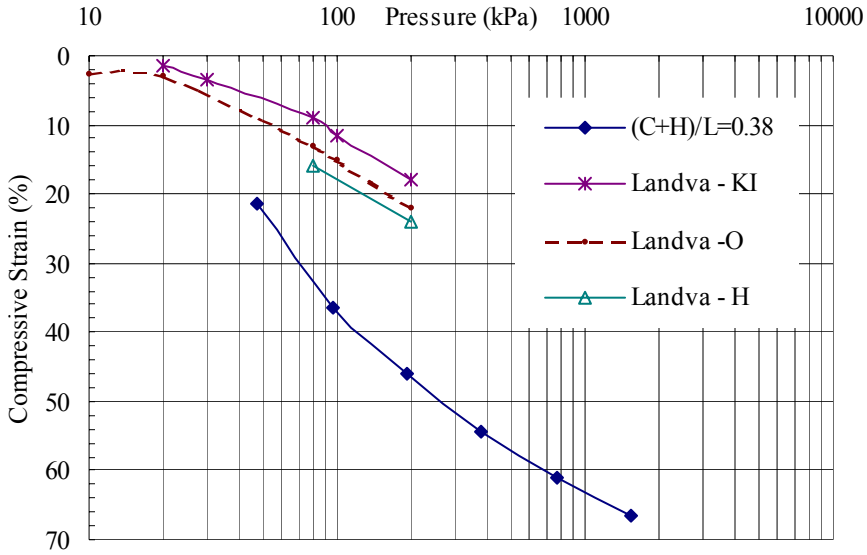

Figure 8. Compressive Strain vs Log Pressure for the Shredded /Un-shredded Samples. Sample B3 is from this study and the other three samples are from Landva and Clark.

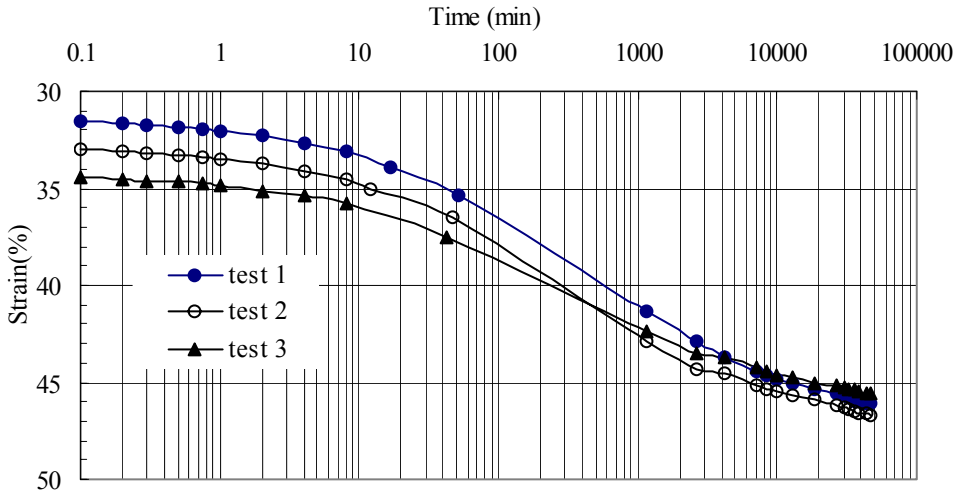

Figure 9. Repeatability Test for Compressibility Parameters on Samples from the Same Reactor

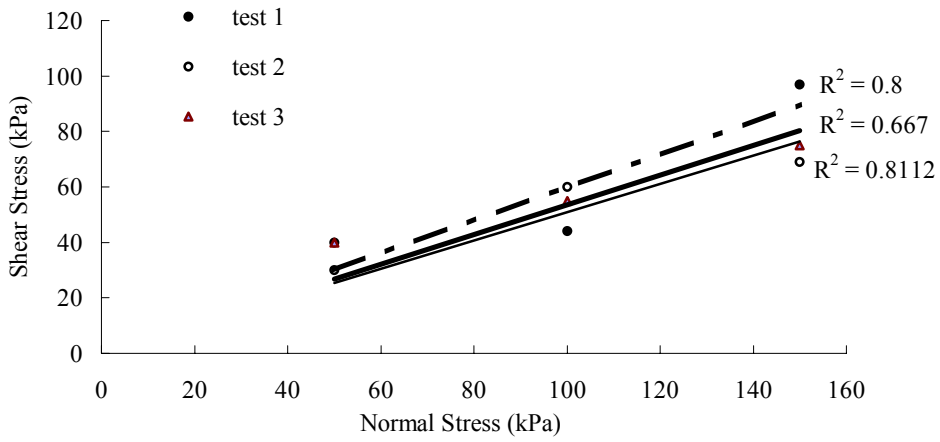

Figure 10. Repeatability Test for Shear Strength Parameters on Samples from the Same Reactor

Compressibility Parameters of Municipal Solid Waste with Leachate Recirculation

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Compressibility Parameters of Municipal Solid Waste with Leachate Recirculation

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ABSTRACT

Settlement is a common phenomenon in landfills and is attributed to both gravity forces acting on buried refuse and the biological decomposition of the organic components to gaseous end products. Recently, there has been substantial interest in the enhancement of refuse decomposition, which will result in increased settlement. The objective of this paper is to measure changes in waste compressibility as a function of the state of decomposition. Samples representative of residential refuse were prepared under conditions designed to simulate decomposition in both traditional and bioreactor landfills. Twenty four one-dimensional oedometer tests (63.5mm cell) were performed on refuse prepared in laboratory-scale reactors for measurement of primary (Cc) and secondary ($C_{\alpha i}$ and $C_{\beta i,}$ representing creep and biological effects) compression indices. The state of decomposition was quantified by the methane yield and the cellulose (C) plus hemicellulose (H) to lignin (L) ratio. Compressibility magnitude was shown to increase as refuse decomposed and compressibility parameters were correlated with the state of decomposition. Results showed that initial settlement strains increased with decreasing (C+H)/L ratio while the creep indices were fairly independent of the state of decomposition. The coefficient of primary compression (Cc) for bioreactor samples showed an increasing trend with decreasing (C+H)/L ratios. Cc increased from 0.16 to 0.36 as (C+H)/L decreased from 1.29 to 0.25 and similar values were obtained when traditional samples were tested at similar (C+H)/L ratios. The creep index range was estimated to be between 0.02 to 0.03 for traditional and bioreactor samples in various states of decomposition. The magnitude of the biological degradation index ($C_{\beta i}$) depended on the degradation phase with the highest value of 0.19 obtained during the

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phase of accelerated methane production. Proposing a single Cc for landfill settlement calculations may lead to inaccurate predictions. Properties of each waste sub-layer will change as a function of the decomposition stage, and dominating mechanics with appropriate compressibility parameters should be applied to individual sub-layers.

INTRODUCTION

Approximately 55% of the 220 million tons of municipal solid waste (MSW) generated in 1998 were disposed of in landfills (U.S. EPA 1999). In a conventional landfill that is designed and operated in accordance with Subtitle D of the Resource Conservation and Recovery Act (RCRA), efforts are typically made to minimize moisture infiltration. As a result, refuse decomposition proceeds at suboptimal rates for decades or even centuries. The idea of enhancing decomposition by the addition of supplemental water and/or recirculating leachate was first proposed over twenty years ago (Pohland 1975, Augenstein et al., 1976), although significant interest at field scale began to develop only in the late 1990s (Pacey et al. 1999). Leachate recirculation increases the refuse moisture content, and the flux of moisture through a landfill stimulates microbial activity by providing better contact between insoluble substrates, soluble nutrients, and the microorganisms (Barlaz et al. 1990). There are many advantages to leachate recirculation including: (1) settlement before placement of the final cover which decreases the risk of damage to the final cover, (2) increased effective refuse density and landfill capacity, (3) in-situ leachate treatment, (4) increased rates of gas production which may make energy recovery more favorable, and (5) acceleration of refuse decomposition which may shorten the regulated post-closure monitoring period and reduce the overall cost of the landfill (Reinhart and Townsend 1998; Pohland and Kim 1999, Barlaz et al., 1990). Accordingly, the biodegradation of MSW and associated settlement assume increased importance at landfills where leachate is recirculated and decomposition is enhanced.

Factors affecting waste compressibility include physiochemical and biological changes in the waste and long term creep (Sowers, 1968; Sowers, 1972). With the enhancement of waste decomposition, compressibility properties and subsequently the rate and magnitude of refuse settlement will change. While there is a dearth of information on settlement related to biological degradation of waste (notable work by

Edgars et. al, 1992), several studies have evaluated a coefficient of secondary compression describing continual settlement with time under constant stress. Wall and Zeiss (1995) studied settlement in a 1.7 m^3 laboratory-scale reactor and concluded, based on 250 days of testing, that decomposition did not significantly affect the rate of secondary settlement. Gabr (1995) reported secondary compression coefficients to be between 0.03 - 0.09 in 15-30 year old waste samples. Coumoulous (1999) measured secondary compression coefficients of 0.02 to 0.07 in 10 to 15 year old traditional landfills. Using data from the Mountain View, CA bioreactor landfill El Fadel and Al-Rashed (1998) reported secondary compression coefficients of 0.1- 0.32. These values are five times the values obtained by Sharma and Coumoulous for traditional landfill refuse. Earth Tech Consultants (2001) reported secondary compression values of 0.18 - 0.26 for the Crow Wing County, MN bioreactor landfill, which are relatively consistent with the El-Fadel and Al-Rashed data. El Fadel and Al-Rashed (1998) used power Creep and one-dimensional consolidation models to analyze data from the Mountain View bioreactor test cells. The authors were better able to curve fit the measured time-settlement data using the 1-D analytical approach (commonly used for clay settlement) as opposed to the power creep model, although neither model accurately described the physical and biological mechanics of settlement. A recent study by Park et.al (2002) also indicated the power creep model to be a poor predictor of waste settlement rate.

Depending on the waste age and the test duration, the coefficients of secondary compression reported above encompass components of creep and biological effects. In general, literature reports do not include the degree of decomposition of the tested waste. In bioreactor landfills, decomposition is accelerated and the rearrangement of waste particles and increase in void space will affect the settlement rate and compressibility. Both load-induced and biologically-induced compressibilities are expected to be higher in bioreactor landfills relative to traditional landfills over the same time-span. Furthermore, the magnitude of settlement in a bioreactor landfill may be higher as stiffness characteristics of the waste are decreased more rapidly relative to waste in traditional landfills. The availability of data to systematically describe the contribution of the dominant compressibility processes will provide a tool for better estimation of

available air space, the design of final and interim cover systems, and a better understanding of expected time dependent deformation under future vertical expansions.

The objective of this study was to characterize the relative changes in waste compressibility during waste decomposition. Samples were prepared in eight 4-liter (~1 gal) reactors and allowed to degrade to various stages of decomposition for compressibility testing. The degree of decomposition was characterized through gas generation rates and the cellulose plus hemicellulose to lignin ratio. Twenty four one-dimensional oedometer tests (63.5 mm cell) were performed and compression indices representing creep and biological effects ($C_{\alpha i}$ and $C_{\beta i}$) were measured on samples ranging from fresh to well-decomposed refuse. In addition, eight "short term" compression tests were conducted to determine the coefficient of primary compression (Cc). Settlement components including creep and biodegradation effects are identified as a function of the state of decomposition.

REFUSE BIODEGRADATION AND GAS PRODUCTION

Cellulose and hemicellulose are the principal biodegradable components of refuse and their concentrations in residential refuse are reported to range from 29 - 51% and 9 - 12% of the refuse dry weight, respectively (Hilger and Barlaz, 2001). Lignin is the other major organic component of refuse, with concentrations ranging from 15 - 28%. Lignin is at best only slowly degradable under methanogenic conditions and interferes with the decomposition of cellulose and hemicellulose by physically impeding microbial access to these degradable carbohydrates (Colberg 1988). The conversion of cellulose to methane (CH_4) and carbon dioxide (CO_2) is described by eqn 1. Methane production per kg of cellulose and hemicellulose decomposed is 414.8 and 424.2 liters, respectively (Barlaz et.al., 1990).

$$(C_6 H_{10} O_5)_n + n H_2 O \longrightarrow 3n CH_4 + 3n CO_2 \quad (1)$$

A complex series of series of chemical and biological reactions is initiated with the burial of refuse in a landfill. After refuse placement, a period ranging from months to years is necessary for the required microbiological system to become established for

biological decomposition. Refuse decomposition has been described in an aerobic phase, an anaerobic acid phase, an accelerated methane production phase and a decelerated methane production phase (Barlaz et al., 1989).

In the aerobic phase (1), the oxygen entrained in the refuse at burial is consumed and there is no mechanism for its replenishment based on conventional landfill practice. CO_2 will be the major gaseous product and there will be little to no cellulose and hemicellulose biodegradation. In the anaerobic acid phase (2), carboxylic acids (acetic, propionic, butyric) accumulate and the pH decreases. These acids accumulate because of an imbalance between the various groups of bacteria required to convert refuse to methane. Phase 2 is characterized by acidic leachate, little gas production and little to no cellulose and hemicellulose decomposition because environmental conditions are not suitable for the bacteria required for refuse decomposition. In the accelerated methane production phase (3), suitable environmental conditions develop and the methane production rate increases to some maximum value; the accumulated carboxylic acids are converted to CH_4 and CO_2; the pH increases; and cellulose and hemicellulose decomposition begin. In the decelerated methane production phase (phase 4), the methane production rate decreases, carboxylic acids are depleted and there is an increase in the rate of cellulose plus hemicellulose hydrolysis. While acid utilization limits methane production in phases 2 and 3, cellulose and hemicellulose hydrolysis limits methane production in phase 4. In a laboratory-scale simulation, 70-75% of the initial cellulose and hemicellulose were converted to CH_4 and CO_2. In applying this description of refuse decomposition to full-scale landfills, it must be recognized that the time required for the onset of each phase will vary based on conditions in the landfill. In bioreactor landfills, the increased moisture enhances progression of the refuse to phases 3 and 4 relative to a traditional landfill.

Gas production from landfills is typically modeled using a first order decomposition rate such as that in the US EPA Landgem Model (1998).

$$G = WL_0ke^{-kt} \qquad 2)$$

G is annual methane generation for a specific year t (ft^3 CH_4/yr);

W is the mass of waste buried annually (tons/yr)

L_o is the methane potential (ft^3 CH_4/ton of waste):

t is time after initial waste placement (yr);

k is the first order decay rate constant (1/yr)

Methane production rates calculated from eqn. 2 for traditional and bioreactor landfills are presented in Fig. 1. It should be noted that the decay rate for a biroeactor landfill has not been verified and is used here to represent accelerated decomposition.

EXPERIMENTAL DESIGN

Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The reactors were destructively sampled to obtain refuse at various states of decomposition based on the reactor's methane production rate curve. In addition, the state of decomposition was quantified by measurement of the concentrations of cellulose, hemicellulose and lignin. Reactors were sampled at each of four time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, and early and late in the decelerated methane production phase. One-dimensional oedometer tests (63.5 mm cell) were then performed on waste specimens and compression indices representing creep and biological effects ($C_{\alpha i}$ and $C_{\beta i}$) were measured and compared. In addition, eight "short term" compression tests were conducted to determine the variation in the coefficient of primary consolidation (Cc) with the extent of decomposition.

PREPARATION OF FRESH AND DECOMPOSED REFUSE

Solid waste representative of residential refuse was collected from a transfer station in Wake County, NC. Approximately 900 kg (2000 pounds) was shredded to about 10 mm x 20 mm pieces. The shredded refuse was then mixed and sequentially quartered until each pile contained 40-50 kg. Twenty piles were collected in separate plastic bags and stored at 4^0C until used in the experimental program.

Eight 4-L reactors were filled with refuse to prepare samples at different stages of decomposition for compressibility testing. Reactors T1-T4 were operated under conditions designed to simulate a traditional landfill and will be referred to as "traditional" samples. Sufficient moisture was added to adjust the moisture content to 55% (wet wt. basis). Reactors B1-B4 were operated under conditions designed to simulate a bioreactor including, (1) the addition of sufficient moisture to induce leachate

production, (2) leachate recirculation and (3) the addition of an inoculum of anaerobically digested sewage sludge. The leachate was neutralized with KOH as necessary and recycled six days a week. All reactors were incubated in a room maintained at 37 to 41^0 C.

Gas was collected in five-layer gas-bags and the volume was measured by pumping into a calibrated carboy using water displacement. Gas concentrations (CO_2 and CH_4) were measured using a GOW-MAC gas chromatograph (Bound Brook, NJ) equipped with a thermal conductivity detector and a CTR1 column (Alltech, Deerfield, IL).

Reactors were destructively sampled based on their methane production rate curve. The contents were thoroughly mixed and a sub-sample was removed for composition analysis. The sub-sample was first dried to constant weight at 75°C and then ground in a Wiley mill to pass a 1 mm screen. Cellulose (C) and hemicellulose (H) concentrations were analyzed by acid hydrolysis followed by HPLC analysis of the hydrolyzed sugars (Wang et al., 1994). Lignin (L) was determined from the combustible (550°C) fraction of the material that remained after the acid hydrolysis. The remaining refuse was used in the Oedometer tests without drying.

OEDOMETER TESTS

Remolded specimens were compacted directly into a 63.5 mm diameter by 19 mm thick circular stainless steel ring with a wooden dowel. Particles of length equal to no more than half the diameter of test cell were included. Tests were performed in conformance with ASTM Test Method (D2435-90). The testing program is shown in Table 1. For determination of the primary compression ratio (Cc), the rapid loading method described by ASTM D2435-90 was adopted. For the determination of long-term compressibility behavior, tests were run for approximately 70 days under a constant stress of 95 kN/m^2. Initially, tests were conducted under conditions that did not eliminate refuse biodegradation during the testing period. As such, settlement associated with primary, creep and biological settlement effects was measured. A second set of test samples was saturated with 6% acetic acid to prevent decomposition during testing. These tests allowed for measurement of primary and creep settlement components while

biological effects were inhibited. Accordingly, settlement components for primary, creep and biological degradation were discerned relative to each other.

RESULTS

The methane production characteristics and solids composition of test samples used for measurement of compressibility parameters are described in the first part of this section, followed by the results of the oedometer tests.

Refuse Decomposition

Methane production rates and volume for the bioreactor and traditional samples are presented in Figures 2 and 3, respectively, and the cumulative volume of methane for each reactor is given in Table 2. The pH of the reactor leachate is presented in Figures 4 and 5 for the bioreactor and traditional landfills, respectively. Comparing results from traditional and bioreactor samples, the more rapid increase in the methane production rate and leachate pH illustrates the enhancement of refuse decomposition when reactors are operated with leachate recycle and neutralization. The anaerobic sewage sludge seed and the external neutralization of the leachate reduced the time span of the anaerobic acid phase of decomposition.

Bioreactor systems were destructively sampled on days 24, 53, 84 and 127. As illustrated by the methane production data in Fig. 2 and Table 2, and the pH data in Fig. 4, the day 24 sample was in the anaerobic acid phase, the day 53 sample was in the accelerated methane production phase and the day 84 and day 127 samples were in the decelerated methane production phase. Traditional landfill reactors were destructively sampled at approximately the same times so that the volume of leachate recirculated through the bioreactor and traditional samples was equivalent. However, only the day 91 and day 130 samples exhibited methane production with the methane volume considerably less than that measured in the corresponding bioreactor samples (Table 2, Fig. 4). The day 91 traditional sample was at the beginning of the accelerated methane production phase and the day 130 sample was later in this same phase. The pH was increasing on day 91 and had reached neutral by day 130.

The composition of solids removed from each reactor at the end of the monitoring period is presented in Table 2. The (C+H)/L ratio in the bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower

decrease in this ratio in the traditional landfill samples. These results were consistent with the low methane production volume (0-13.8 L) for the traditional samples. In general, the (C+H)/L ratios of traditional samples are higher than those of the bioreactor samples at the same time point. While bioreactor samples had completed all phases of degradation, the traditional samples were still in early Phase 3.

Compressibility Parameters

A summary of results from the Oedometer tests for bioreactor and traditional samples are presented in Table 3, and Figures 6 and 7, respectively. As described above, samples were recovered from laboratory-scale reactors at different states of decomposition as quantified by the (C+H)/L. Samples decomposed in the bioreactor simulations were tested at (C+H)/L ratios of 1.29, 0.71, 0.38 and 0.25. The measured primary settlement strains shown in Table 3 are indicative of the induced primary compression due to the placement of 95 kN/m^2. The more thoroughly decomposed samples (lower (C+H)/L ratios) had a weakened structural matrix, as solid–to-gas conversion took place, leading to an increase in initial settlement under the same applied stress. Compressibility with time for sample B1 (Fig. 6) was at a relatively constant rate, which is indicative of creep mechanics while the specimen was in the acid phase. After approximately 3000 min, the slope of the strain-time plot for B1 slightly increased indicating biological degradation. Creep and biological indices were estimated to be 0.030 and 0.050, respectively. Sample B2 exhibited two distinct components: an initial slope $C_{\alpha 2}$ and a steeper slope $C_{\beta 2}$. The steeper slope is likely due to the fact that the sample underwent additional decomposition during testing. The initial slope $C_{\alpha 2}$, is parallel to the slope for B1 ($C_{\alpha 1} = 0.030$) and is indicative of the creep behavior. Biologically-induced settlement began after about 20,000 min and $C_{\beta 2}$ is estimated to be approximately 0.190. The initial slopes for both B3 and B4 (Fig. 6) samples ($C_{\alpha 3}$ and $C_{\alpha 4}$) are estimated to be approximately 0.028, and are similar to samples B1 and B2. No biologically-induced settlement was observed for B3 and B4 as these samples were well decomposed prior to the oedometer tests.

