DYNAMIC CHRACTERISTICS AND STABILITY ANALYSIS OF MUNCIPAL SOLID WASTE IN BIOREACTOR LANDFILLS

by

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ABSTRACT

DYNAMIC CHRACTERISTICS AND STABILITY ANALYSIS OF MUNCIPAL SOLID WASTE IN BIOREACTOR LANDFILLS

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Bioreactor landfills are operated to enhance refuse decomposition, gas production, and waste stabilization. The major aspect of bioreactor landfill operation is the recirculation of generated leachate back through the refuse mass. Due to the accelerated decomposition and settlement of solid waste, bioreactor landfills are gaining popularity as an alternative to the conventional landfill designed under Subtitle D regulations. However, recirculation of leachate or addition of water to accelerate the waste decomposition changes the biodegradation and geotechnical characteristics of waste mass. Our understanding of changes in engineering characteristics of solid waste with accelerated decomposition is limited. There is a need to understand and explain the changes in characteristics associated with stability analysis of landfills.

The objective of this research is to study the changes in strength characteristics of municipal solid waste (MSW) in bioreactor landfills with time and decomposition. In order to understand the changes in strength properties of MSW in bioreactor landfills with time and decomposition an experimental program was developed. Eight small scale reactors, representative of bioreactor landfill, were built in laboratory, and samples were prepared to represent different phases of decomposition. The state of decomposition was quantified by methane yield, pH, and volatile solids.

The geotechnical testing program (CD triaxial test and resonant column tests) was performed to determine shear strength and dynamic characteristics of MSW in bioreactor landfill. The test results indicated that the measured shear strength and dynamic properties of MSW are significantly affected by the degree of decomposition. The friction angle of MSW decreased from 26.7° in Phase I to 19° in Phase IV. The shear modulus increased from 2.11 MPa in Phase I to 12.56 MPa in Phase IV. The change in shear strength and dynamic properties of MSW was attributed to the breakdown in fibrous nature of solid waste particles with degradation.

Based on the measured experimental results, stability analyses were conducted. The finite element program PLAXIS and limit equilibrium program STABL was used to analyze the stability of MSW in bioreactor landfills. The stability was evaluated at both under normal and those during earthquake conditions. The factor of safety estimated using PLAXIS and GSTABL under both the conditions decreased as the solid waste degraded with time. The results indicates that the stability of bioreactor landfills should be evaluated using the strength characteristics determined as a function of time and decomposition rather than using average values.

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CHAPTER 1

INTRODUCTION

1.1 Background

Municipal solid waste (MSW), commonly known as trash or garbage is the household waste, which includes paper, plastic, package wrappings, food scraps, grass clippings, etc. It does not contain industrial, hazardous, or construction waste. According to USEPA (2005) the total annual generation of MSW has increased more than 60 percent to its 2005 level of nearly 246 million tons per year. In 2005, recycling and composting diverted 32 percent of waste, the rest was disposed.

Incineration and landfilling remains the primary source of disposal in US, nearly 14 percent of the generated waste is incinerated (USEPA, 2005). Incineration is the application of thermal treatment to wastes at very high temperatures in specifically designed furnaces. The volume of waste can be reduced by up to 90% and the weight of the waste by up to 60% (Bridgewater and Lidgren, 1981). However, the main disadvantage of incineration is the dioxins that are produced from the treatment. These dioxins can cause acid rain which destroys vegetation, wildlife, rivers, soils and even architecture. In addition, incineration is not a total waste disposal method; the ash left over from the treatment had to be landfilled. Therefore, landfilling still remains the primary source of solid waste disposal in United States.

About 54% of the generated solid waste goes in to the landfills (US EPA, 2005). 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. Due to the absence of moistures, refuse decomposition proceeds at suboptimal rates for decades or even centuries. The idea of enhancing decomposition by the addition of supplemental water and/or re-circulating generated leachate was first proposed nearly 30 years ago (Pohland, 1975). Based on his proposed methodology, a new type of landfilling technology known as Bioreactors has emerged. A bioreactor landfill accelerates the decomposition and stabilization of solid waste by the re-circulating the generated leachate, which creates a more favorable environment for the biological decomposition of organic matter in the landfill. Some of the potential advantage of bioreactor landfills are: (1) increased effective refuse density and landfill capacity; (2) Insitu leachate treatment; (3) increased rates of gas production which may make energy recovery more favorable; (4) settlement before placement of the final cover which decreases the risk of damage to the final cover; and (5) acceleration of refuse decomposition which may shorten the regulated post closure monitoring period and reduce the overall cost of the landfill (Barlaz et al., 1990; Reinhart and Townsend, 1998; and Pohland and Kim, 1999). The number of landfills operated as bioreactor landfills are expected to increase in near future.