The primary settlement strains for samples recovered from the traditional simulations are indicative of the induced immediate compression due to the placement of

95 kN/m^2 (Table 3). Creep indices for all traditional samples are estimated to be approximately 0.02 and indicated that compressibility under applied stress was at a relatively constant rate. In samples T2 and T3 (Fig. 7), biologically-induced compressibility becomes apparent at approximately 10000 min and biological index values of 0.1 and 0.08, respectively, are estimated. The relatively higher creep index values for bioreactor samples, as compared to traditional samples, may be a reflection of a decrease in particle size as decomposition takes place.

Results indicated that the coefficient of biological degradation (C_β) was dependent on the decomposition phase. For samples from the acid phase, the coefficient was measured to range from 0.05-0.10 with an average value of 0.075 for both traditional and bioreactor samples (Table 3). During the accelerated methane production phase, the C_β values varied depending on whether the sample was tested while at initial or peak accelerated methane production. In the case of T3 (Fig. 7), which was producing very little methane, C_β was 0.08. In contrast, B2, which was actively producing CH_4, C_β was 0.19. Samples B3 and B4 were well decomposed prior to the start of compressibility testing. As such, there was little additional decomposition during compressibility testing. This resulted in a low secondary compression index and biologically induced settlement was difficult to identify.

The secondary compressibility parameters, obtained from laboratory tests, for both bioreactor and traditional samples are consistent with the back-calculated field data provided by Edgar and Noble (1992), El Fadel and Al-Rashid (1998) and Earth Tech Consultants (2001). Edgers and Noble (1992) found that creep coefficients varied from 0.01 to 0.04 (average 0.025) and biological coefficients varied from 0.02 to 0.5 (average 0.1). El Fadel and Al-Rashed (1998) reported creep coefficients of 0.015 - 0.035 and biological coefficients of 0.1 - 0.32 for the Mountain View CA Landfill. Earth Tech Consultants (2001) reported biological coefficient values of 0.18 - 0.26 for the Crow Wing County, MN bioreactor landfill.

Additional testing of the bioreactor samples were conducted under conditions designed to eliminate further biological decomposition during the testing period. These results are presented in Figure 8 and Table 3. The measured settlement can be viewed to represent primary and creep strains only as further biodegradation was inhibited. The

creep index for all samples ranges from 0.015 to 0.03. The lowest value was for the least decomposed sample ((C+H)/L=1.29), while higher creep indices were measured for the more decomposed samples. This is similar to creep index values obtained from traditional and bioreactor samples.

Coefficient of Primary Compression

Eight oedometer tests were conducted under increasing loading conditions, to determine the coefficient of primary compression (Cc). Tests were run for approximately 8 hr under a stress range of 50-1500 kN/m^2. The high compressibility of the bioreactor samples in comparison to traditional samples was evident in all tests (Fig. 9, Table 3). The coefficient of primary compression (Cc) increased from 0.16 to 0.36 as (C+H)/L ratio decreased (Table 3). In comparison, the coefficient of primary compression (Cc) for the traditional samples was estimated to be 0.16 in refuse with little decomposition and increased to 0.25 in more decomposed refuse (Fig 10, Table 3). These results suggest that the use of a single Cc for settlement calculations in a landfill will lead to inaccurate predictions. Properties of each waste sub-layer will change as a function of the decomposition stage, and dominating mechanics with appropriate compressibility parameters should be applied to each sub-layer (Gabr, et. al, 2000).

There appears to be a general trend of an increase in Cc with a decrease in (C+H)/L ratio as presented in Figure 11. This trend shows the state of refuse decomposition rather than how the landfill is operated controls compressibility parameters.

Figure 12 compares compression index values obtained by back calculation from field studies by Sowers (1973), laboratory test results from Gabr (1994) and Wall (1995), and values reported herein. Sowers reported compression index variation as a function of both initial void ratio and organic content. The laboratory test results for both bioreactor and traditional samples are within the boundaries provided by Sowers. Compression indices for well decomposed bioreactor samples are towards the upper boundary limit while, generally, for traditional samples they are towards the lower limit. Cc increases as refuse decomposition proceeds.

Effect of Shredding

Given the extreme heterogeneity of MSW, there is a strong incentive to homogenize samples for laboratory testing. One way to obtain well mixed samples of a size appropriate for laboratory testing is to shred large quantities of refuse and then work with sub-samples as was done in this study. To investigate the effect of shredding on compressibility, published data from Landva and Clark (1990) for three samples excavated from Kinston, Ottawa and Hantsport landfills as well as sample B3 from this research were plotted (Fig. 13). Sample B3, as indicated by its gas production trend, pH, and a low (C+H)/L ratio, was in an advanced stage of decomposition. In Fig. 13, B3 is compared to 10-15 year old Kinston (KI), Ottawa (O) and Hantsport (H) landfill samples. It is assumed that these later three samples have undergone significant decomposition and are most comparable to B3. This is supported by excavations at other landfills in which refuse with a C/L of 0.16-0.24 was reported (Bookter and Ham,1982). Landva and Clark used 470 mm cells and unshredded samples. The measured coefficients for primary compression were 0.17, 0.22, 0.21 and 0.37 for the Kinston, Ottawa, Hantsport and B3 samples, respectively. The respective compressive strains at a 100 kPa load are 12%, 15%, 18% and 37%. The cell size for the unshredded samples tested by Landva and Clark (1990) was approximately 7.5 times larger than the cell used in this research (470 mm versus 63 mm) with their measured compressibility, on the average, 54%-150% of the value measured here. One explanation for the increased compressibility of the shredded sample is that shredding the light weight reinforcing material, including plastics, textiles and paper reduced the reinforcement effect, giving rise to higher compressibility during the test. Nonetheless, the rate of strain increase with time under constant load does not seem to be greatly affected by shredding as values of C_α and C_β obtained for shredded samples are within range of values reported in literature. While this preliminary analysis provides insight into how shredding may affect the primary compressibility results, this issue needs further investigation as demand for evaluation of compressibility parameters increases with the operation of landfills as bioreactors.

SUMMARY AND CONCLUSIONS

Work in this paper utilized data from laboratory oedometer tests to illustrate compressibility parameters for refuse at different degrees of degradation. The extent of

degradation was documented by gas production rates as well as (C+H)/L ratios. Sixteen one-dimensional oedometer tests were run for approximately 20 days under a constant stress of 95 kN/m^2. An additional eight "short term" tests were conducted to determine the coefficient of primary compression (Cc) with decreasing (C+H)/L ratios. Based on the results obtained in this study, the following conclusions are advanced:

1. Compressibility increased with increasing gas production as solid-to-gas conversion took place. (C+H)/L was used to quantify the state of waste decomposition. Testing results indicated a correlation between the compressibility parameter (Cc) and this ratio. For example, measured primary settlement strains for bioreactor samples under 95 kPa increased from 26% to 35% as (C+H)/L ratio decreased from 1.29 to 0.25.
2. Results indicated the creep index (C_α) to be independent of the state of waste decomposition. The creep index range was 0.02 to 0.03 for traditional and bioreactor samples in various states of decomposition.
3. The magnitude of the biological indices varied with the state of decomposition and yielded the highest values when samples were actively decomposing and had substantial methane potential remaining.
4. The coefficient of primary compression (Cc) for all samples showed a general trend of increasing with decreasing (C+H)/L.
5. The coefficient of primary consolidation (Cc) for both bioreactor and traditional samples are within the boundaries provided by Sowers (1972). Compression indices for more thoroughly decomposed bioreactor samples are towards the higher limit as proposed by Sowers, while traditional samples are towards the lower limit.

Based on the results presented in this study, proposing a single Cc for landfill settlement calculations may lead to inaccurate predictions. Within a landfill profile, the properties of the waste sub-layers will vary as a function of the state of decomposition. Accordingly, mechanics with appropriate compressibility parameters should be applied to each waste sub-layer for estimation of settlement.

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Table 1 Number of Tests for Measuring Compressibility Parameters

Day Sampled[a] (From Reactors)	Primary and Creep (degradation inhibited)		Primary, Creep, and Biodegradation		Compression Index, Cc
	Bioreactor	Traditional	Bioreactor	Traditional	B+T[b]
24	1	1	1	1	1+1
53	1	1	1	1	1+1
84	1	1	1	1	1+1
127	1	1	1	1	1+1

a. Reactors were destructively sampled on these days;

b. b. B- Bioreactor, T – Traditional;

Table 2 Description of the Sampled Reactors and Their Gas Production Record

Sample Identification[a]	Day Sampled[b]	Cumulative Methane Production (L)	% Cellulose (C)	% Hemi-Cellulose (H)	%Lignin (L)	(C+H)/L
Fresh Refuse	n/a	n/a	41.91	8.47	19.96	2.52
B1	24	0.5	32.79	6.55	30.53	1.29
B2	53	70.5	21.87	4.95	38.08	0.71
B3	84	102.2	13.48	3.94	46.26	0.38
B4	127	53.5	11.88	2.29	56.44	0.25
T1	27	0	37.32	8.10	19.17	2.37
T2	56	0.7	27.45	6.03	26.06	1.29
T3	91	3.0	29.40	6.25	19.88	1.79
T4	130	13.8	16.92	3.88	28.47	0.73

a. B and T designate bioreactor and traditional samples, respectively

b. Traditional reactors were filled with MSW 3 days before bioreactors

n/a - not applicable

Table 3 Compressibility Parameters for Bioreactor and Traditional Samples

Sample Identification	(C+H)/L	Primary Compression (%)	C_c	C_α	C_β
B1	1.29	26	-	0.030	0.050
B2	0.71	30	-	0.030	0.190
B3	0.38	33.5	-	0.028	0.022
B4	0.25	35	-	0.028	0.022
T1	2.37	12	-	0.020	0.050
T2	1.29	22	-	0.020	0.100
T3	1.79	28	-	0.020	0.080
T4	0.73	35	-	0.020	0.050
B1[a]	1.29	21	-	0.015	-
B2[a]	0.71	26	-	0.030	-
B3[a]	0.37	30	-	0.025	-
B4[a]	0.25	32	-	0.030	-
B1[b]	1.29	26	0.16	-	-
B2[b]	0.71	30	0.25	-	-
B3[b]	0.38	33.5	0.37	-	-
B4[b]	0.25	35	0.35	-	-
T1[b]	2.37	12	0.16	-	-
T2[b]	1.29	22	0.16	-	-
T3[b]	1.79	28	0.20	-	-
T4[b]	0.73	35	0.25	-	-

a. Degradation was inhibited during the compressibility test

b. The tests were completed quickly (within 6-8 hours)

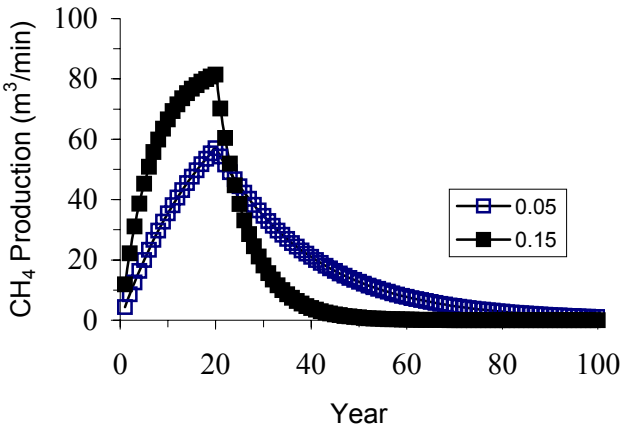

Figure 1. Methane production rate for a landfill that receives 286,000 metric ton/yr for 20 years. With reference to eqn. 2, Lo = 170 L/kg, the default value used for NSPS guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 and enhanced decomposition in a bioreactor (k = 0.15).

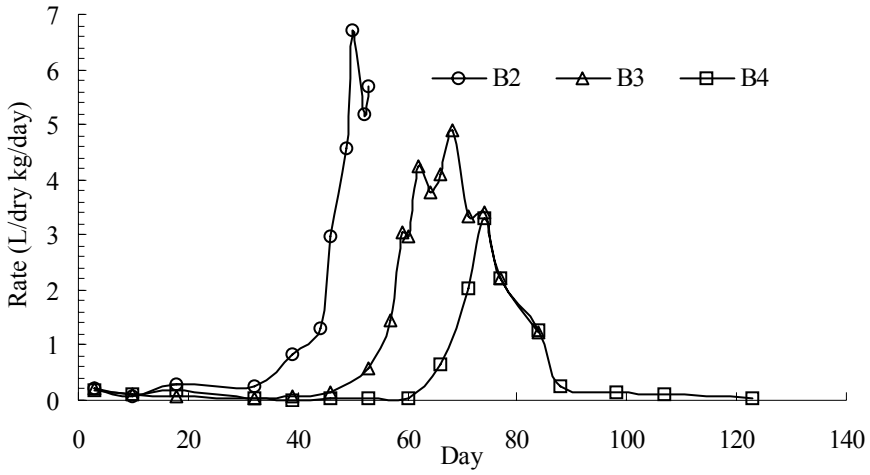

Figure 2. Rate of Methane Production for Bioreactors

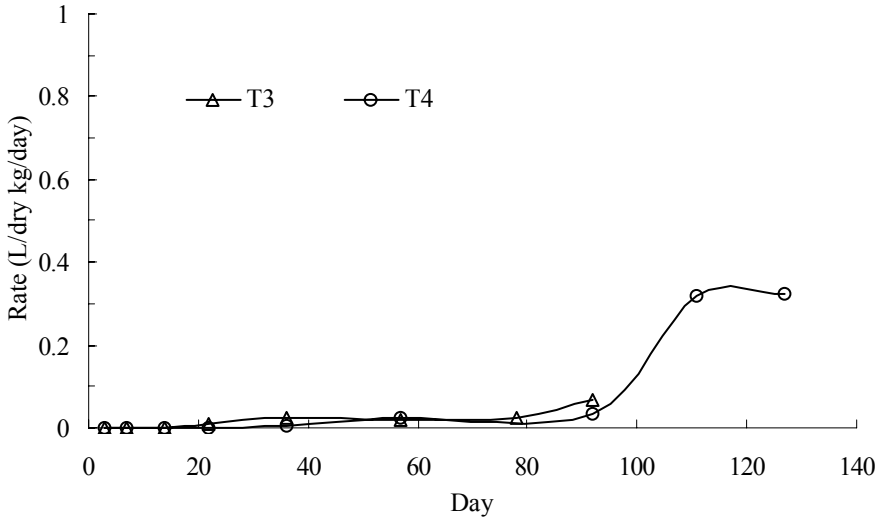

Figure 3. Rate of Methane Production for Traditional Reactors

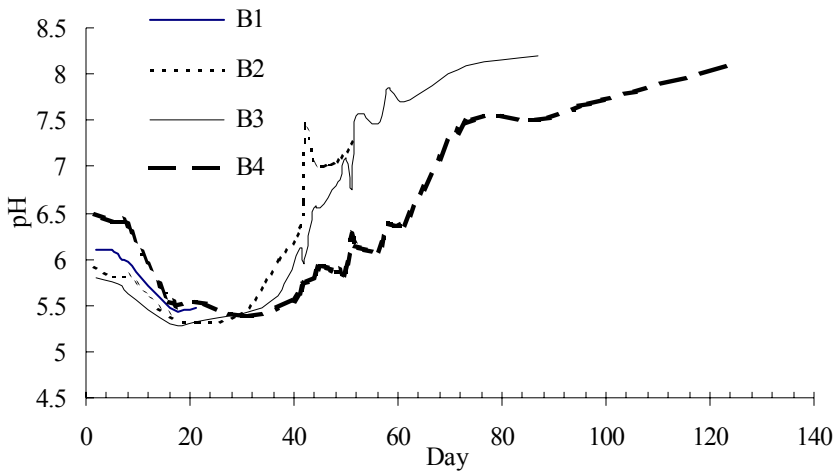

Figure 4. Variation of pH with Time for Bioreactors

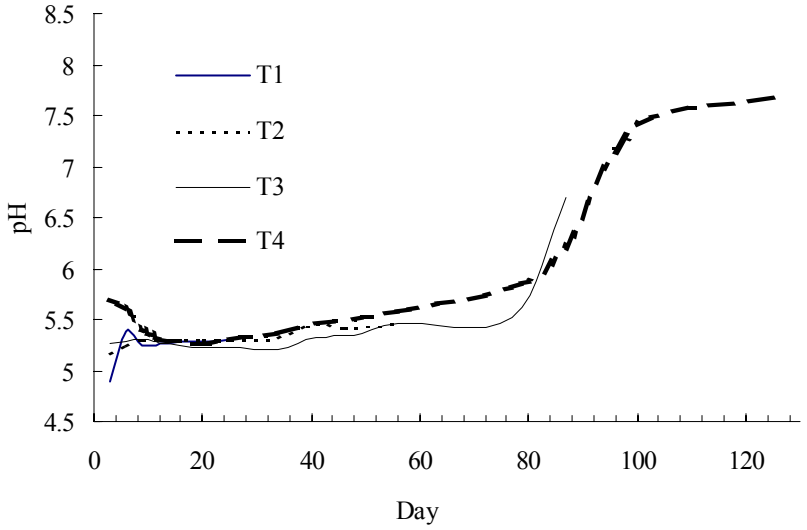

Figure 5. Variation of pH with Time for Traditional Reactors

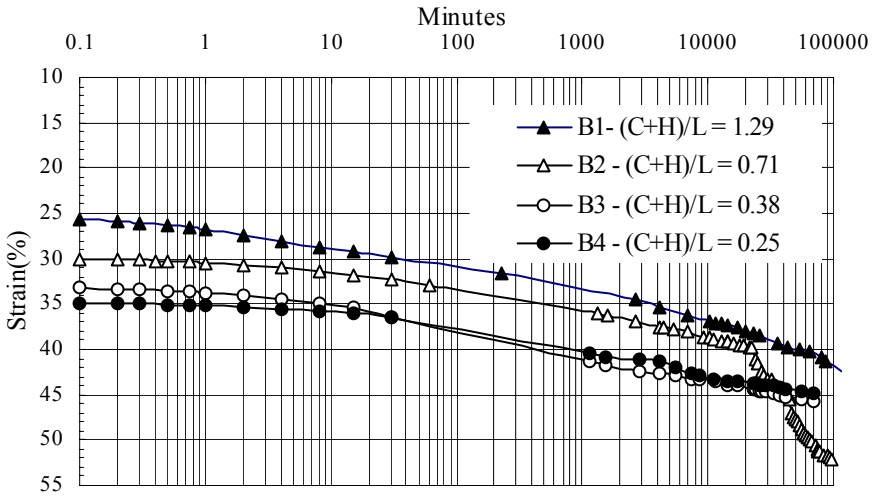

Figure 6. 1-D Oedometer Test Results for Bioreactor Samples

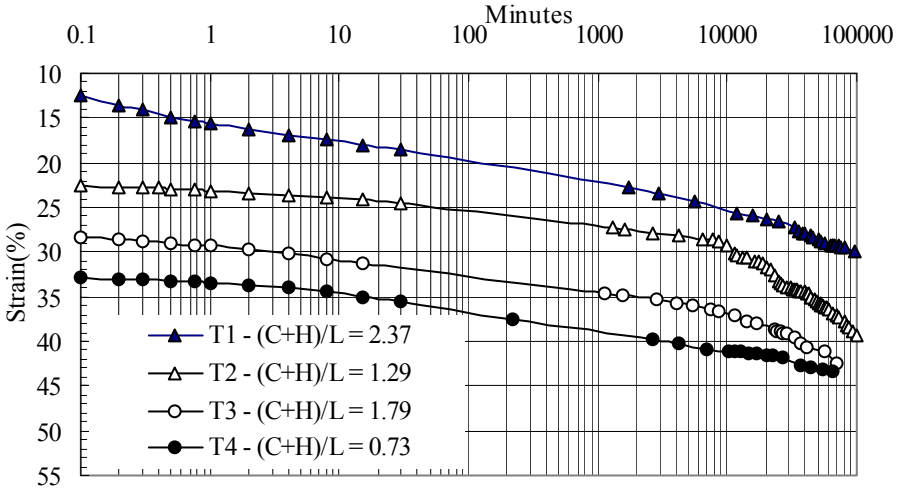

Figure 7. 1-D Oedometer Test Results for Traditional Samples

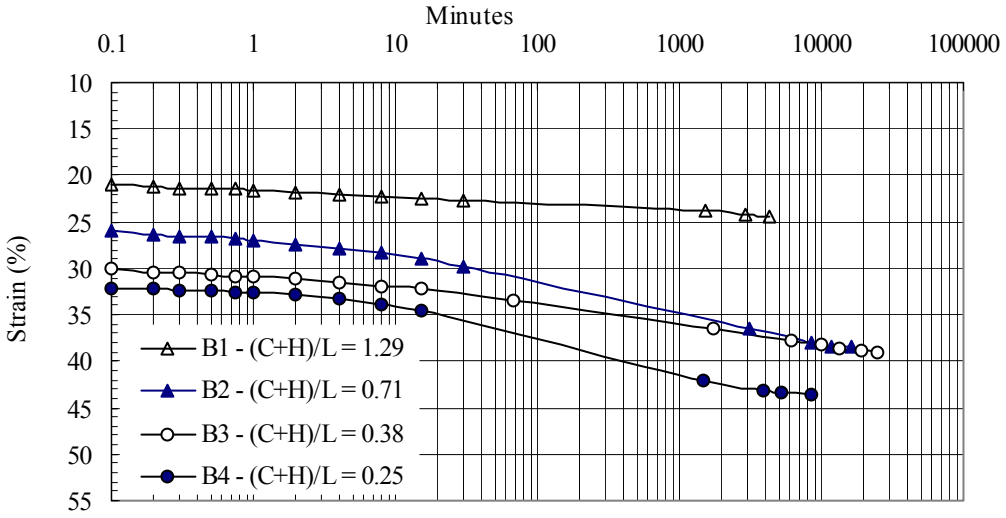

Figure 8. 1-D Oedometer Test Results for Bioreactor Samples (Degradation Inhibited)

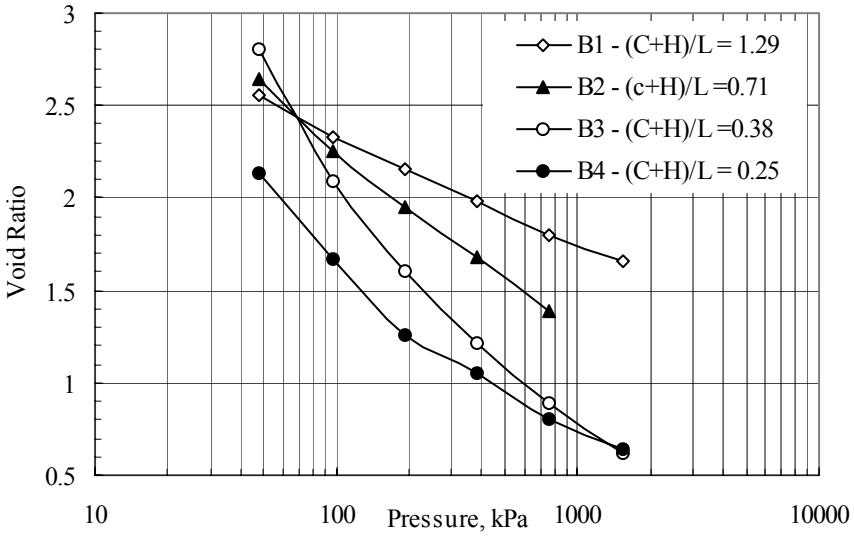

Figure 9. Void Ratio vs Log Pressure for the Bioreactor Samples

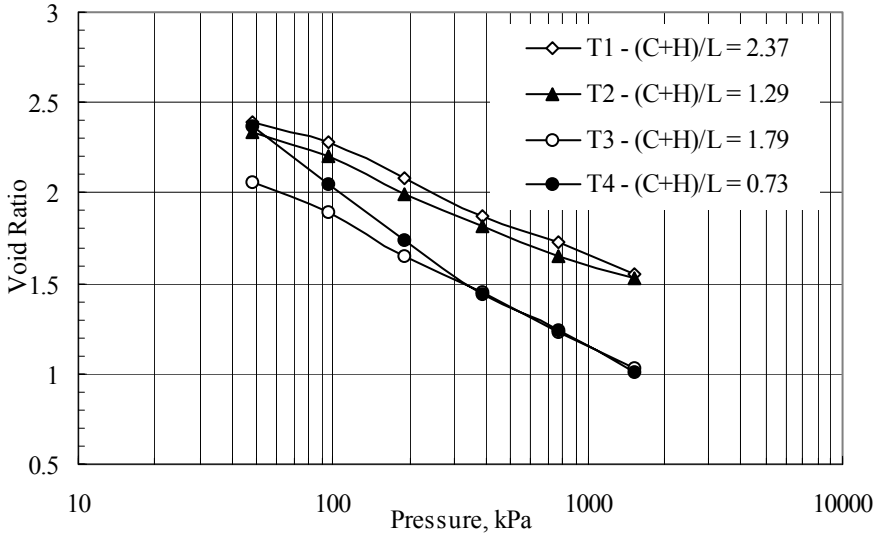

Figure 10. Void Ratio vs Log Pressure for the Traditional Samples

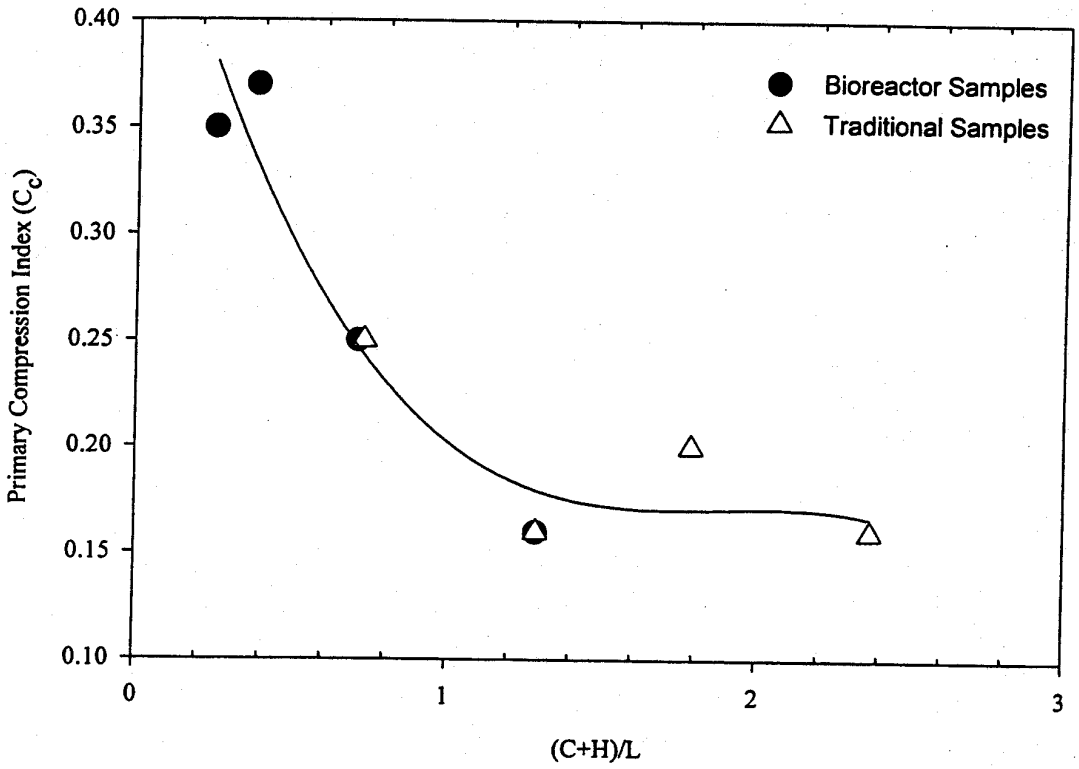

Figure 11. Variation of Cc with Decreasing (C+H)/L Ratio

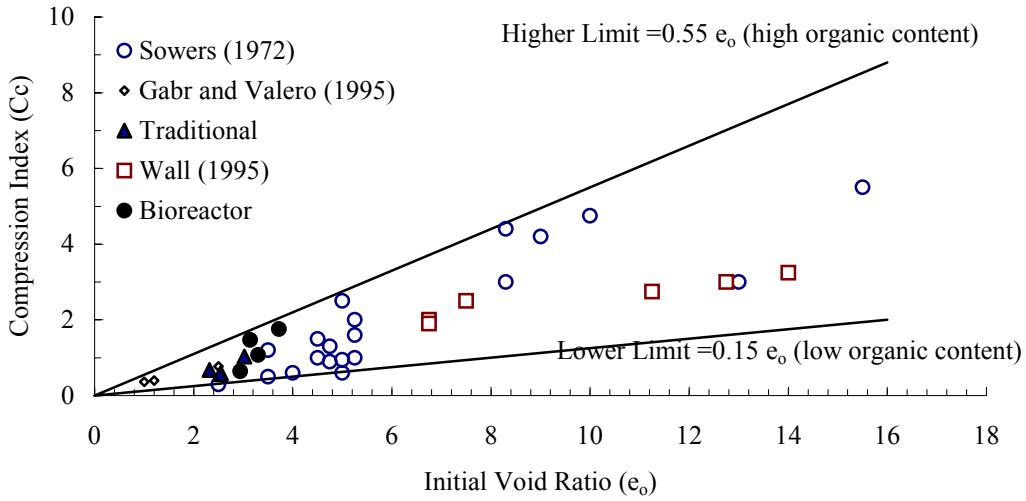

Figure 12. Primary Compression Parameter as a Function of Initial Void Ratio

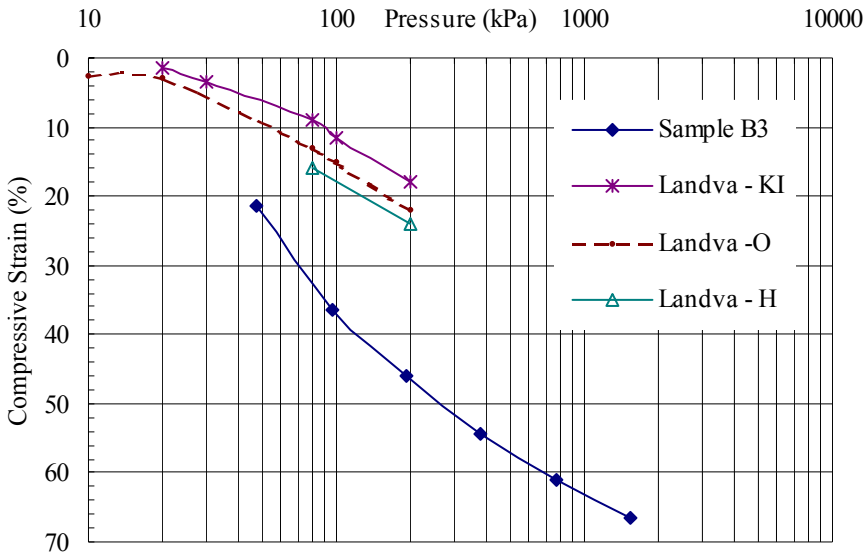

Figure 13. Compressive Strain vs Log Pressure for the Shredded /Un-shredded Samples. Sample B3 is from this study and the other three samples are from Landva and Clark.

Prediction of Municipal Solid Waste Landfill Settlement with Leachate Recirculation

To be submitted for review

Prediction of Municipal Solid Waste Landfill Settlement with Leachate Recirculation

M. S. Hossain[1], M. A. Gabr[2], and M.A. Barlaz[3]

ABSTRACT

The degradation of MSW over time, and associated settlement, is of special importance when estimating air space, designing interim and final closure covers of landfills, as well as planning vertical expansion of existing facilities. Most settlement models applied to solid waste were developed for inorganic soils or peat. Furthermore, these models were not developed considering the leachate recirculation effect on settlement. In case of bioreactor landfills, waste settlement will include creep and biological components due to the heterogeneous nature of waste particles, and accelerated biodegradation, respectively, as leachate is recycled. The objective of this paper is to present a settlement prediction model, which accounts for changes in material characteristics as a function of the waste degradation rate. As biodegradation takes place, the organic solid mass is converted to gas and the void ratio increases with a subsequent increase in waste settlement. In general, published models do not capture these phenomena. The model developed herein is based on the results of an experimental program. Settlement components including creep and biodegradation effects are identified as a function of the state of decomposition. Based on twenty four one-dimensional oedometer tests (63.5 mm cell), compression indices representing creep and biological effects ($C_{\alpha i}$ and $C_{\beta i}$) were measured on samples ranging from fresh to well-decomposed refuse. In addition, the coefficients of primary compression (Cc) were measured. The time factors, t_1, t_2, t_3 and t_4 for the compressibility were determined from the gas production curve and existing settlement data, and utilized for model development. The proposed model was verified using the settlement model parameters obtained from laboratory test and comparing predicted settlement with observed field settlement from seven landfills.

INTRODUCTION

The degradation of MSW over time, and associated settlement, is of special importance when estimating air space, designing interim and final closure covers for

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landfills, as well as on planning the vertical expansion of existing facilities. Factors affecting changes in waste compressibility include physiochemical and biological changes of waste, distortion and reorientation of the refuse, erosion of the fine material into large void and long term creep processes (Sowers, 1968 and 1972). As landfill technology evolves to include the use of leachate recycle and the operation of landfills as bioreactors, the gas production characteristics as well as the leachate quantity and quality will change. These changes will impact the geotechnical compressibility properties and settlement rate and magnitude of the buried waste. Models are required to predict landfill settlement accurately.

Most landfill settlement models were developed for inorganic soils or peat. Furthermore, these models were not developed considering the effect of leachate recirculation on settlement. There is a clear difference in controlling mechanisms between inorganic soils and MSW, with additional complications added when leachate recycle is considered. In case of bioreactor landfills, time-dependent settlement will be due to compressibility of the waste matrix as manifested by rapid changes in waste stiffness due to enhanced decomposition as well as waste density. Waste settlement will include creep and biological components due to the heterogeneous nature of waste particles, and accelerated cellulose and hemicellulose biodegradation, respectively, as leachate is recycled.

On a conceptual level, the compressibility of waste can be viewed as due to layers own weights, creep (rearrangement of waste particles as physiochemical changes takes place) and biological (increase in void space and compressibility as solid-to-gas conversion takes place). A settlement model needs to incorporate changes in waste properties that take place during the decomposition of the waste matrix. Such a model will provide engineers and regulators with an analytical tool to estimate available air space, provide estimates of deformation associated with future vertical expansions/land use of landfills, and assist with the design of interim and final cover systems.

In applying such a model, it is important to recognize that changes in waste properties in multiple sub-layer over time affect settlement predictions. For example, assume a landfill is to be analyzed in 2 sub-layers. The amount of compression due to the placement of layer 2 (top layer) will be a function of the degree of decomposition of

layer 1 at the time layer 2 is placed. Similarly, cover design and post-closure settlement will be a function of the decomposition profile with depth at the time these covers are installed. The overall landfill properties can then be viewed as depth-dependent as waste progresses through various phases of degradation. This shows the importance of defining compressibility parameters as a function of degree of decomposition.

The objective of this paper is to present a new settlement prediction model, which will account for changes in material characteristics as a function of the waste degradation rate. The simple compressibility model is developed to predict time-dependent waste settlement in bioreactor landfills. As biodegradation takes place, the organic solid mass is converted to gas and the void ratio increases with a subsequent increase in waste settlement. In general, published models do not capture these phenomena. The model developed herein was based on the results of experimental program. Settlement components including creep and biodegradation effects are identified as a function of the state of decomposition. Based on the results of laboratory testing (Hossain et. al, 2002), the degree of decomposition was characterized through gas generation rates and the cellulose plus hemicellulose to lignin ratio. Based on twenty four one-dimensional oedometer tests (63.5 mm cell), compression indices representing creep and biological effects ($C_{\alpha i}$ and $C_{\beta i}$) were measured on samples ranging from fresh to well-decomposed refuse. In addition, the coefficients of primary compression (Cc) were measured. The time factors, t_1, t_2, t_3, t_4 for the compressibility were determined from the gas production curve and utilized for model development. Finally the proposed model was verified using the settlement data obtained from seven different landfills.

Background

Municipal solid waste settles substantially under its own weight as well as under external loads. Sowers (1972) estimated that waste settles 10 to 30 percent of its original height under its own weight within one to two years of burial. This was recently confirmed by laboratory test results presented by Gandolla (1995) with rate of settlement decreasing to less than 5% per year after approximately 5 years. In general, mechanisms governing waste compressibility are complex due to waste particles deformability as well as heterogenuity of the material. Traditionally, settlement models in the literature have relied on formula developed by Terzaghi (1925) for consolidation of clays including

secondary compression terms, or on rate process theories such as the power creep model presented by Edil (1990) and power creep/hyperbolic model presented by Ling et al (1998). Sowers (1972) showed that the settlement of waste was similar to that of peat with large initial consolidation and substantial secondary compression. Rao (1974) indicated that a settlement time curve from waste specimens may vary from those for typical clay soils but similar to those from organic soils and peat. Bjarngard and Edgers (1990) and Fassett et.al (1990) compiled MSW landfill data and proposed a model for the prediction of settlement as follows:

$$\frac{\Delta H}{H} = CR \log \frac{P_o + \Delta p}{P_o} + C\alpha_1 \log \frac{t_2}{t_1} + C\alpha_2 \log \frac{t_3}{t_2} \qquad (1)$$

Where:

ΔH = settlement

H = initial thickness of waste layer

$\Delta H/H$ = vertical strain (normalized settlement)

Po = Initial average vertical effective stress

ΔP = average induced vertical stress increment

t_1 = time (days) for completion of "initial" compression

t_2 = time (days) for completion of "intermediate" compression

t_3 = period of time (days) for prediction of settlement

CR = compression ratio

$C_{\alpha 1}$ = intermediate secondary compression index

$C_{\alpha 2}$ = long term secondary compression index

Fassett et al. (1994) later presented an extension of the 1990 model with the two secondary compression indices ($C_{\alpha 1}$ and $C_{\alpha 2}$) for intermediate and long term compression combined into one term, denoted as C_α. It is important to emphasize that these models were developed for traditional landfills and their authors did not specify them to be applicable to landfills with leachate recycle.

Mitchell et al. (1995) and Wall and Zeiss (1995) discussed the use of Terzaghi's classical one-dimensional consolidation settlement approach for prediction of waste compressibility. Mitchell et al. (1995) recognized that the mechanistic-based behavior of

MSW during the early phases of landfilling did not conform to Terzaghi's model. Wall and Zeiss stated that fresh refuse was normally not saturated and has a coefficient of permeability similar to that of sand and gravel such that liquid is readily expelled from the voids. Zornberg et al (1999) presented data where degree of saturation of MSW in a landfill in Southern California was approximately 27% near the surface and 70% toward the bottom (approximately depth of 60 m). Notwithstanding, Wall and Zeiss (1995) used Terzaghi's approach in analyzing measured settlement results from field test cells that were monitored for approximately 8 months. They were able to curve fit the measured data using a form of Terzaghi's model. El Fadel and Al-Rashed (1998) used the power Creep model and a one-dimensional consolidation model to analyze data from the Mountain View CA bioreactor test cells (tests by Emcon, 1982-1986) in which leachate recycle was one of the test parameters. The authors were able to curve fit the measured data using Terzaghi's 1-D approach although the fit was not possible without field measurements being known in advance. A recent study by Park et.al. (2001) indicated the power creep model to be a poor predictor of waste settlement rate. With the exception of Mountain View Landfill data and the recently-started Yolo County test, past work reported in the literature did not document solids composition and gas generation potential in conjunction with compressibility parameters. There is a lack of knowledge how these parameters impact the biological changes and the corresponding waste compressibility properties with time in landfills with leachate recycle operation.

PROPOSED COMPRESSIBILITY MODEL

The model proposed here will take into consideration the increase in void ratio due to solid-to-gas conversion as well as the changing nature of the waste particles and density during the decomposition. The proposed approach is based on evaluating the variation of waste stiffness as a function of time and taking into account the decomposition profile with depth. Model development will proceed as follows:

Early Stages of Decomposition: Initially, the compressibility of the waste is governed by rearrangement of waste particles as physiochemical changes takes place, the material physical size and moisture, and stiffness with no consideration to a hydrodynamic lag effect. Moreover, there is a little conversion of solids to gas which leads to increase in the void ratio. An example of such an increase is presented in Figure 1.

Data in Figure 1 is based on the assumption of initial water content of landfill is 30% by volume, porosity is 25% (as total moisture holding capacity of the landfill assumed to be 55%), solid content is 45% (60% of the solids is cellulose/ hemicellulose which is degradable and 40% is considered as non-degradable solids). In this example, phase 0 is the initial phase (fresh refuse) before any biochemical reactions takes place with initial void ratio (e=volume of voids/volume of solids) of approximately 120%. As accelerated degradation takes place with leachate recycle, the solids-to-gas conversion lead to increase in void ratio. An increase in void ratio to 350% is possible if 80% of the degradable solids volume was converted to gas. The data show that at the end of the five phases of degradation, some percentages of solids–to-gas potential still remains. This is due to cellulose and hemicellulose parts that are surrounded by lignin, which inhibits the gas production and causes some percentage of cellulose to remain as non-degradable. While in a traditional landfill the created voids will not necessarily be saturated, it is still unresolved whether, with recirculation, near saturation will be achieved as solids-to-gas conversion takes place.

Concurrent with the increase in void ratio due to decomposition, a physical change in the particle size and distribution also takes place. Therefore, if one accepts the characterization of the waste by its stiffness, then the amount of compression due to the increase in void ratio as well as the compressibility of solids will be governed by the matrix stiffness changes under the weight/external loads as represented by waste moduli. In addition, nonlinearity in waste modulus as a function of applied stress can be included in the analysis by using the proper stiffness values corresponding to the applied stresses at various stages of filling. The settlement component in this case can be generally evaluated and represented as:

$$\varepsilon_t = \varepsilon_p + \varepsilon_c \qquad (2)$$

where ε_t = total strain, ε_p= initial strain due to applied stress, ε_c=creep strain due to applied stress. At the early stages of decomposition, the strain can be instantaneous and dependent on the degree of saturation. The creep strain (ε_c) can be evaluated as equal to

$$\varepsilon_c(t) = C_{\alpha i} \log\left(\frac{t_2}{t_1}\right) \qquad (3)$$

where

t_1 = time for completion of initial compression,

t_2 = time duration for which "creep" compression is to be evaluated.

The value of $C_{\alpha i}$ may be a function of stress level and degree of decomposition. Variation in $C_{\alpha i}$ will be discerned from experimental observations. While the waste samples are still in the acid phase, little-to-no biological decomposition will take place and the settlement strain from this component may be negligible.