1.2 Problem Statement

Stability of landfills is one of the major geotechnical tasks in landfill design and operation. The accelerated decomposition of the waste in bioreactor landfills increases the potential hazard associated with the slope failure of a municipal solid waste (MSW). Therefore, in order to assess the stability of these landfills, a strong understanding of their strength characteristics is essential. However, 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 strength parameters. Unfortunately, there are difficulties associated in performing these tests on MSW materials due to the heterogeneity and wide range of particle sizes. This leaves the professional community and the regulatory agencies with some uncertainty regarding the design and permitting of bioreactor landfills.

In addition, most of the existing researchers did not make a clear distinction between the degree of decomposition and geotechnical properties. Currently, average values of strength parameters are used to compute the stability of MSW in bioreactor landfills. However, based on the in-situ tests, Matasovic and Kavazanjian (1998) showed that the values of Poisson’s ratio at deeper portions of the landfill were greater than those located closer to the surface. This observation confirms that MSW is degraded more at bottom compared to the top. Therefore, considering properties of MSW to be uniform throughout the bioreactor landfill is not a reasonable assumption, and would lead to erroneous result during stability analysis.

1.3 Objective

The overall objective of the research is to develop an understanding between the changes in refuse strength and stability to its state of decomposition in landfills operated as bioreactors. An experimental program was developed to provide data on parameters describing MSW strength properties as a function of state of its decomposition. The research links the measured parameters to the physical and biological changes that take place as waste decomposition is accelerated. Specific objectives are to:

1. Prepare MSW Samples at different stages of degradation, and define them as a function of its gas generation, pH and volatile solids content.
2. Measure and define waste shear strength properties as a function of decomposition.
3. Measure and define waste dynamic properties as a function of decomposition.
4. Investigate the dominant mode of waste stability at different stages of waste decomposition using a finite element analysis.
5. Determine the effects of cover soil on waste strength properties with decomposition of MSW

1.4 Methodology

The objective of this research is achieved by an extensive literature search, laboratory studies, and numerical modeling efforts. The research objectives are broadly divided into four categories, and these categories are briefly discussed below.

1.4.1 Solid Waste Collection and Physical Characterization

Samples were collected from a transfer station in Burlington, Texas. The standard collection procedure was followed for obtaining a representative well mixed sample. The collected samples would then be stored at 4 ˚C to avoid any degradation before filling into reactors. Before filling the reactors with solid waste, physical characterization of the waste would be done. These include visual inspection of refuse composition, weight percentage of each constituent, moisture content, unit weight, and particle size distribution.

1.4.2 Reactor Setup and Sample Generation

Two sets of bioreactor cells would be setup, each set consist of four reactors representing the four different stages of decomposition. The first set of reactors would be set up without soil and the second with soil, layers of soil would be added to simulate the intermediate covers. At each phase of decomposition, (i.e., the anaerobic acidogenic phase, the accelerated methanogenic phase, and in the early and late decelerated methanogenic phase) the reactors are dismantled and destructively sampled. The waste degradation rate is dependent on change in temperature, oxygen levels and availability of liquids; hence the estimates of degradation rates would be based on these factors. In general, the stage of decomposition would be determined from the gas composition and by the volatile solids composition. The parameters to be checked at each stage of decomposition and the corresponding test methods are presented in Table 1.1.

Table 1.1 Tests conducted to determine the stage of decomposition

Parameters	Test Method
Gas Composition	Gas Chromatograph (Model No. SRI 8610C)
Volatile Solids	SM APHA Method 2440-E (Gravimetric Method)
pH	ASTM D 1293 (pH Meter Model No. AR50)

1.4.3 Geotechnical Testing

At each stage of decomposition various physical, chemical, mechanical, and biological properties of the sample would be determined. Some of the most important tests to be conducted are given in Table 1.2. Resonant column, true triaxial tests would be conducted to determine the strength parameters for static and dynamic conditions. Resonant column test would be conducted to evaluate the small-strain shear modulus. Using the results from the tests modulus reduction and damping curves would be developed to evaluate the stability of bioreactor landfill.