Later Stages of Decomposition: As decomposition takes place, waste decomposition may lead to an increase in surface area. As waste decomposes, a time-dependent settlement may take place as the waste hydraulic conductivity decreases to 10^{-5} cm/s or less. The settlement, including primary and creep, can be evaluated in accordance with eqn. 2 & 3. The added component of the settlement model is related to biological decomposition. This component is represented by a biodegradation index (C_β), which is expected to be a function of the extent of solids decomposition as well as the degree of saturation. This "biological" strain component can be represented as

$$\varepsilon_b(t) = C_\beta \log\left(\frac{t_3}{t_2}\right) \qquad (4)$$

where

t_2 = time duration for which "creep" compression is to be evaluated.

t_3 = time for completion of biological compression,

Once biological degradation is completed, a creep component may still induce waste settlement and the creep component can be calculated as

$$\varepsilon_{cf}(t) = C_{\alpha f} \log\left(\frac{t_4}{t_3}\right) \qquad (5)$$

The time factor t_4 is the time for creep at the end of biological degradation. The values for C_β, $C_{\alpha f,}$ t_3, and t_4 has been derived from the experimental results.

The onset of each settlement component, its magnitude, and variation with time will be determined from the experimental results. In addition to compressibility parameters, key factors in this model are t_1, t_2, t_3, and t_4. These will be evaluated from the experimental results. In addition, the model will be verified using field data from bioreactor landfills.

COMPRESSIBILITY PARAMETERS

Experimental Design

The detailed experimental program, sample preparation, data collection are presented in Hossain et. al. (2002). Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The state of decomposition was quantified by measurement of the concentrations of cellulose, hemicellulose and lignin. Reactors were sampled at each of four time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, and early and late in the decelerated methane production phase. One-dimensional oedometer tests (63.5 mm cell) were then performed on waste specimens and compression indices representing creep and biological effects ($C_{\alpha i}$ and $C_{\beta i}$) were measured and compared. In addition, eight "short term" compression tests were conducted to determine the variation in the coefficient of primary consolidation (Cc) with the extent of decomposition.

The methane production characteristics and solids composition of test samples used for measurement of compressibility parameters are presented Table 1 as obtained from (Hossain et. al., 2002). Comparing results from traditional and bioreactor samples, the more rapid increase in the methane production rate and leachate pH illustrates the enhancement of refuse decomposition when reactors are operated with leachate recycle and neutralization. The (C+H)/L ratio in the bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower decrease in this ratio in the traditional landfill samples. In general, the (C+H)/L ratios of traditional samples are higher than those of the bioreactor samples at the same time point. The results of the oedometer tests for compressibility parameters are presented Table 2 as obtained from Hossain et. al. (2002). The more thoroughly decomposed samples (lower

(C+H)/L ratios) had a weakened structural matrix, as solid–to-gas conversion took place, leading to an increase in initial settlement under the same applied stress.

Model Parameters

Two important sets of parameters are required for the settlement model: first one, the compressibility parameters (primary, creep and biological) and the second one, the critical time factor (t_1, t_2, t_3, and t_4), that define the change of degradation state. The compressibility parameters were obtained from laboratory experimental results (Hossain et. al, 2001) and tabulated according to decomposition stages in Table 2. The compressibility parameters has been defined as initial decomposition state, accelerated decomposition state and advance decomposition state. The parameters has also been presented in terms of (C+H)/L ratio and time in Figure 2.

The time factor required for the model was determined from both methane production rate curve and oedometer test results. Figure 3 presents the plotted diagram for MSW sample with all degree of decomposition stage. The detailed explanation for defining each of time factors are described as follows:

***Time factor for completion of initial/instantaneous compression, t_1*:** Initial compression takes place instantaneously once the load is applied. The laboratory experimental results show the initial compression time as 0.1 minutes. In order to predict the landfill settlement, it has been assumed as 1 to 10 days in the field.

***Time factor for creep compression, t_2*:** The methane production rate-curve (Figure 4) shows that initially, the rate of methane production is very small (when sample is in acid phase) and continues till the oxygen entrained in the refuse is consumed. The time up to which slope of the methane production rate curve increased significantly can be identified as creep compression time factor t_2. The laboratory experimental results show that at the end of 35 days, methane production takes place at an accelerated rate and slope of the methane production rate curve increased significantly. In this case, the time for creep compression is 35 days. In actual field conditions this time varies. In case of Yolo county landfill test cell (Mehta et.al, 2002), the accelerated gas production starts after 200 days and for MVCLP (El Fadel and Al Rashed,1998) landfill the time is 520 days. It is very difficult to define actual time for the accelerated methane production. For the settlement prediction purpose we can assume the time to be between 0-3 years (0 – 1000

days) and confirm the time with the actual gas production data from field and settlement calculation can be revised at the same time.

Time factor for biological compression, t_3: Accelerated gas production starts at the end of 35 days and continues to produce gas at an increasing rate until 68-70 days, when the rate of gas production starts decelerating. At the end of 90 days, gas production rate becomes significantly small (Figure 4). Oedometer test results (Figure 3) show that sample, tested at accelerated gas production state, experiences compressibility due to biological decomposition until 130000 minutes (90 days) and then the rate of strain becomes very small (creep state). Considering the gas production rate and biological strain, the biological compression time can be taken as 90 days. Using the first order gas model (EPA, 1998) and different decay rate, the time for complete methane production can be calculated. The range of time obtained for different decay rate can be used as the biological compression time t_3. Figure 5 presents decomposition rate curve on the basis of different decay rate for Yolo county landfill. The time factor t_3 can be easily determined from these curves. In case of decay rate k=0.3, the time factor is 15 years when the methane production rate becomes very small and for k=0.05, the time factor is 45 years.

Time factor for creep at the end of biological compression, t_4: Gas production continues at a very small rate at the end of 90 days and continues till the observation period 130 days. The volume of gas produced after 130 days is negligible. Therefore, the complete decomposition time can be taken as 130 days. In the field, the complete decomposition time can be predicted using gas model and can be used for determining time factor, t_4. For the model this is not an important time factor because the creep settlement after biological settlement is insignificant.

Finally, the settlement model can be presented as:

$$\varepsilon(t) = C_{\alpha i} \log\left(\frac{t_2}{t_1}\right) + C_{\beta} \log\left(\frac{t_3}{t_2}\right) + C_{\alpha f} \log\left(\frac{t_4}{t_3}\right) \qquad (6)$$

MODEL VALIDATION

The developed model validation is an important part of the model development process. Utilizing the model, the predicted MSW settlement was compared with the

observed field settlement from seven different bioreactor landfills. The settlement data have been collected from Mountain View Control Landfill Project (Havaldakis, 1988), Yolo county landfill (Mehta et. al., 2002) and five other landfills (Earth Tech Consultants, 2001). The model parameters used for the prediction are tabulated in Table 3. A brief description of the bioreactor landfills and their gas production record, state of biodegradation and settlement data are presented below.

Mountain View Controlled Landfill Project (Halvadakis et. al, 1998)

The Mountain View controlled landfill project (MVCLP) was undertaken to investigate the possibility of optimizing energy recovery from landfills, accelerate stabilization, and mitigate gas migration and explosion hazards in the vicinity of landfills (Halvadakis et. al 1988). The test site was within the Mountain View landfill, located approximately 15 miles northwest of San Jose, California. The field experiment included construction of six landfill cells to simulate various processes including leachate recirculation while monitoring settlement and gas production. Each cell was 30 x 30 m and 15m deep. Relatively thick clay base liner and walls formed the perimeter of each cell to prevent downward/outward movement of liquids and gases. Waste placement called for the deposit of equal amount of refuse concurrently in each cell. Waste placement began on December 9, 1980 and concluded on March 3, 1981. All test cells were covered with impermeable 36 mil reinforced chlorosulfonated polyethylene membrane. The leachate recirculating system was installed in cell A and monitoring of the landfill gas production, settlement started on June 01, 1981 and lasted for approximately 1600 days.

The methane production curve presented by Halvadakis et.al (1988) for cell A shows that the gas production cumulative rate in the cell with leachate recirculation reached a value of 0.76 scf per dry pound per year during monitoring period of 700 to 800 days. After this period, there was no gas production for few days. Exact reason for that was not explained in the report but gas production resumed later and the cumulative rate at the end of the test period was approximately 0.36 scf per dry pound per year. Data indicated the onset of accelerated landfill gas production cumulative rate seems to be around the period of 400-500 days.

Chemical analysis data reported in Fifth annual report by EMCON (1985) showed that at the end of the monitoring period the percent cellulose present is 16.3% and lignin is 13.4%. The results of Biochemical Methane Potential analysis showed that methane potential remaining was 1.08 scf / dry lb. Accordingly, it seems that the refuse was between an accelerated methane production phase (will be referred to as Phase 3) and decelerated methane production phase (will be referred to as Phase 4) at the termination of the test. Based on the monitored field data, it is estimated that accelerated biological degradation phase began after approximately 520 days into the monitoring period when the gas production started to rise. There fore, model parameter t_2 in this case should be 520 days. Using this time factors and compressibility parameters obtained from experimental results, the model predicted settlement has been compared with the field observed settlement data in Figure 6.

Yolo County Landfill Project (Mehta et. al., 2002)

The Yolo County landfill project was initiated in 1995 to investigate the effect of leachate recirculation on settlement, methane production and solid decomposition. The field experiment included construction of two landfill cells and filling them with MSW while monitoring settlement, gas production, p^H and moisture content. Two test cells, one operated with control moisture and one without control moisture, were filled with MSW from April to October 1995. Each cell was about 12m deep and has a surface area of 930 m^2. Green waste chips of 30cm thickness were used as daily cover. In the enhanced cell leachate was recirculated through injection well. The monitoring of the landfill gas production, settlement started on June 12, 1996 and leachate recirculation was initiated after 133 days and no leachate was recirculated after 910 days.

The measured methane yield through 1231 day is 63.1 L CH_4/wet-kg of MSW (Mehta, 2002) The gas production cumulative rate in the enhanced cell shows that the accelerated gas production starts at the end of 230 days and gas production continues at a accelerated rate till 650 days. At the end of 900 days gas production rate become very small and continues at the same rate till the end of the monitoring period.

Chemical analysis data reported by Mehta et.al (2002) showed that at the end of the monitoring period the percent cellulose present is 15% (approximately 50% of the degradable solid is cellulose, Barlaz, 1990) and lignin is 17% and (C+H)/L ratio is 1.09.

Analysis of 1-3 years old samples collected from traditional landfill shows an average (C+H)/L ratio of 2.61 (Barlaz, unpublished work). Therefore the sample in Yolo county is clearly below fresh samples. The results of Biochemical Methane Potential analysis showed that methane potential remaining was 24.0 L CH_4/dry-kg. Considering the results of the laboratory tests, it can be inferred that 70% of degradable solids has been decomposed. Accordingly, it seems that the refuse was between an accelerated methane production phase (will be referred to as Phase 3) and decelerated methane production phase (will be referred to as Phase 4) at the termination of the test. Based on the monitored field data, it is estimated that accelerated biological degradation phase began after approximately 200 days into the monitoring period when the gas production started to rise. There fore, model parameter t_2 in this case should be 200 days. Using this time factors and compressibility parameters obtained from experimental results, the model predicted settlement has been compared with the field observed settlement data in Figure 6.

Spruce Ridge Landfill, MN (Earth Tech Consultants, 2001)

Leachate recirculation system was installed in gravel filled trenches within the waste in Spruce Ridge Landfill, MN. The gravel in the trench has a minimum depth and width of two feet. The trenches were installed in different elevation. Operation of leachate recirculation system commenced on July 1, 1997. About 2.1 million gallons of leachate were recirculated over a period of 2.5 years. Observed settlement for a period of 1100 days was 15 to 18 feet which is about 20-24% settlement of the original waste thickness. The gas production data are not available for the same period. Therefore the actual degradation phase cannot be predicted before the settlement prediction. The degradation parameters for creep index and biological index were taken from the laboratory test results to predict the settlement.

Richmond Landfill, Virginia (Earth Tech Consultants, 2001)

Leachate recirculation was commenced in Richmond landfill, VA through horizontal trenches. Initial readings were not measured due to active filling during that time. Observed settlement for a period of 165 days was 3 feet which is about 7.5-8% settlement of the original waste thickness. The gas production data are not available for

the same period. The degradation parameters for creep index and biological index were taken from the laboratory test results to predict the settlement.

Atlantic Landfill, Virginia (Earth Tech Consultants, 2001)

Leachate recirculation was commenced through horizontal trenches located in the upper and lower half of the cell since 1998. Observed settlement for a period of 523 days was 5.9 to 8.7 feet which is about 5.9-8.2% settlement. The first year settlement could not be measured due to leachate recirculation and could result in additional settlement.

Keele Valley Landfill (Earth Tech Consultants, 2001)

Leachate recirculation was commenced through the injection well between May 1990 and December 1999. Approximately 674,111 gallons of moisture were added during this period. Observed settlement for a period of 10 years was 17.1 to 22.1 feet which is about 3.9-5.5% settlement. The settlement record for the first two years is missing as there were no settlement plate during that period. The gas production data are not available for the same period.

Mid- Penninsula Landfill, Virginia (Earth Tech Consultants, 2001)

The landfill facility opened for operation in 1995 and the leachate recirculation commenced at the beginning of 1998. Settlement survey started on April, 1999. The settlement affect of leachate recirculation for first 16 months are missing. Settlement measurement were taken quarterly to determine the affect of leachate recirculation during a period of 523 days. Approximately 777,600 gallons of leachate were recirculated during this period. Observed settlement for a period of 523 days was 5.9 to 6.3 feet which is about 6.8-7.4% settlement.

Results of Model Predictions

The Mountain View controlled landfill project (MVCLP) and Yolo county landfill project have a record of gas production and settlement data. Based on the monitored field data, it is estimated that accelerated biological degradation phase began after approximately 520 days and 200 days for MVCLP and Yolo County, respectively, (the time when the gas production started to rise). The model parameter t_2 in these cases has been taken as 520 and 200 days. Using this time factors and compressibility parameters obtained from experimental results, the computed settlement has been

compared with the field observed settlement data in Figure 6. The predicted results match quite well with the measured field data.

Landfill gas production data were not available for all other cases. The time factor t_2 has been assumed a value of 100, 200, 500 and 2000 days for prediction purpose. The observed and predicted settlement data presented in Figure 6 show that in most of the cases the time factor t_2 is between 100 and 500 days. The measured laboratory creep index (0.03) and biological degradation index (0.19) match well with all the field rates as shown in Figure 6. The observed and predicted settlement data are matching quite well for all the cases except Keele Valley landfill. The observed settlement data for first two years in case of Keele landfill are missing and that could be one reason for such anomaly. As observed for most other cases, the accelerated degradation takes place within 100 to 500 days. Similar to the case of Atlantic Landfill, settlement readings were not taken for first one year in Mid-Penninsula Landfill. Therefore, it is hypothesized that settlement should have been more than the observed settlement (8%).

The model settlement prediction considers all the aspects of biological decomposition, creep and matrix stiffness change as decomposition takes place with time. The case studies show that the model predicts landfill settlement quite well including the biological decomposition.

SUMMARY AND CONCLUSIONS

Most settlement models applied to solid waste were developed for inorganic soils or peat. It is important to emphasize that these models were not developed considering the leachate recirculation effect on settlement. In the case of bioreactor landfills, waste settlement will include creep and biological components due to the heterogeneous nature of waste particles, and accelerated cellulose and hemicellulose biodegradation, respectively, as leachate is recycled. A settlement model developed to incorporate the changes in waste properties that take place during the decomposition of the waste matrix.

Work in this paper utilized data from laboratory oedometer tests to illustrate compressibility parameters for refuse at different degrees of degradation and to define the time factors required for modeling. Based on the results obtained the study conducted by Hossain et al (2002) and work in this paper, it can be advanced that

1. The creep index ($C_{\alpha i}$) is independent of the state of waste decomposition and has been obtained as 0.03. The magnitude of the biological indices varied with the state of decomposition and yielded the highest values (C_β = 0.19) when samples were actively decomposing and had substantial methane potential remaining. The creep index at the end of biological degradation, $C_{\alpha f}$, has been estimated as 0.022. For the model prediction, C_α and C_β have been taken as 0.03 and 0.19, respectively.
2. The time factors (t_1, t_2, t_3, and t_4) vary and a range for each of them has been provided to consider the variation. Time factor t_2 is the time when accelerated methane production starts. The time factor t_2, as observed in most of the field studies, can be taken as between 100 and 500 days. The time factor t_3 is the time when methane production is almost zero. Using the gas model, t_3 can be determined.
3. Model parameters and gas production data were to used to predict the landfill settlement for Mountain View Controlled landfill project (MVCLP) and Yolo County Landfill. The measured field behavior was properly predicted using the obtained laboratory parameters. The settlement prediction matches well with the assumed time factor t_2 between 100 and 500 days. Five other landfill settlement cases were also studied and the predicted results match well with observed field settlement data.
4. The model settlement prediction considers all the aspects of biological decomposition, creep and matrix stiffness change as decomposition takes place with time. The case studies show that the model predicts landfill settlement quite well including the biological decomposition.

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Table 1 Description of the Sampled Reactors and Their Gas Production Record

Sample Identification[a]	Day Sampled[b]	Cumulative Methane Production (L)	% Cellulose (C)	% Hemi-Cellulose (H)	%Lignin (L)	(C+H)/ L
Fresh Refuse	n/a	n/a	41.91	8.47	19.96	2.52
B1	24	0.5	32.79	6.55	30.53	1.29
B2	53	70.5	21.87	4.95	38.08	0.71
B3	84	102.2	13.48	3.94	46.26	0.38
B4	127	53.5	11.88	2.29	56.44	0.25
T1	27	0	37.32	8.10	19.17	2.37
T2	56	0.7	27.45	6.03	26.06	1.29
T3	91	3.0	29.40	6.25	19.88	1.79
T4	130	13.8	16.92	3.88	28.47	0.73

a. B and T designate bioreactor and traditional samples, respectively

b. Traditional reactors were filled with MSW 3 days before bioreactors

n/a - not applicable

Table 2 Compressibility Parameters for Bioreactor and Traditional Samples

Sample Identification	(C+H)/L	Primary Compression (%)	C_c	C_α	C_β
B1	1.29	26	-	0.030	0.050
B2	0.71	30	-	0.030	0.190
B3	0.38	33.5	-	0.028	0.022
B4	0.25	35	-	0.028	0.022
B1[a]	1.29	-	0.16	-	-
B2[a]	0.71	-	0.25	-	-
B3[a]	0.38	-	0.37	-	-
B4[a]	0.25	-	0.35	-	-

a. The tests were completed within 6-8 hours

Table 3. Model Parameters for Settlement Prediction

Landfills	$C_{\alpha i}$	C_{β}	[1]$C_{\alpha f}$	t_1 (days)	t_2 (days)	t_3 (days)	[1]t_4 (days)
MVCLP	0.03	0.19	-	10-15	520	3500	-
Yolo County	0.03	0.19	-	10-15	200	3500	-
Spruce Ridge	0.03	0.19	-	10-15	100	3500	-
Richmond	0.03	0.19	-	10-15	2000	3500	-
Atlantic	0.03	0.19	-	10-15	500	3500	-
Keele	0.03	0.19	-	10-15	500	3500	-
Mid-Penninsula	0.03	0.19	-	10-15	400	3500	-

[1] All the available data are within biological degradation stage. $C_{\alpha f}$ and t_4 were not required for prediction

Figure 1. Phase Diagram as a Function of Degradation Phases

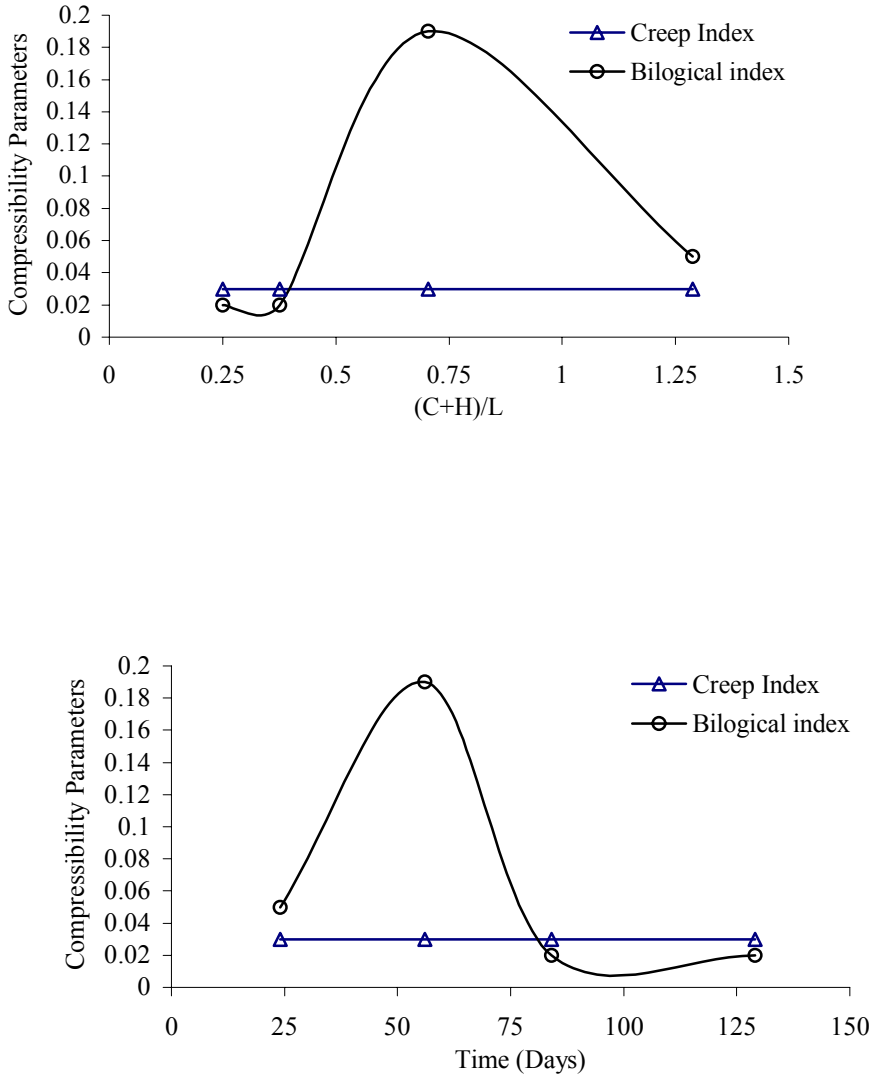

Figure 2. Compressibility Parameters for Bioreactor Samples

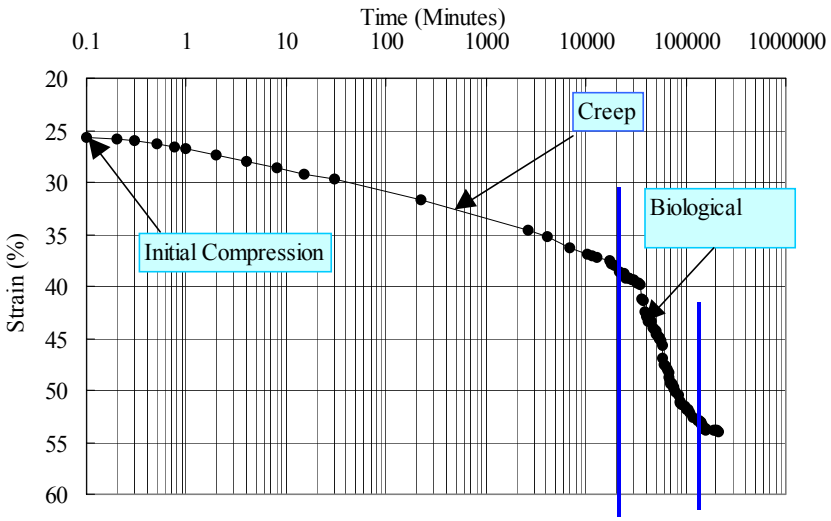

Figure 3. Compressibility Plot for Bioreactor Samples

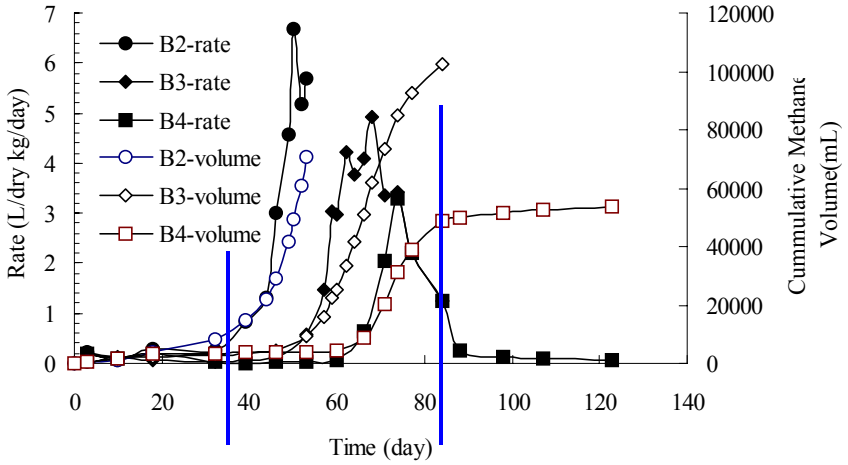

Figure. 4 Time Factor Determination for The Compressibility Model

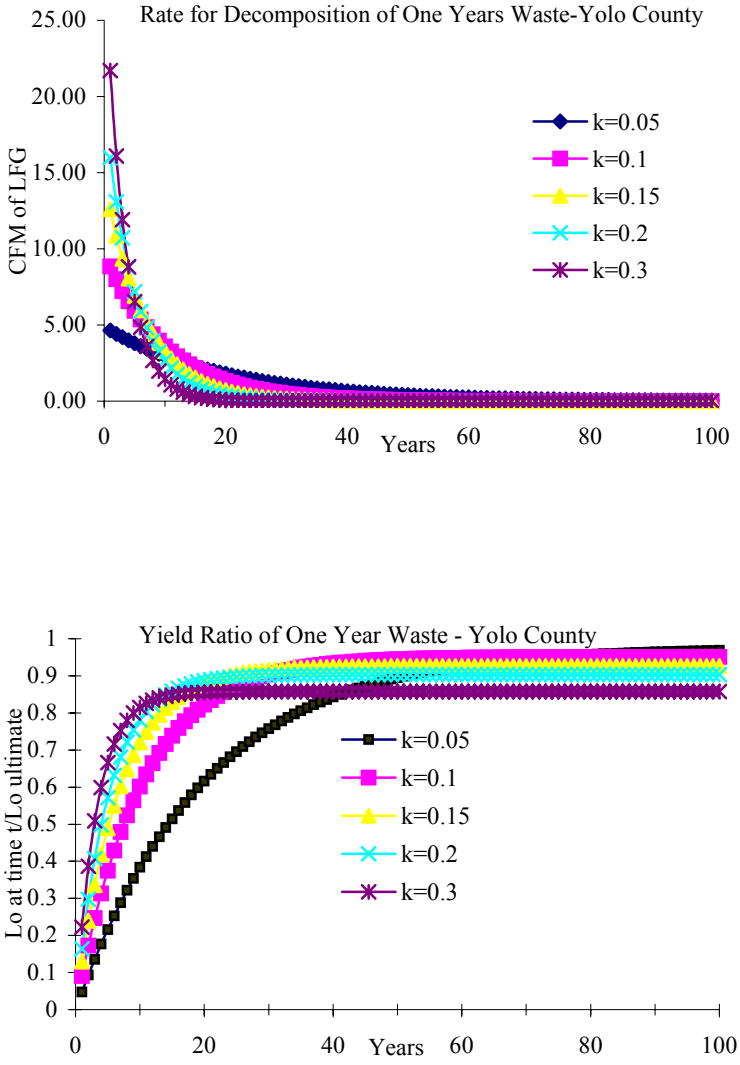

Figure 5. Time Factor t_3 for Yolo County Landfill (One Year Waste)

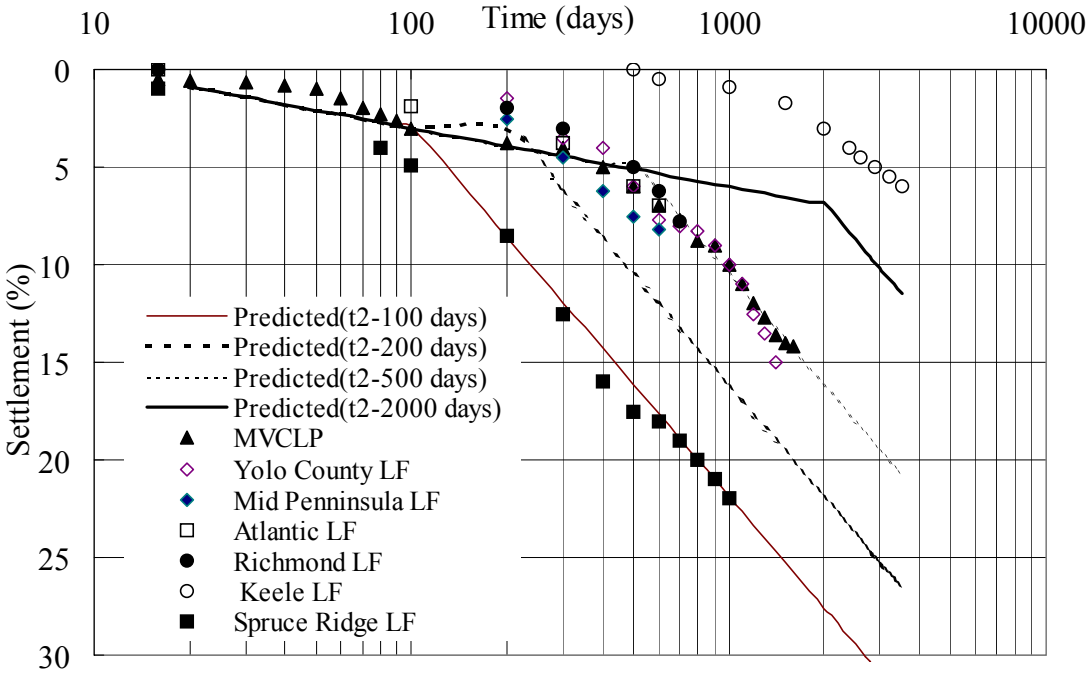

Figure 6. Comaprison of Predcietd and Observed Field Settlement for Bioreactor Landfills

Shear Strength Parameters and Model of Municipal Solid Waste with Leachate Recirculation and Degradation

Paper to be submitted for review

Shear Strength Parameters and Model of Municipal Solid Waste with Leachate Recirculation and Degradation

M. A. Gabr[1], M. S. Hossain[2]

ABSTRACT

Understanding changes in the shear strength of waste in bioreactor landfills is critical for the design of waste slope, above grade covers, future vertical expansions, future land use and the seismic stability of landfill. The objective of this study was to characterize the relative changes in waste shear strength parameters during waste decomposition and develop a model for shear stress displacement behavior. Samples were prepared in eight 4-litre (~ 1 gal) reactors and the degree of decomposition was characterized through gas generation rates and the cellulose plus hemicellulose to lignin ratio. Twelve direct shear tests (100 mm diameter and 50 mm thickness) were performed on waste specimens ranging from fresh to well-decomposed refuse. The shear strength has been presented as mobilized friction angle as a function of decomposition stages. Nine direct shear tests were performed on major MSW components (fresh paper, degraded paper and plastics) in order to explain the shearing pattern with displacement of decomposed waste. Results indicated that there is strength incompatibility within the MSW components. Small displacement is required for mobilization of peak shear strength in organic material and degraded textile and larger displacement is required for maximum strength mobilization in fresh paper. Non-degradable plastic remains as the same content and paper content decreases with degradation. The interface friction angle of plastics and friction angle for fresh shredded paper are estimated as 18 ^{o}-19° and 33 ^{o}, respectively. The experimental result indicates that with degradation of degradable material, percentages of plastic content increases and contributes to decrease in friction angle. For example, measured friction angle for bioreactor samples decreased from 32 ^{o} to 24 ^{o} as (C+H)/L ratio decreased from 1.29 to 0.25. Friction angle increases with increasing shearing displacement. The friction angle for (C+H)/L at 0.38 increased from14 ^{o} at 2 mm displacement to 25 ^{o} at 10 mm displacement. The predicted shear

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behavior by the developed constitutive model for shear stress displacement match with the experimental results.

INTRODUCTION

The evaluation of waste strength is a major issue for the design of waste slope, above grade covers, future vertical expansions, future land use and the seismic stability of landfill. Current municipal solid waste (MSW) landfill regulations do not necessarily address the evolving nature of landfills with leachate recycle. Understanding changes in the shear strength of waste in bioreactor landfills is critical, yet few data exist on the subject. Traditionally, failures of waste slopes are not highly publicized, or published, although they are known to occur. One of few cases reported in literature was by Eid et al (2000) in which they indicated that strain incompatibility and progressive failure can occur between MSW and underlying materials and lead to a reduction in mobilized shear strength and failure. A number of studies have been conducted on the shear strength of MSW, e.g. Landva and Clark (1986); Siegel et al. (1990); Singh and Murphy (1990); Gabr and Valero (1995);

Shear Strength Parameters: Past Work

Similar to soils, the shear strength parameters normally used for waste characterization are cohesion and friction angle. Landva and Clark (1986) determined drained shear strength parameters for old refuse samples. They measured friction angles ranging from 38° to 42° and cohesion's (c) ranging from 16 to 19 kPa. The same samples were stored in plastic containers for one year. Landva and Clark (1986) reported that specimens underwent decomposition during storage which was evidenced by gas generation. When they evaluated the strength parameters for the sample again, they found the friction angle decreased to 33° with cohesion of 16 kPa. While typical friction angles for waste samples ranged from 38°-42°, the friction angle reported on samples made entirely from plastic waste was 9° (Landva and Clark 1990). Landva and Clark (1986) also conducted direct shear tests on fresh shredded refuse containing a large amount of plastic waste and found the friction angle to be 24° and cohesion of 23 kPa. Howland and Landva (1992) performed direct shear test in a large direct shear box (43.2 cm x 27.9 cm) on 10 to 15 year old waste sample. They reported that the strength of MSW is primarily frictional in nature and found a friction angle of 33° and cohesion of 17 kPa. Gabr and

Valero (1995) tested 10 to 15 year old MSW in small direct shear box (6.4 cm diameter and a thickness of 2.3 cm) and found that shear strength kept increasing at horizontal displacement more than 10% of the specimen diameter. They reported friction angles ranging from 20° to 39° and cohesion ranging from 0 to 28 kPa at 20% strain level. Gabr and Valero (1995) conducted consolidated undrained triaxial tests on MSW and reported an average effective friction angle of 34° and effective cohesion of 17 kPa at an axial strain of 20%. The authors reported a decrease in shear strength with an increase in water content. Howland and Landva (1992) back-calculated shear strength from load tests and analysis of slope failure assuming a factor of safety of one (Edincliler et. al., 1996). The strength reported were directly measured for a landfill failure in New Jersy, load tests at a landfill in California and plate load test in New York. They reported the friction angle to be between 23° to 31° and cohesion of 0 to 10 kPa. The authors concluded that MSW is frictional in nature and the shear strength increases with increasing normal stress. Van Impe (1998) summarized the available shear strength data and concluded that shear strength parameters are dependent on normal stress. The author proposed three different zones for shear strength parameters on the basis of the normal stress working on them. Thomas et.al. (2000) determined the in situ shear strength parameters for Torcy landfill in France using a direct shear box (LxL = 1000 x 1000 mm^2). The shearing angle for the waste was 29.6^o and cohesion 23.4 kPa at 180 mm shearing displacement. The authors found that the shearing strength is greatly influenced by the presence of plastics content in the sample. The shearing strength is less for the specimen with more plastic content. They also have shown the shearing displacement dependency of shear strength.

In comparison to data on MSW from traditional landfills, a review of published literature yielded no data on the shear strength of waste from landfills operated under high moisture conditions despite the significant influence of moisture on waste shear strength, and, consequently, on the stability of slopes and cover systems. Gabr and Valero (1995) showed that a 15% increase in moisture resulted in a 50% decrease in waste cohesion. This decrease in strength was attributed to changes associated with the physical characteristics of waste particles as decomposition takes place. None of the existing literature has attempted to discern and explain changes in strength and stiffness characteristics as a function of the physical and chemical properties of the waste. Such

characterization, however, is of utmost importance as bioreactor landfills are operated to accelerate changes in the physical and chemical properties of the waste. In bioreactor landfills, decomposition is accelerated and the rearrangement of the waste particles may lead to increase in void spaces and changes in waste stiffness which affect the stability of the waste.

The objective of this study was to characterize the relative changes in waste shear strength parameters during waste decomposition and develop a constitutive model for shear stress displacement behavior. The degree of decomposition was characterized through gas generation rates and the cellulose plus hemicellulose to lignin ratio. Samples were prepared in eight 4-litre (~ 1 gal) reactors and allowed to degrade to various stages of decomposition for shear strength measurements. Twelve direct shear tests (100 mm diameter and 50 mm thickness) were performed on waste specimens and shear strength parameters were measured on samples ranging from fresh to well-decomposed refuse. The shear strength has been presented as mobilized friction angle as a function of decomposition stages. In addition, nine direct shear tests were performed on major MSW components (fresh paper, degraded paper and plastics) in order to explain the shearing pattern with displacement of decomposed waste. Variations in shearing strength of MSW were presented as a function of shear displacement. The results obtained from these tests were compared with the previously-obtained laboratory and field test results. Finally a constitutive model has been developed, calibrated with experimental results and validated with experimental results from Pelky et.al (2002).

Refuse Biodegradation and Gas Production

Cellulose and hemicellulose are the principal biodegradable components of refuse and their concentrations in residential refuse are reported to range from 29 - 51% and 9 - 12% (on dry weight basis), respectively (Hilger and Barlaz, 2001). Lignin is the other major organic component of refuse, with concentrations ranging from 15 - 28%. Lignin is at best only slowly degradable under methanogenic conditions and interferes with the decomposition of cellulose and hemicellulose by physically impeding microbial access to these degradable carbohydrates (Colberg 1988). The conversion of cellulose to methane (CH_4) and carbon dioxide (CO_2) is described by eqn 1. Methane production per kg of

cellulose and hemicellulose decomposed is 414.8 and 424.2 liters, respectively (Barlaz et.al., 1990).

$$(C_6 H_{10} O_5)_n + n H_2 O \longrightarrow 3n CH_4 + 3n CO_2 \qquad (1)$$

A complex series of chemical and biological reactions is initiated with the burial of refuse in a landfill. After refuse placement, a period ranging from months to years is necessary for the required microbiological system to become established for biological decomposition. Refuse decomposition has been described in an aerobic phase, an anaerobic acid phase, an accelerated methane production phase and a decelerated methane production phase (Barlaz et al., 1989).

The gas production from landfills is typically modeled using a first order decomposition rate such as that in the US EPA Landgem Model (1998).

$$G = WL_0 k e^{-kt} \qquad (2)$$

G is annual methane generation for a specific year t (ft^3 CH_4/yr);

W is the mass of waste buried annually (tons/yr)

L_o is the methane potential (ft^3 CH_4/ton of waste):

t is time after initial waste placement (yr);

k is the first order decay rate constant (1/yr)

Methane production rates calculated from eqn. 2 for traditional and bioreactor landfills are presented in Fig. 1. It should be noted that the decay rate for a biroeactor landfill has not been verified or established. The value of 0.15 is used here to represent the accelerated decomposition.

EXPERIMENTAL DESIGN

Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The reactors were destructively sampled to obtain refuse at various states of decomposition based on the reactor's methane production rate curve. In addition, the state of decomposition was quantified by measurement of the concentrations of cellulose, hemicellulose and lignin (Hossain et. al, 2002). Reactors were sampled at each of four

time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, and early and late in the decelerated methane production phase.

Twelve direct shear tests (100 mm diameter and 50 mm thickness) were performed on waste specimens and shear strength parameters were measured on samples ranging from fresh to well-decomposed refuse. Plastics and paper are two major constituents of MSW. The highly degradable paper content decreases with decomposition and its matrix structure breaks down, while at the same time plastic content remains the same. Plastics and paper content are expected to influence the shear strength of MSW. Therefore nine direct shear test were performed on fresh paper, degraded paper and plastics.

Preparation of Fresh and Decomposed Refuse

Solid waste representative of residential refuse was collected from a transfer station in Wake County, NC. Approximately 900 kg (2000 pounds) was shredded to about 10 mm x 20 mm pieces. The shredded refuse was then mixed and sequentially quartered until each pile contained 40-50 kg. Twenty piles were collected in separate plastic bags and stored at 4^0C until used in the experimental program.

Eight 4-L reactors were filled with refuse to prepare samples at different stages of decomposition for compressibility testing. Reactors T1-T4 were operated under conditions designed to simulate a traditional landfill and will be referred to as "traditional" samples. Sufficient moisture was added to adjust the moisture content to 55% (wet wt. basis). Reactors B1-B4 were operated under conditions designed to simulate a bioreactor including, (1) the addition of sufficient moisture to induce leachate production, (2) leachate recirculation and (3) the addition of an inoculum of anaerobically digested sewage sludge. The leachate was neutralized with KOH as necessary and recycled six days a week. All reactors were incubated in a room maintained at 37 to 41^0 C.

Gas was collected in five-layer gas-bags and the volume was measured by pumping into a calibrated carboy using water displacement. Gas concentrations (CO_2 and CH_4) were measured using a GOW-MAC gas chromatograph (Bound Brook, NJ) equipped with a thermal conductivity detector and a CTR1 column (Alltech, Deerfield, IL).

Reactors were destructively sampled based on their methane production rate curve. The contents were thoroughly mixed and a sub-sample was removed for composition analysis. The sub-sample was first dried to constant weight at 75°C and then ground in a Wiley mill to pass a 1 mm screen. Cellulose (C) and hemicellulose (H) concentrations were analyzed by acid hydrolysis followed by HPLC analysis of the hydrolyzed sugars (Wang et al., 1994). Lignin (L) was determined from the combustible (550°C) fraction of the material that remained after the acid hydrolysis. The remaining refuse was used in the direct shear tests without drying.

Direct Shear Tests

Remolded specimens (collected from the reactors) were compacted directly into a circular 100-mm diameter and 50 mm thick direct shear box with a wooden dowel. Particles of maximum length equal to half the diameter of test cell were included and therefore test specimen consisted of particle size smaller than or equal to 50 mm. During the testing, a strain rate was calculated based on consolidation of the specimen under normal stress as recommended by Head (1982). The strain rate used for the direct shear testing was 0.03 mm/ min. The sample were consolidated under normal load for 24 hours and sheared at the same normal load. Tests were performed in conformance with ASTM Test Method for Direct Shear Tests of Soils under Consolidated Drained conditions (D 3080-90). The tests were strain controlled and readings were taken at particular strain interval. The testing program and sample description are presented in Table 1.

RESULTS

The methane production characteristics and solids composition of test samples used for measurement of shear strength parameters are described in the first part of this section, followed by the results of the direct shear tests.

Refuse Decomposition

Methane production rates and volume for the bioreactor and traditional samples are presented Figure 2 and Table 2. Comparing results from traditional and bioreactor samples, the more rapid increase in the methane production rate and leachate pH (shown in Figure 3) illustrates the enhancement of refuse decomposition when reactors are operated with leachate recycle and neutralization. The anaerobic sewage sludge seed and

the external neutralization of the leachate reduced the time span of the anaerobic acid phase of decomposition.

Bioreactor systems were destructively sampled on days 24, 53, 84 and 127. As illustrated by the methane production and pH data in Table 2, the day 24 sample was in the anaerobic acid phase, the day 53 sample was in the accelerated methane production phase, and the day 84 and day 127 samples were in the decelerated methane production phase.

The composition of solids removed from each reactor at the end of the monitoring period is presented in Table 2. The (C+H)/L ratio in the bioreactor samples decreased concurrent with the increasing volume of methane produced while there was a slower decrease in this ratio in the traditional landfill samples. These results were consistent with the low methane production volume (0-13.8 L) for the traditional samples. In general, the (C+H)/L ratios of traditional samples are higher than those of the bioreactor samples at the same time point. While bioreactor samples had completed all phases of degradation, the traditional samples were still in early Phase 3.

Shear Strength Parameters of Major Constituents

Plastic and paper are the two major components for shear strength of MSW. Plastic, a non-degradable waste component, remains as the same content where as the paper content decreases with degradation. Plastics taken from the reactor with (C+H)/L ratio of 0.73 were tested for shear strength. The shearing pattern presented in Figure 4 and Figure 5 show that shear strength for plastics and fresh paper keeps increasing with displacement and no distinct peak shear strength is observed. The rate of increase in shear strength for fresh paper is higher than the rate of increase in shear strength for plastics. The interface friction angle of plastics (when cohesion is neglected) and friction anlge for fresh shredded paper are estimated as 18°-19° and 33°, respectively. In case of plastics, if cohesive component is included, cohesion is estimated to be 23 kPa with a friction angle of 8° at 10 mm displacement (Fig. 6). The friction angle for plastics reported by Landva and Clark (1990) was 9° and the friction angle of fresh shredded paper was reported as 25° -30° by Pelky, et.al, (2001).

Mobilized Strength Incompatibility

The shearing pattern for degraded paper, organic and textiles taken from reactor with (C+H)/L ratio of 0.73 is shown in Figure 7. Initially, there is a peak and residual stresses followed by increase in shear stresses with displacement at a rate similar to that observed in fresh paper. Results indicated that small displacement is required for mobilization of peak shear strength in the tested organic material and degraded textile. In comparison, larger displacement is required for maximum strength mobilization in fresh paper. These data confirm the mobilized strength incompatibility within the MSW components.

The experimental results obtained from current research co-related the degree of degradation with friction angle. The degree of decomposition is characterized through the (C+H)/L ratio. The ratio of (C+H)/L decreases with decomposition and shear strength have been obtained experimentally as a function of (C+H)/L ratio. The summary of the three test results on (C+H)/L at 0.73 are presented at Fig. 8. The shearing pattern for this case is same as that observed for degraded paper and explained by the mobilized strength incompatibility of the MSW components. Initially the strength of the organic material with lower strength will be mobilized at peak followed by reduction in residual strength until sufficient strain is induced for the mobilization of strength of paper and plastics present in the test specimen. The same shearing pattern was also observed by Bowders (2002) as shown in Figure 9. This trend was observed for all the samples except samples in anaerobic phase (Figure 10). In anaerobic sample, fresh paper was predominant with 5-10% organic content to have significant influence on the shearing pattern. Like fresh paper, shear strength in sample at initial (anaerobic) phase keeps increasing with displacement and no distinct peak shear strength is observed.

Decrease in Strength with Decomposition

During the decomposition process, certain components (mainly cellulose and hemicellulose) in paper, organic material and textiles degrade, and non-degradable plastic content remains relatively unchanged. This results in increase in percentages of plastic content. Therefore with increase in percentages of plastics content and decrease in percentages of fresh paper, the shear strength of MSW is expected to decrease with degradation.

Results obtained by Landva and Clark (1986), on fresh shredded refuse with a large amount of plastic waste indicated low friction angle (24°) and conform the above hypothesis. According to the authors, the sliding between aligned plastic sheets contributed to the low friction angle. Such finding was also confirmed by Thomas et.al. (2000) who showed that the shearing strength was less for the specimen with more plastic content.

The friction angles are estimated to be 32°, 27°, 25°, 24° at (C+H)/L of 1.29, 0.73, 0.38 and 0.25, respectively (Fig. 11). At initial decomposition stage the friction angle is 32° and the friction angle for the fully decomposed waste is 24°. This shows a trend of decreasing friction angle with decomposition, as expected due to percentage increase in non-degradable plastic. The results of decreasing shearing strength with increasing decomposition contradicts the aging effect reported by Van Impe (1998), who indicated the higher shear strength for old refuse compared to fresh refuse. But Pelky (2001) concluded that more data were required to contradict were verify the trend. Moreover, the author had no systemic data of MSW shearing strength as a function of various stages of decomposition. This research has clearly identified the decomposition phases, measured the shearing angle and synthesized all the data to conclude that shearing strength decreases with decomposition. The shear strength obtained from the this research are quite similar to the results obtained from in-situ test in Torcy landfill in France (Thomas et.al.,2000) and laboratory test results of Edmonton, Blackfoot landfill refuse in Canada (Landva, 1990), as presented in Figure 12. The shear strength of Torcy landfill refuse (29.6^o) and shredded Edmonton refuse (24°) is reported within the strength boundary obtained from this research. But the shear strength results obtained from Blackfoot landfill refuse (39°) is higher than others. Figure 13 presents the effective shear strength parameters for MSW and design shear strength region recommended by Singh and Murphy (1990). The results obtained from the current research falls within the recommended region except the results for highly degraded sample with (C+H)/L ratio of 0.25. Most of the shear strength parameters obtained by Singh and Murphy are for samples with no or little degradation. Singh and Murphy (1990) had not considered the effect of decomposition on shear strength parameters and their recommended strength need to be revised for degraded MSW.

MSW is extremely heterogeneous in nature and the variation of MSW within the same reactor can be significant. Arguably, the test results conducted on samples from same reactor are supposed to vary at the same degree. Therefore, it is very important to check the repeatability of direct shear test conducted on MSW. Figure 14 presents the direct shear test results on samples collected from same reactor. The obtained friction angles for the three tests are 28.2 ^{o}, 27.2 ^{o} and 26.5 ^{o}. The standard deviation and coefficient of variation for shearing angle are 0.85 and 3%, respectively. This indicates that the tests are quite accurate and they can be repeated. Therefore the friction angle of 25° and 24° at (C+H)/L of 0.38 and 0.25, respectively may not be very different from each other. But the friction angle of 32 ^{o} at (C+H)/L of 1.29 is clearly different from friction angle of 27 ^{o} and 24 ^{o} at (C+H)/L= 0.73 and 0.25, respectively.

Increase in Strength with Displacement

Another interesting observation was the increase in strength components with displacement for both paper and plastics (Fig.15). The same observation of increase in strength with displacement was previously made by Gabr et. al. (1995), Pelky et. al. (2001) and Thomas et. al. (2001) for MSW. The shear strength increased with displacement and the trend was observed for all the decomposition phases (Fig. 16). The mobilized friction angles increased from 13° at 2mm displacement to 24° at 10mm displacement at (C+H)/L of 0.25. Jones (1997) tested municipal solid waste samples (38% paper, 18% plastics and 17% textiles) and reported that mobilized friction angle increased from 7 ^{o} at 5 mm displacement to 25 ^{o} -30 ^{o} at 100 mm displacement for normal stress between 100 to 400 kPa. Pelky et.al. (2001) reported mobilized friction angle for MSW sample collected from Blackfoot landfill increased from 5° at 5mm displacement to 29° at 100mm displacement for a normal stress of 496 kPa. Van Impe (1998) reported the same observation. These results clearly indicate that shear strength of MSW is a function of degree of decomposition as well as shear displacement.

Non-Linear Failure Envelope

The concept of a linear relationship between shear strength and normal stress, as applied to conventional soils, may not apply in highly compressible and erratic MSW (Landva and Clark, 1990). The experimental results presented in Figure 17 show that the Mohr failure envelop is curved, if they are not forced through zero. The curved mohr

failure line, in corformace with Landva and Clark, validates the non linear failure envelop for MSW.

MODEL

Jandel Corporation's Singma Plot nonlinear curve fitter tool was utilized for model development by curve fitting the experimental results obtained from direct shear test. The curve fitter uses the Marquardt-Levenberg algorithm to find the parameters of the independent variable (shear displacement) that can best fit shear stress-displacement (Ellithy, 1995). The algorithm finds the values of the parameters that minimize the sum of the squared differences between the observed and predicted values of the dependent variable (shear stress).

By curve fitting the shear stress-shear displacement results, the combination of following equations has been found to best fit the plotted results:

$$\tau(\delta) = a_1.e^{\left(-0.5\left(\frac{\delta-\delta_o}{b_1}\right)^2\right)} \qquad \delta < \delta_1 \qquad (1a)$$

$$= \mathbf{r} \qquad \delta_1 < \delta < \delta_2 \qquad (1b)$$

$$= a_3\left(1-e^{-b_3.\delta}\right) \qquad \delta > \delta_2 \qquad (1c)$$

where:

τ	Shear stress (kPa)
δ	Percentage of shear displacement w.r.t. cell diameter
δ_o	Percentage of shear displacement at peak shear stress
a_1	Initial peak shear strength (kPa)
a_3	Second peak shear strength (kPa)
r	Residual shear strength after 1st peak shear strength (kPa)
δ_1	Percentage of starting displacement of residual strength
δ_2	Percentage of end displacement of residual strength/percentage of starting displacement of 2nd peak shear strength

The parameter b_1 and b_3 can be obtained from the following relations:

$$b_1 = \delta_o / 2$$

b_3 = initial slope of the 2nd peak shear strength curve/ a_3

b_3 have dimensions of (percentages^{-1}) and b_3 values are directly proportional to initial slope of curve.

Experimental results showed that MSW at advance stage of decomposition ((C+H)/L = 0.73, 0.38 & 0.25) experienced peak, residual and second peak due to material strength incompatibility. Degraded paper, textile and organics have less strength than slightly degraded paper, fresh paper and plastics, and their presence in the same specimen cause strength incompatibility as observed from direct shear test results. In these cases, all three equations will be combined together to predict the strength behavior. The samples at acid phase, at the initial stage of degradation did not exhibit peak shear strength, and strength kept increasing with displacement. Accordingly, in case of MSW at initial decomposition stage and for samples prepared with only plastics or fresh paper, only equation 1c will be used for prediction of shear strength. Figure 18 shows the schematic representation of equations 1a, 1b and 1c.

MODEL PARAMETERS

The model parameters a_1, b_1, a_3, b_3, r, δ_1, δ_2 for MSW samples at different decomposition stages, plastics, fresh paper and degraded paper, organics, textiles were obtained from the direct shear test results. They are plotted as a function of normal stress in Figure 19 through Figure 21.

Samples at Advance Decomposition Stage

Experimental results showed that MSW at advance stage of decomposition ((C+H)/L = 0.73, 0.38 & 0.25) experienced peak, residual and second peak due to material strength incompatibility with the MSW. The model parameters, a_1, b_1, a_3, b_3, r, are required to predict the shear behavior of MSW.

Figure 19 (a) shows that model parameter a_1 (peak strength) increases linearly with stress and is quiet consistent for most of the decomposition stages. Shear parameter b_1 varies with the stress levels and the behavior is not consistent. Figure 19 (c) shows that parameter r, residual strength, increases linearly for all cases that have been obtained from experimental results. The parameters for the 2nd peak strength a_3 and b_3 are presented in Figure 20. The residual strength, r, should be added to a_3 to obtain the actual stress or displacement component (as it is part of the combined three equations). The

percentages of displacement corresponding residual shear strength, δ_1, can be taken at the point where the peak strength reduces to the same value as residual strength. The percentages of end displacement of residual strength and starting displacement of 2nd peak shear strength is found to be 5-7 % for most of the cases. In this case, we will assume it to be 6% (average value).

Samples at Initial Decomposition Stage, Fresh Paper and Plastics

Experimental results showed that MSW at initial stage of decomposition ((C+H)/L = 1.29) experienced no peak and shear strength keeps increasing with displacement. In this case, only equation 1c is required to predict the shear behavior.

Model parameter a_3 (peak shear strength) increases with stress and presented in Figure 21. The parameter b_3 for initial degradation stage decreases linearly with normal stress. The decrease in b_3 is mainly due to the increase in peak shear stress with normal stress whereas the initial slope for most of the degradation phases is very close to each other. The same trend of the shear behavior is observed for fresh paper and plastics, and the model parameters for this materials are also presented in Figure 21.

CALIBRATION OF MODEL

Utilizing the model, the predicted MSW shear behavior were compared with the observed experimental results to explain the reliability of the model. Most of the cases, they matches perfectly. Figure 22 compares the observed experimental results with the model prediction for sample at (C+H)/L=0.73 and plastics. For sample at (C+H)/L=0.73, the model utilized all three equations but for plastics only equation 1c was utilized. The observed experimental results match quite well with model prediction for both the cases. Such good fit between measured and computed data is expected since the measured data was used to obtain the model parameters. Figure 23 compares the observed experimental results by Pelky et.al. (2002) with the model prediction. The model parameter has been obtained from the experimental results (Figure 19-21).The predicted model behavior is comparable to the observed.

SUMMARY AND CONCLUSIONS

The operation of landfills with leachate recycle (bioreactors) offers a number of advantages including leachate treatment and disposal as well as recovery and reuse of landfill airspace due to enhanced refuse decomposition. Work in this paper utilized data

from directs shear tests to evaluate strength parameters for refuse in different degree of degradation. Samples for strength testing were prepared in 4-litre (approximately one-gallon) reactors and allowed to degrade to various stages of decomposition for compressibility testing. Refuse decomposition was enhanced by adding anaerobic wastewater sludge and by recirculating leachate (termed bioreactors). On the basis of the methane production data, samples were collected for strength testing. Twenty-one direct shear tests (100mm diameter cell) were performed on waste specimens. Based on the results obtained in this study, the following conclusions are advanced:

1. Results indicated that small displacement (2-4%) is required for mobilization of peak shear strength in the tested organic material and degraded textile. In comparison, larger displacement (>10%) is required for maximum strength mobilization in fresh paper. These data confirm the mobilized strength incompatibility within the MSW components.
2. The interface friction angle of plastics and friction angle for fresh shredded paper are estimated as 18 ^{o}-19° and 33 ^{o}, respectively. The experimental results found that with degradation of degradable material, percentages of plastic content increases and contributes to decrease in friction angle.
3. Accordingly, testing results indicated a correlation between strength parameters and (C+H)/L ratio. For example, measured friction angle for bioreactor samples decreased from 32 ^{o} to 24 ^{o} as (C+H)/L ratio decreased from 1.29 to 0.25 samples.
4. Shear strength increases with increasing shearing displacement. The friction angle for (C+H)/L at 0.38 increased from 14 ^{o} at 2 mm displacement to 25 ^{o} at 10 mm displacement.
5. The Mohr failure envelope for MSW is non-linear.
6. The predicted shear behavior by using the developed model for shear stress displacement match with the experimental results from Pelky et.al.(2001).

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Table 1 Number of Tests for Measuring Shear Strength Parameters

Sample No.	(C+H)/L	Direct Shear	Sample Description
1	1.29	3	Sample at the initial stages of decomposition
2	0.73	3	Sample at accelerated methane production Phase
3	0.38	3	Samples at decelerated methane production phase
4	0.25	3	Samples at stable methane production phase
5	Fresh Paper	3	Fresh shredded paper
6	Plastics	3	All material except plastics were removed from samples at (C+H)/L=0.38;
7	Degraded paper, organics and textiles	3	Plastics were removed from samples at (C+H)/L=0.38;

Table 2 Description of the Sampled Reactors and Their Gas Production Record

Sample Identification[a]	Day Sampled[b]	Cumulative Methane Production (L)	% Cellulose (C)	% Hemi-Cellulose (H)	%Lignin (L)	(C+H)/L
Fresh Refuse	n/a	n/a	41.91	8.47	19.96	2.52
B1	24	0.5	32.79	6.55	30.53	1.29
B2	53	70.5	21.87	4.95	38.08	0.71
B3	84	102.2	13.48	3.94	46.26	0.38
B4	127	53.5	11.88	2.29	56.44	0.25
T1	27	0	37.32	8.10	19.17	2.37
T2	56	0.7	27.45	6.03	26.06	1.29
T3	91	3.0	29.40	6.25	19.88	1.79
T4	130	13.8	16.92	3.88	28.47	0.73

a. B and T designate bioreactor and traditional samples, respectively

b. Traditional reactors were filled with MSW 3 days before bioreactors ;

n/a - not applicable

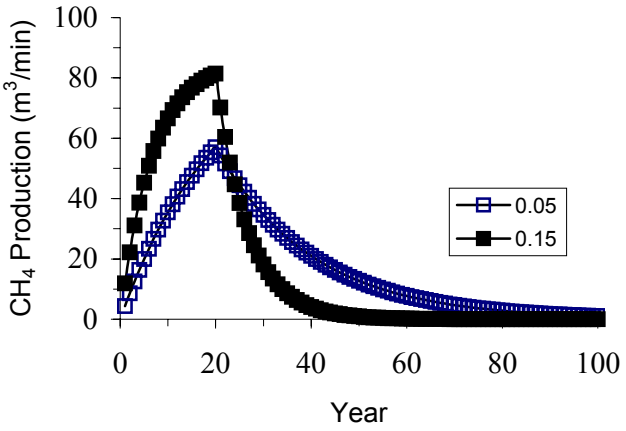


Figure 1. Methane production rate for a landfill that receives 286,000 metric ton/yr for 20 years. With reference to eqn. 2, Lo = 170 L/kg, the default value used for NSPS guidelines. The decay rate (k) varies to represent the NSPS default value of 0.05 and enhanced decomposition in a bioreactor (k = 0.15).

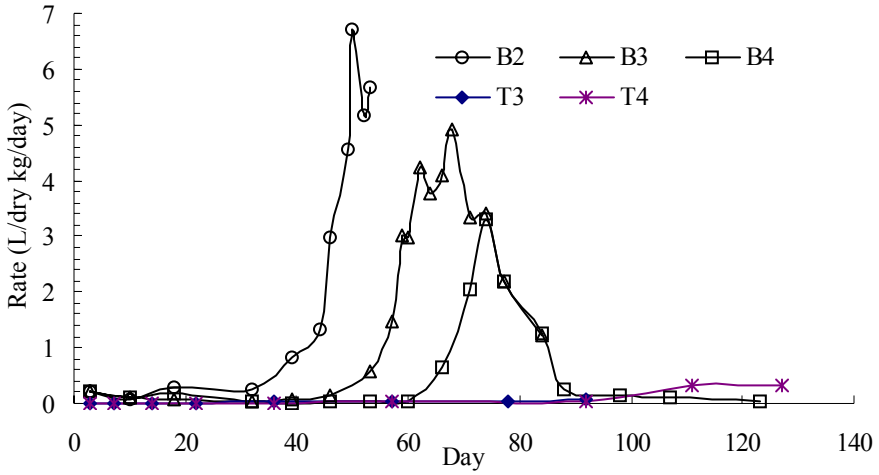


Figure 2. Rate of Methane Production for Bioreactor and Traditional Samples

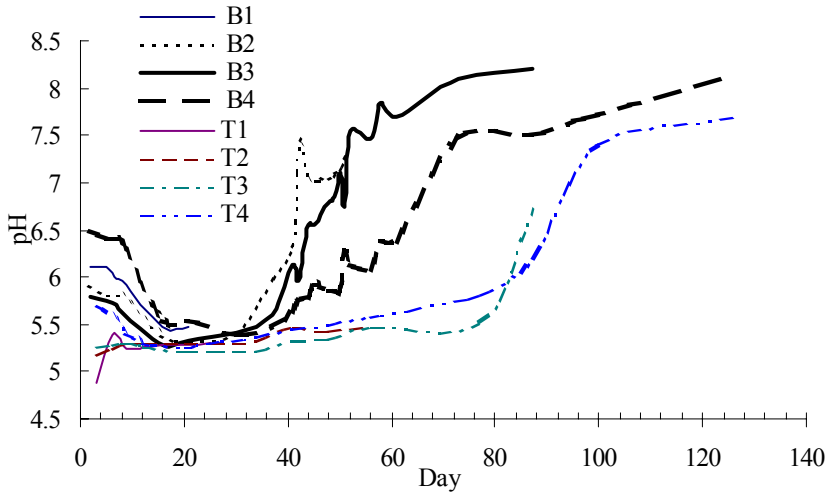


Figure 3. Variation of pH with Time for Bioreactor and Traditional Samples

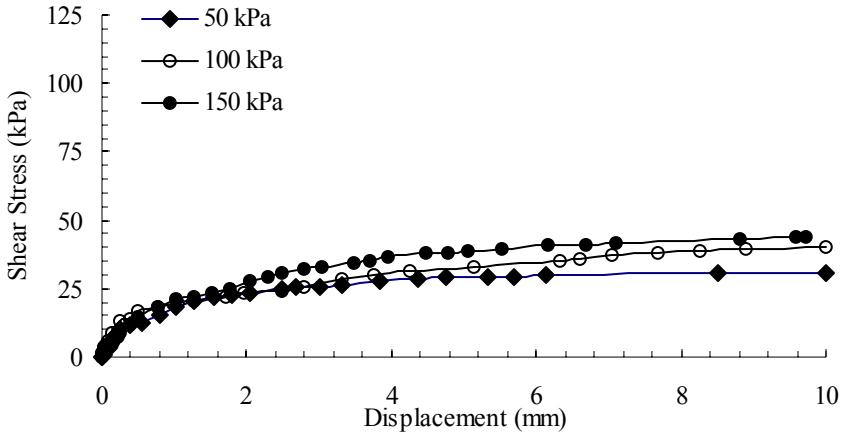


Figure 4. Direct Shear Test Data for Plastics

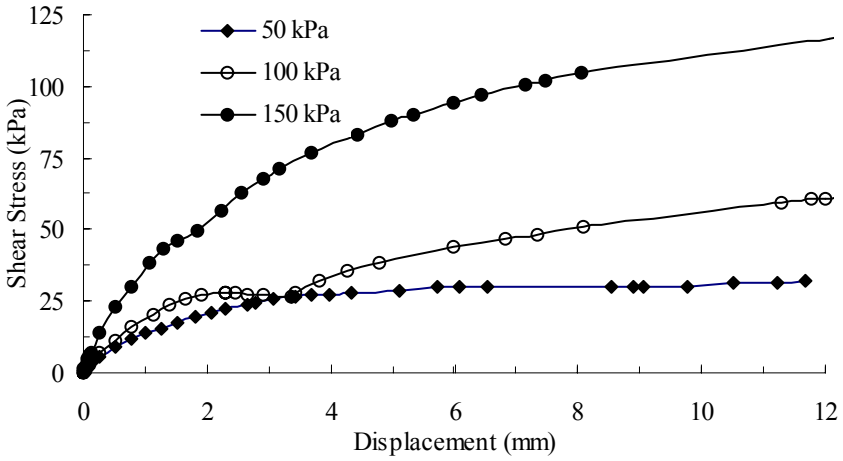


Figure 5. Direct Shear Test Data for Fresh Paper

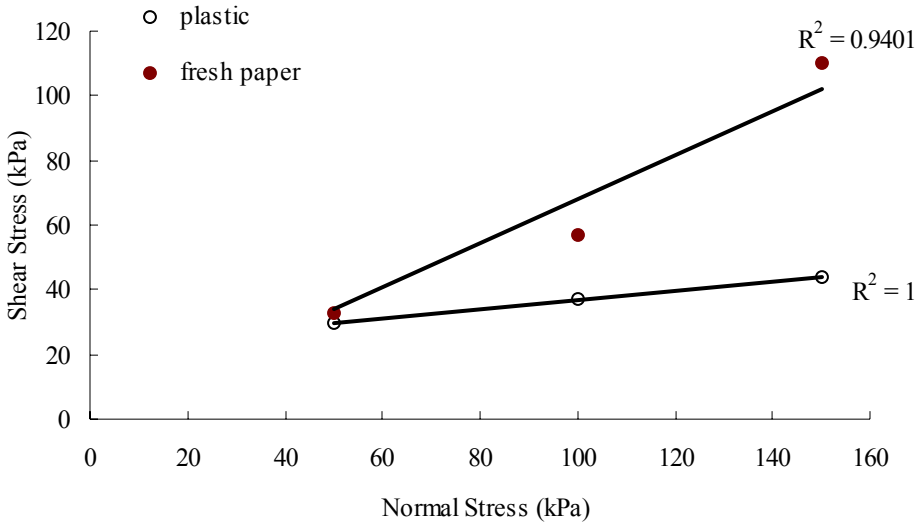


Fig. 6 Shear Strength Parameters for Fresh Paper and Plastics at 10 mm displacement

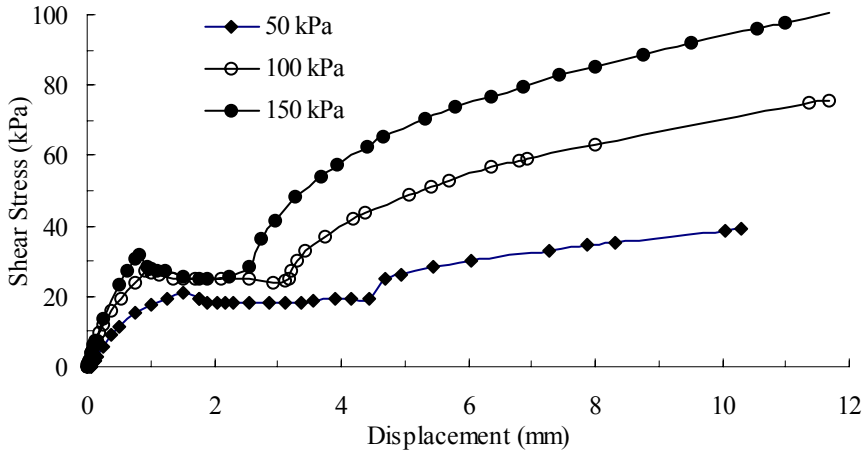


Fig. 7 Direct Shear Test Results for Degraded Paper, Organics and Textiles

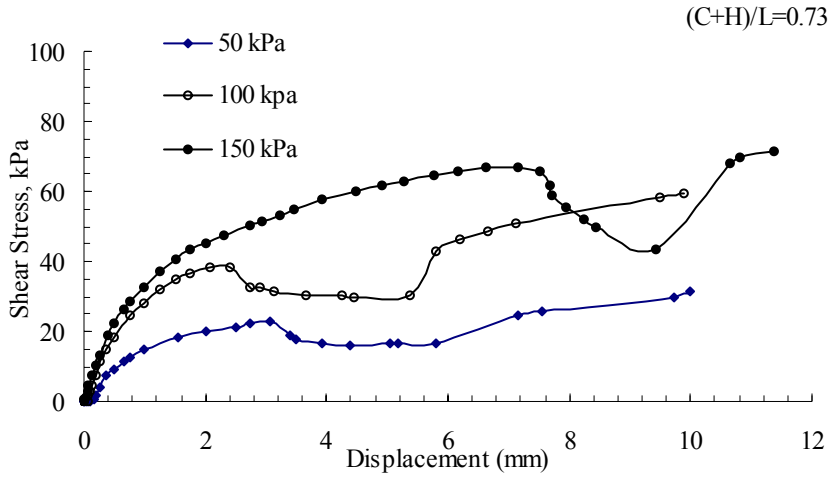


Figure 8. Direct Shear Test Data for Samples at (C+H)/L=0.73

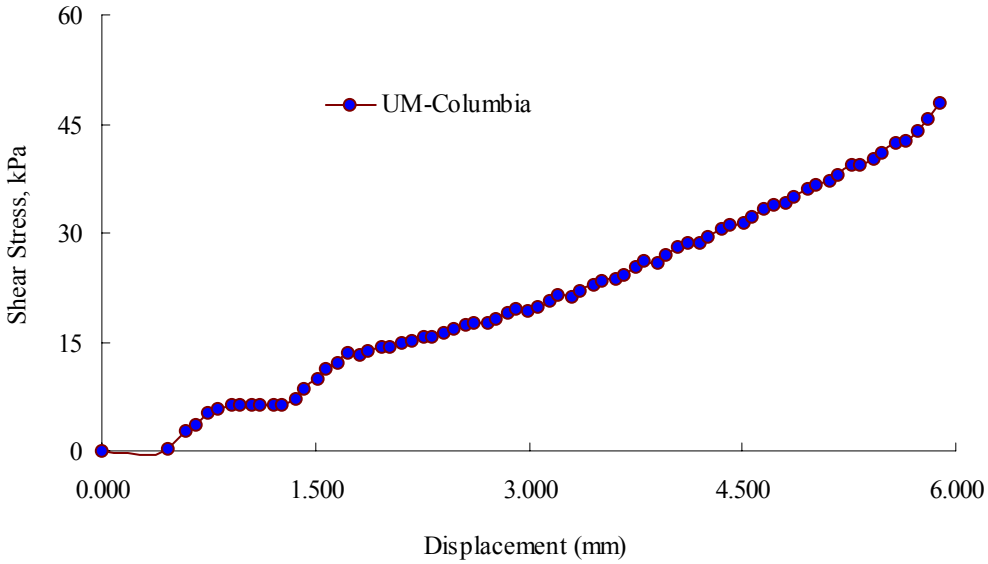


Figure 9. Direct Shear Test Data for MSW Samples (Bowders, 2002)

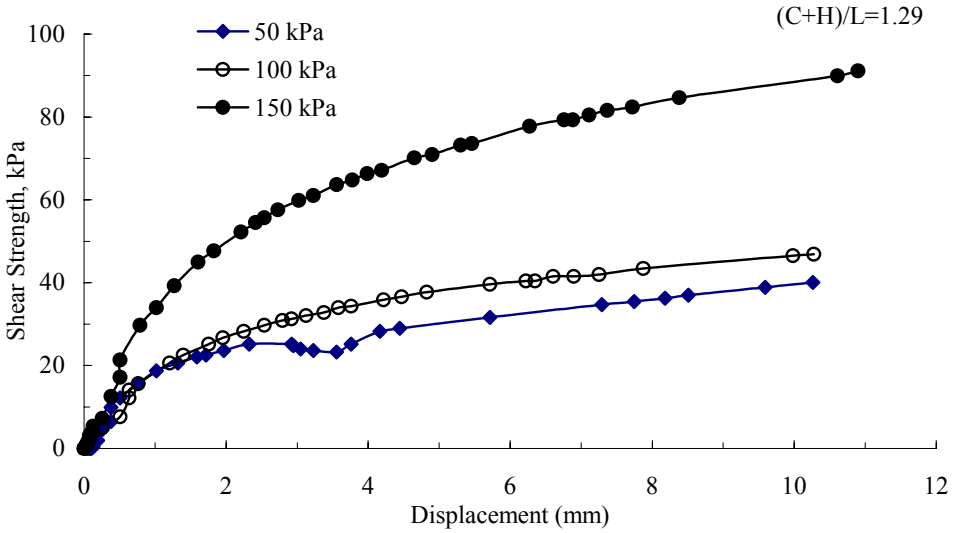


Figure 10. Direct Shear Test Data for Samples at (C+H)/L=1.29

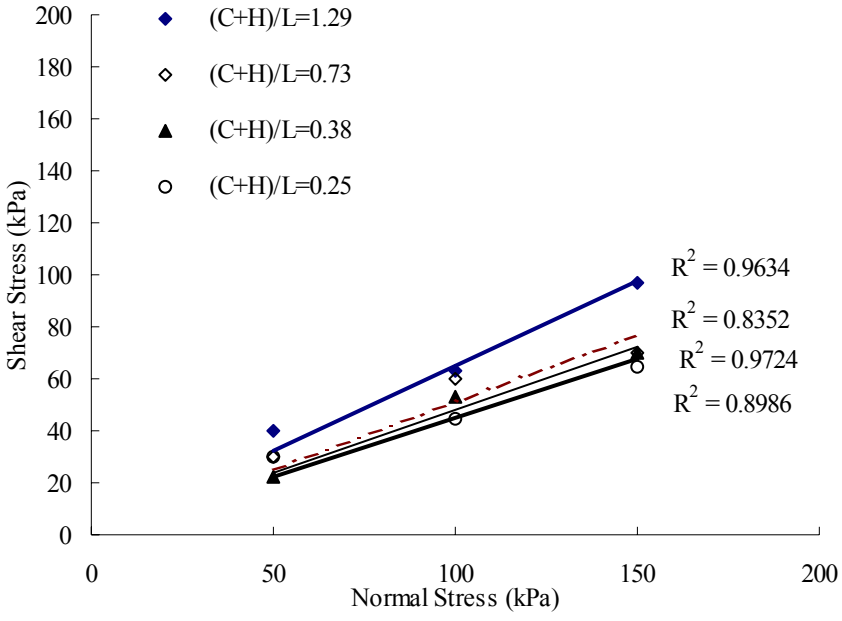


Figure 11. Shearing Angle for MSW at 10 mm Displacement

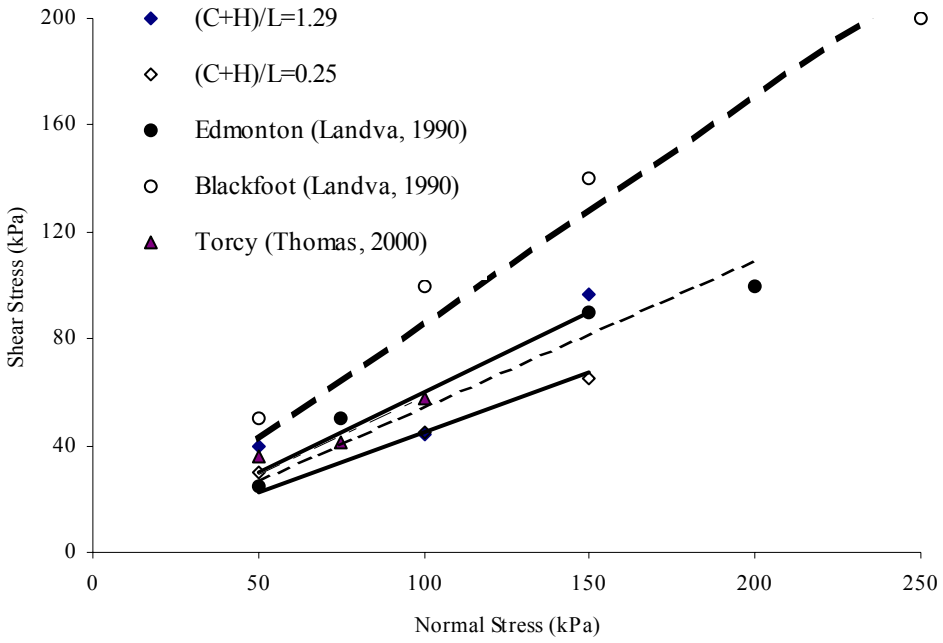


Figure 12. Comparison of Shear Strength Parameter with Existing Results

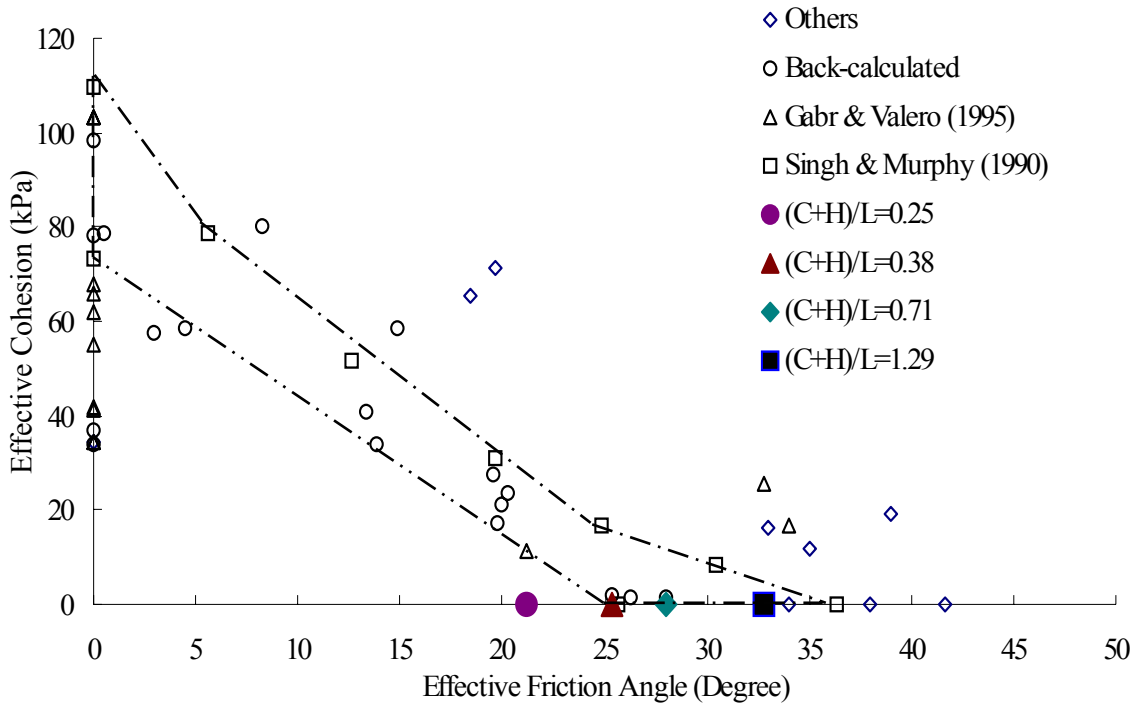


Figure 13. Effective Shear Strength Parameters for Municipal Solid Waste

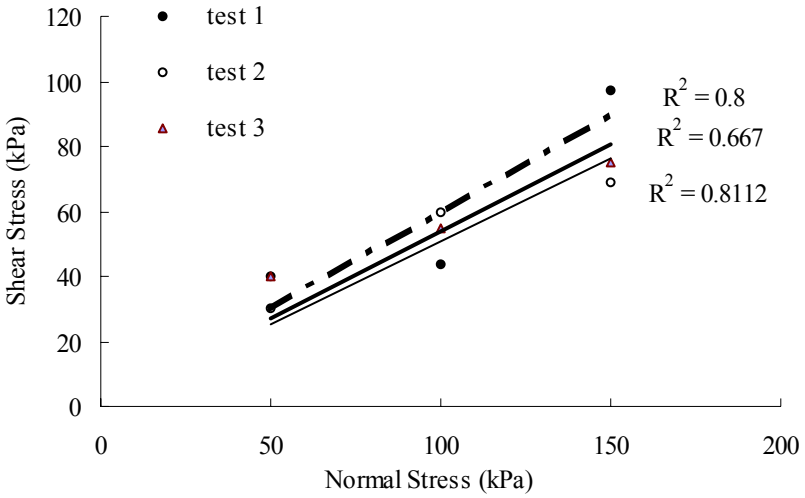


Figure 14. Repeatability Test for Shear Strength Parameters on Samples from the Same Reactor

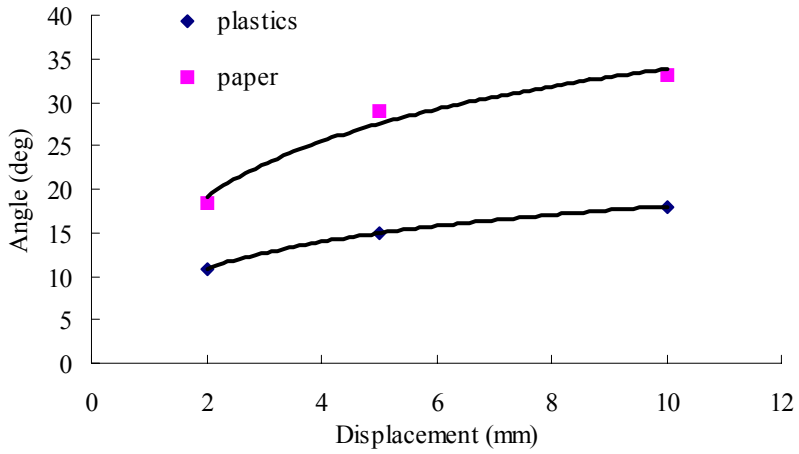


Figure 15. Mobilized Friction Angle with Displacement for Paper and Plastics

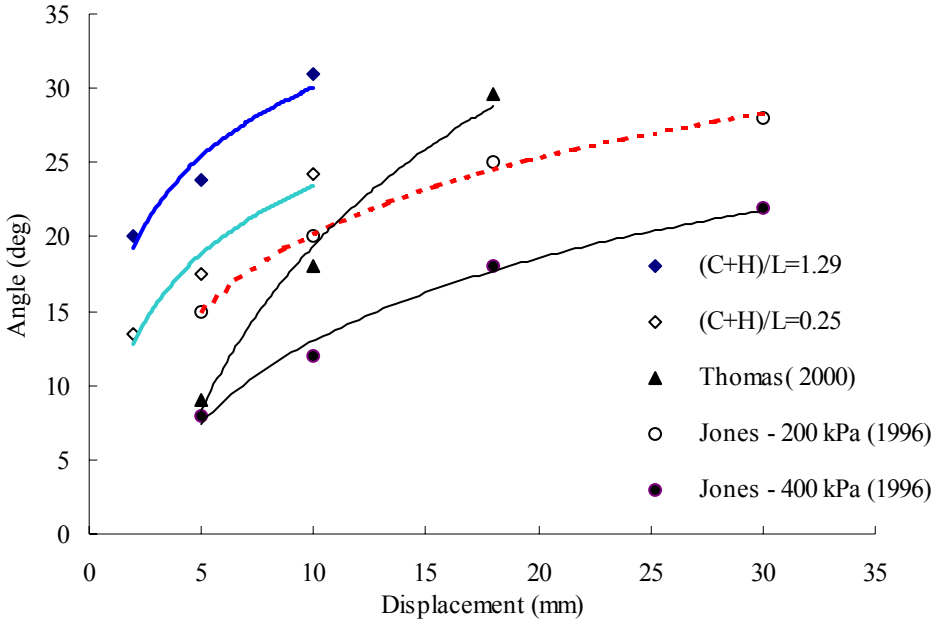


Figure 16. Comparison of Mobilized Friction Angle with Existing Results

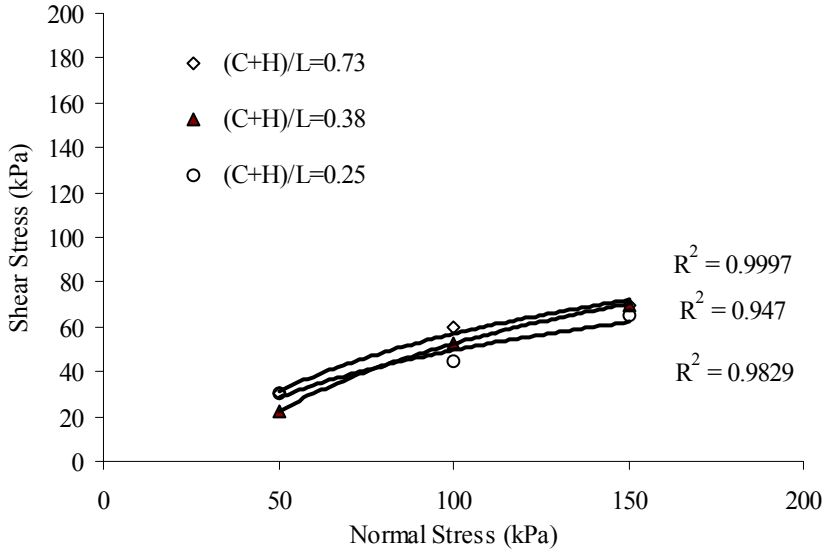


Figure 17. Non-Linear Mohr Envelope for MSW

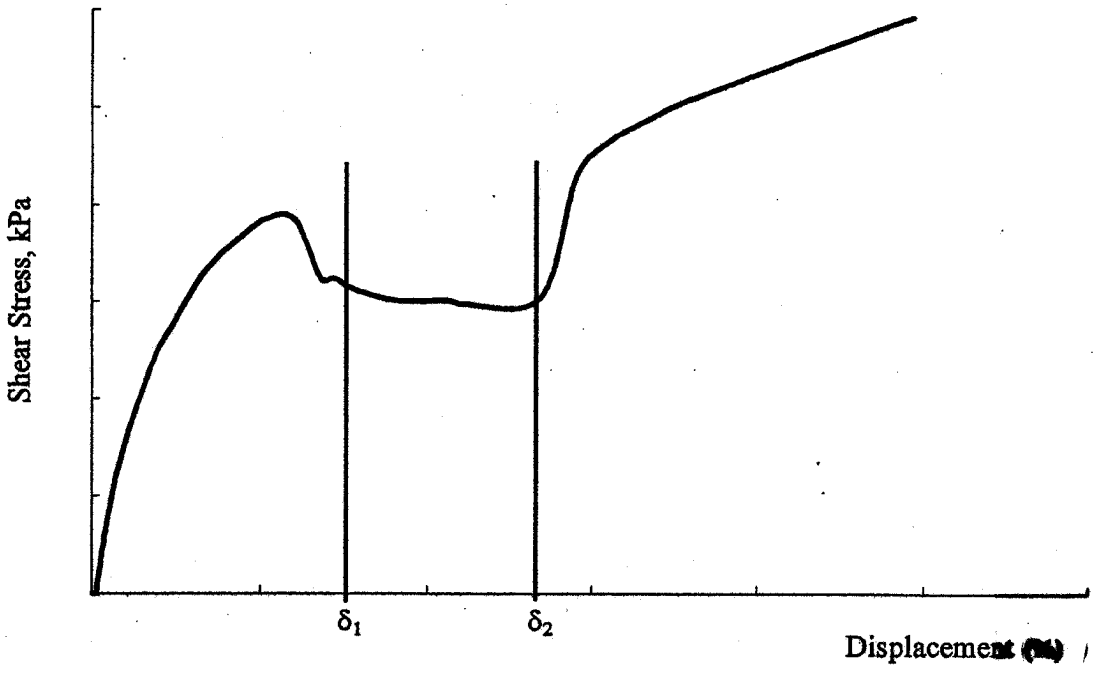
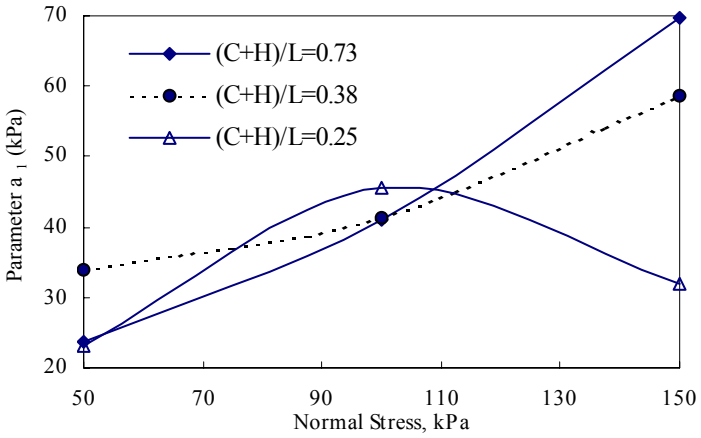
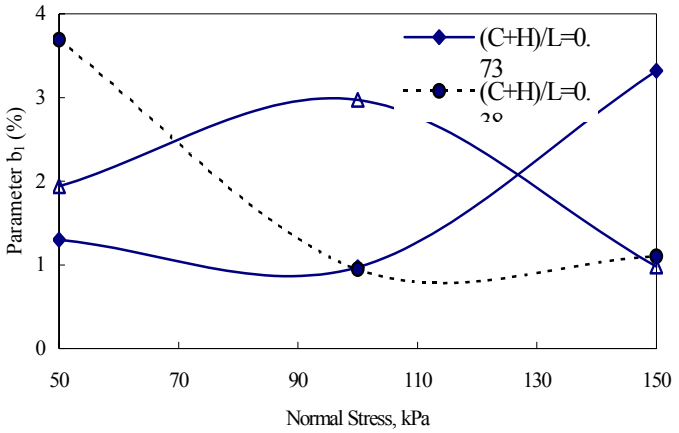


Figure 18. Schematic Diagram of Shear Stress – Displacement Behavior of MSW





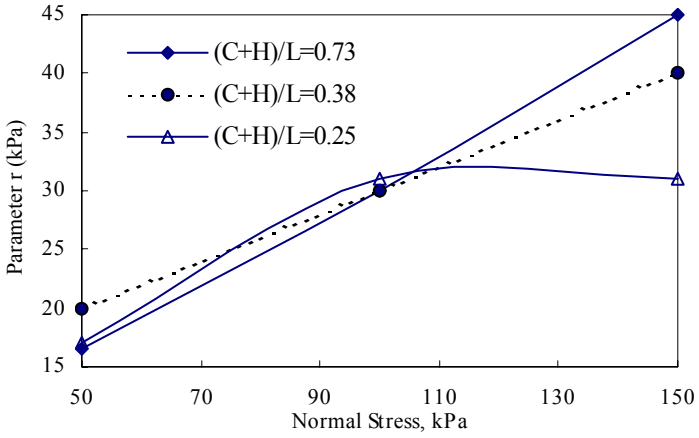


Figure 19 Variation of Model Parameters against Normal Stress

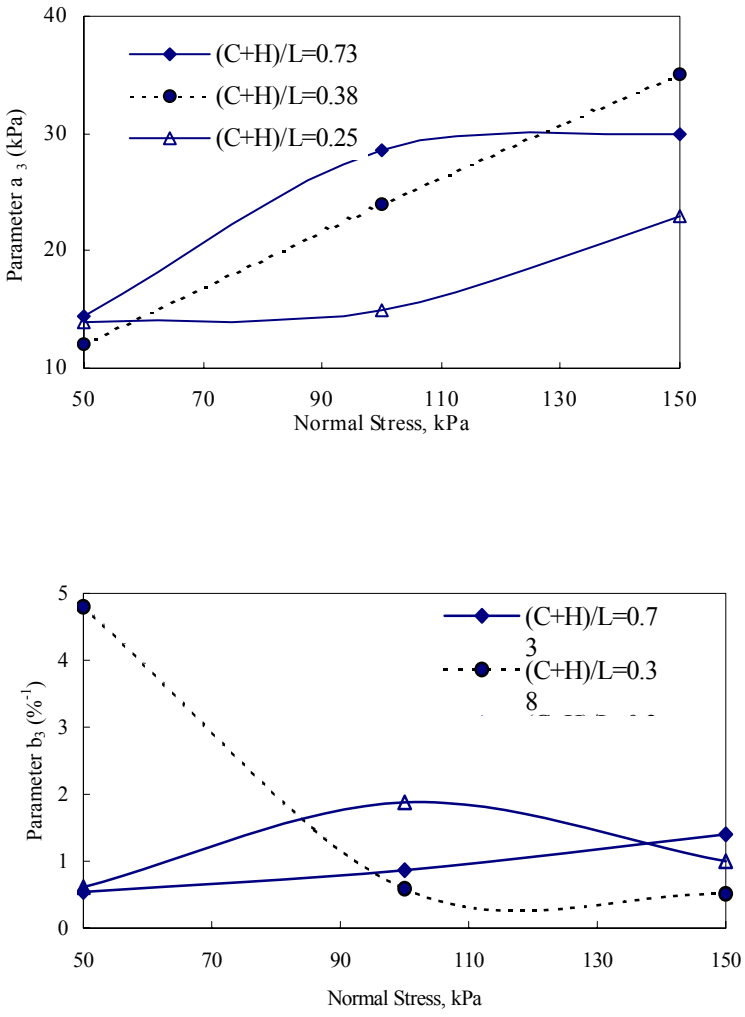


Figure 20. Variation of Model Parameters against Normal Stress

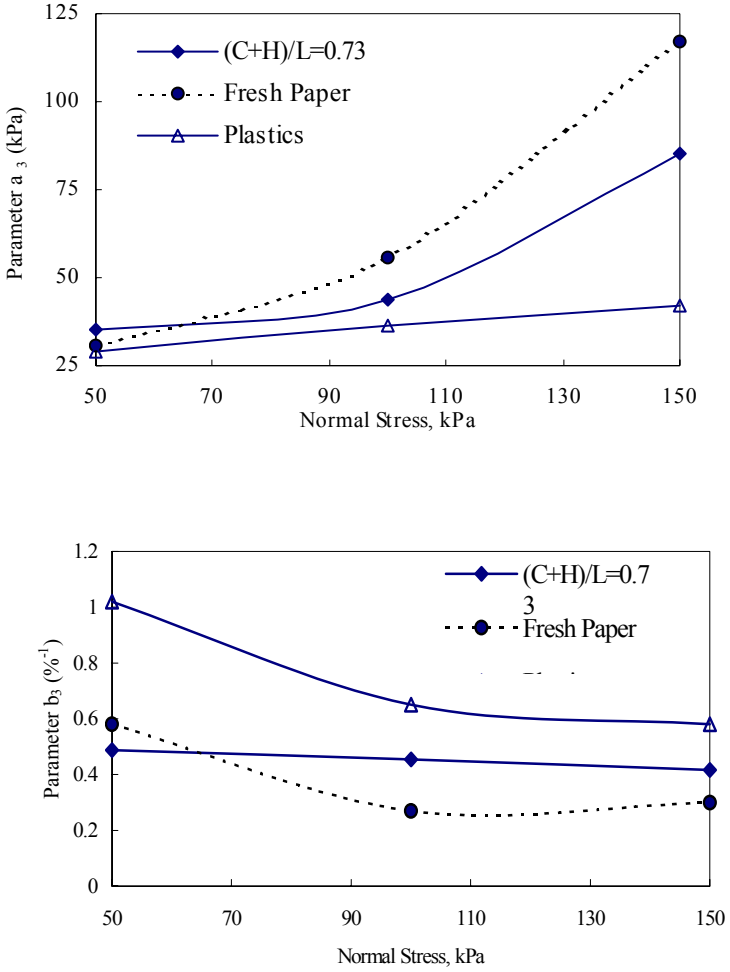
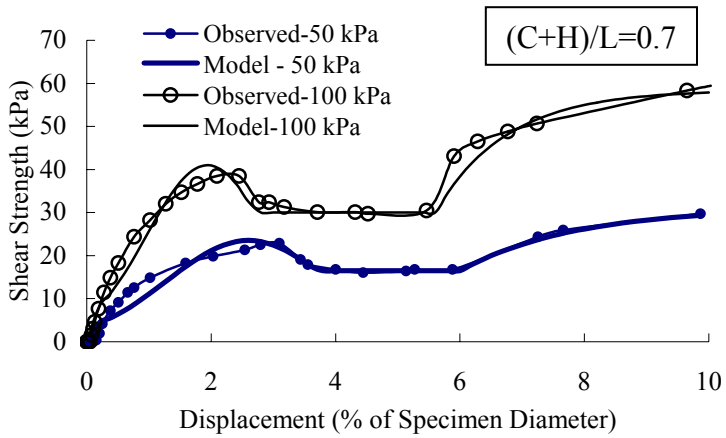


Figure 21 Variation of Model Parameters against Normal Stress



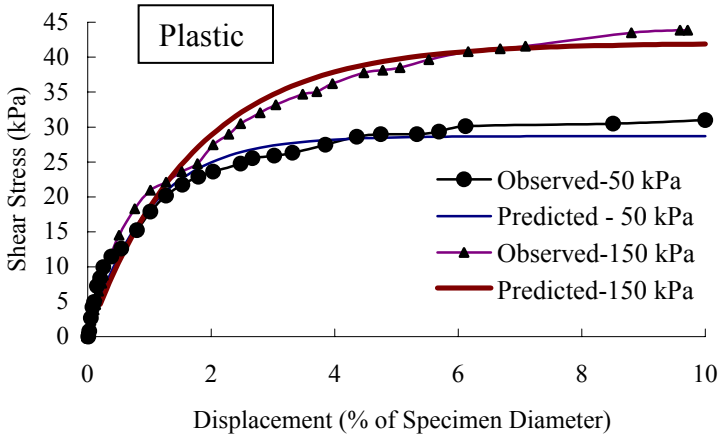


Figure 22 Shear Stress vs Displacement Model Verification Using Experimental Results

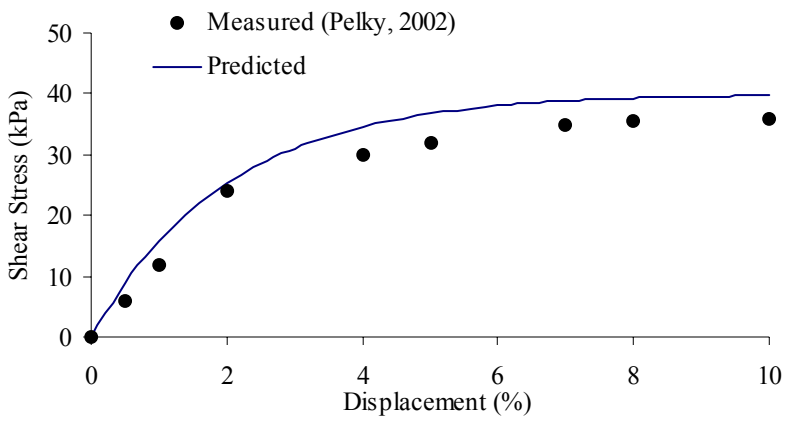


Figure 23. Comparison of Predicted and Measured Shear Stress Displacement as a Percentages of Specimen Diameter

SUMMARY AND CONCLUSIONS

The degradation of MSW over time, and associated settlement, is of special importance when estimating air space, designing interim and final closure covers of landfills, as well as planning vertical expansion of existing facilities. Rate and magnitude of settlement in these cases are a function of refuse composition and moisture content, operational management practices, waste nutrient level, and presence, or absence, of buffering agent. In addition to settlement, the evaluation of waste shear strength is important for the design of waste slopes, covers, vertical expansions and future land use, as well as assessing the seismic stability of landfills. The existing literature lacks in explaining changes in strength and stiffness characteristics as a function of the physical and chemical changes in waste with decomposition. Such characterization is of utmost importance as landfills are operated to accelerate changes in the physical and chemical properties of the waste.

Municipal Solid Waste (MSW) particles are usually larger than particles of sand, clay, or organic soils. Therefore, they are usually processed and shredded before being used for laboratory experiments using conventional soil testing equipment. It is important to understand the effect of shredding and equipment size on measured compressibility and shear strength characteristics. In this study, measured compressibility and shear strength dependency on the ratio of the waste particle size to equipment size (R) has been investigated.

Refuse samples representing various stages of decomposition, from fresh refuse to well decomposed refuse, were generated in laboratory-scale reactors that were operated under conditions designed to simulate decomposition in both traditional and bioreactor landfills. The reactors were destructively sampled to obtain refuse at various states of decomposition, based on the reactor's methane production rate curve. In addition, the state of decomposition was quantified by measurement of the concentrations of cellulose (C), hemicellulose (H), and lignin (L), and (C+H)/L ratio. Reactors were sampled at each of four time points to obtain refuse in the anaerobic acid phase, the accelerated methane production phase, and early and late in the decelerated methane production phase.

The experimental program was performed using oedometer and direct shear tests to determine the compressibility parameters and shear strength parameters as a function

of waste decomposition and illustrate shredding and equipment size effect on compressibility and strength parameters for refuse (at different degrees of degradation). The extent of degradation was characterized by gas production rates as well as (C+H)/L ratios.

For the shredding effect on compressibility parameters, oedometer tests were performed on fresh and decomposed samples using devices that are 63.5 mm, 100mm, 200mm and 300 mm in diameter. Initially, oedometer tests were conducted using constant R with different equipment size, and, then tests were performed using variable R for same equipment size. Sixteen one-dimensional oedometer tests were run for approximately 20 days under a constant stress of 95 kN/m^2. An additional eight "short term" tests were conducted to determine the coefficient of primary compression (Cc) with decreasing (C+H)/L ratios.

In addition, twenty-one direct shear tests (seven three points tests) using 100mm diameter cells were performed on waste specimens. Direct shear test were performed for R=0.5 and R=0.25 using 100 mm (4 inch) shear boxes for the preliminary evaluation of the shredding effect on shear strength parameters.

The research developed a model of waste settlement that considers the effect of high moisture content and time-dependent property changes on waste compressibility. The model settlement prediction considers all the aspects of biological decomposition, creep and matrix stiffness change as decomposition takes place with time. This research also developed a constitutive model for shear stress-displacement behavior of MSW in bioreactor landfills. Field data for compressibility and shear strength have been compiled from literature and compared with estimates from the developed compressibility and shear strength models.

Based on the results obtained in this study, the following conclusions are advanced:

1. Oedometer tests conducted on 63.5 mm, 100mm, 200mm diameter equipment with constant R, indicate that compressibility parameters are dependent on R. Compressibility parameters are similar with constant R even though the equipment size varies.

2. Shredding of MSW affects mainly initial compression parameters as observed from the test results using same equipment with variable R. Creep and biological strain rates of MSW are not affected by shredding. For example, initial compression for MSW using 200mm equipment is 31% and 35% for R =0.34 and 0.17, respectively.
3. (C+H)/L was used to quantify the state of waste decomposition.
4. Compressibility increased with increasing gas production as solid-to-gas conversion took place. Testing results indicate a correlation between the compressibility parameter (Cc) and (C+H)/L ratio. The coefficient of primary compression (Cc) for all samples showed a general trend of increasing with decreasing (C+H)/L. The measured primary settlement strains for bioreactor samples under 95 kPa increased from 26% to 35% as (C+H)/L ratio decreased from 1.29 to 0.25.
5. Results indicated the creep index (C_α) to be independent of the state of waste decomposition. The creep index range is 0.02 to 0.03 for traditional and bioreactor samples tested in various states of decomposition ((C+H)/L varied from 1.29 to 0.25).
6. The magnitude of the biological indices varied with the state of decomposition. The highest value (C_β = 0.19) is measured when samples were actively decomposing and had substantial methane potential remaining.
7. Seven field case studies show that the proposed compressibility model predicts landfill settlement quite well including the biological decomposition component.
8. The shear strength of the tested samples is affected by shredding as the light-weight reinforcing materials are shredded into smaller pieces during specimen preparation. The measured friction angles are 31° and 27° for R=0.50 and 0.25, respectively. This may be explained by assuming the larger components in the specimen act as better reinforcing element than shredded smaller components during shear.
9. Based on the calculated strength parameters from experimental results, the co-efficient of variation for the materials collected from same reactors is small (3-5%). The results are relatively accurate and can be repeated within the estimated variability.
10. Results indicated that 2-4% displacement is required for mobilization of peak shear strength in the tested organic material and degraded textile. In comparison, more than 10% displacement is required for maximum strength mobilization in fresh paper.

These data confirm the mobilized strength incompatibility within the MSW components due to presence of different type of materials. Therefore, direct shear test results show an initial peak once the strength of degraded material is mobilized, followed by residual strength, and then a second peak once the strength of the fresh or less degraded paper is moblized.

11. The amount of plastic, a non-degradable waste component, within the test sample remains the same whereas highly degradable paper content decrease with degradation as their structure matrix breaks down. The interface friction angle of plastics and friction angle for fresh shredded paper are estimated as 18°-19° and 33°, respectively. The experimental results found that with degradation of degradable material, percentages of plastic content increases and contributes to decrease in friction angle.
12. Accordingly, testing results indicated a correlation between strength parameters and (C+H)/L ratio. For example, measured friction angle for bioreactor samples decreased from 32° to 24° as (C+H)/L ratio decreased from 1.29 to 0.25 samples.
13. Shear strength increases with increasing shearing displacement. The friction angle for (C+H)/L at 0.38 increased from 14° at 2 mm displacement to 25° at 10 mm displacement.
14. The Mohr failure envelope for MSW is non-linear.
15. The predicted shear behavior by using the developed constitutive model for shear stress displacement match with the experimental results from Pelky et.al.(2001)

The performed research work provides a fundamental geotechnical characterization of waste in bioreactor landfills. Workshops held at two different national meetings (GRI Las Vegas meeting in December 2000 and Environmental Industries Association (EIA) San Diego meeting in February 2001) emphasized the lack of knowledge regarding geotechnical properties of waste in bioreactor landfills. The implementation of leachate recycle will lead to a more rapid waste decomposition and the waste will be considerably wetter than is typical of conventional landfills. The lack of understanding of using conventional testing techniques to measure waste properties and the lack data explaining changes in compressibility and strength with decomposition can have grave consequences. The specific contributions of the research are:

1. Development of a fundamental understanding of factors governing refuse compressibility and strength as waste decomposes, linking gas generation, chemical composition with geotechnical properties, which will enhance design and operating practices for bioreactor landfills,
2. Development of a simple model of bioreactor waste settlement that provides the professional community with a tool to study key scenarios during design, operation, and post-closure periods,
3. Establishment of a model for waste strength as a function of the state of waste decomposition,

In general, results from this research advance rational design, operation and regulation of MSW landfills.