Table 1.2 Geotechnical test conducted on bioreactor waste

Condition	Test Method	Parameters	ASTM Standard
General Characterization	Grain Size Distribution	-	D6913-04
	Moisture Content	*w*	D2216-98
Strength Properties	Triaxial (CD)	$c^{'}, \Phi^{'}$	WK3821
	Resonant Column	G, D	D 4015

1.4.4 Numerical Modeling

A numerical modeling would be done to predict the Static and seismic stability of waste mass slopes at each stage of decomposition, using a finite element program PLAXIS. For the dynamic stability analysis, the developed modulus reduction and damping curves would be used in a permanent deformation analysis to estimate the maximum deformation at particular yield acceleration. The developed dynamic modulus degradation and damping curves would be calibrated to field conditions by comparing the values with existing and/or observed field values to better simulate the field conditions. Finally the results from finite element program PLAXIS and limit equilibrium program STABL would be compared.

1.5 Thesis Organization

This report contains a comprehensive literature review and the results of laboratory testing and slope stability analysis. Chapter 2 presents an extensive literature review of municipal solid waste classification, degradation, and geotechnical characteristics of MSW. Chapter 3 describes all the experimental variables and procedures used for sample preparation, particle size analysis, consolidated drained (CD) triaxial and resonant column testing, and slope stability analysis. Chapter 4 presents all the experimental results and a comprehensive discussion on the test results from the current research. Comparison of the results with existing literature is also presented. Chapter 5 presents the results and discussion on numerical modeling performed at different stages of decomposition. Finally, Chapter 6 summarizes the main conclusions from the current research and some key recommendations for future work.

1.6 Scope of the Report

Various questions pertaining to the stability of bioreactors during static and seismic conditions would be addressed by this research. Shear strength parameters estimated at each stage of decomposition will provide answers to stability of bioreactors during long-term operational conditions. It is believed that the developed guide would serve as a design manual for estimating the static and seismic stability of bioreactor landfills, and an approach method to solve the stability problems.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A bioreactor landfill accelerates the decomposition and stabilization of solid waste by the re-circulating the leachate. Unlike the conventional landfills that are designed and operated to minimize contact between water and solid waste, the operation of a bioreactor relies on the addition of liquids to increase the moisture content of the solid waste to the optimum level for decomposition. The increase in waste degradation and stabilization is accomplished through the addition of liquid and air to enhance microbial processes. Repa (2003) summarized the operational function of these reactors and they are presented in Table 2.1.

Leachate is a liquid formed by the interaction between the incoming moisture in the solid waste augmented by rainfall and snowmelt. This leachate contains high concentrations of organic contaminants and heavy metals. The concentration of the contaminant depends upon the composition of the waste and the age of the waste. Recirculation of the generated leachate back into the landfill accelerates the MSW decomposition. The accelerated decomposition of the MSW considerably changes the geotechnical characteristics of the waste in the landfill. Therefore the stability of MSW is expected to be affected.

Table 2.1 Types of Bioreactor Landfill Configurations (Repa, 2003)

Type	Description	Configuration
Aerobic	In an aerobic bioreactor, biodegradation occurs in the presence of air, which contains oxygen.	Air is injected into the waste mass using vertical or horizontal wells to promote aerobic bacteria to accelerate waste decomposition. The degradation of waste occurs under conditions similar to compost operations. The byproducts of aerobic degradation are carbon dioxide (CO_2) and water (H_2O).
Anaerobic	In an anaerobic bioreactor, biodegradation occurs in the absence of air and oxygen.	Without air, methanogeneic bacteria are promoted to accelerate waste degradation. The byproducts of anaerobic degradation are methane (CH_4) that can be used as an alternative energy source and CO_2.
Hybrid (Aerobic-Anaerobic)	In a hybrid bioreactor landfill the waste is first degraded under aerobic conditions followed by anaerobic conditions.	Aerobic conditions usually occur in the newly placed waste in the upper sections of the landfill, while anaerobic conditions occur in the lower sections. Because anaerobic conditions exist in the older lower sections of the landfill, methane production still occurs.

2.2 Refuse Decomposition

The organic biodegradable component in the solid waste begins to undergo bacterial degradation as soon as the solid waste is placed in the landfill. During this decomposition process various physical, chemical, and biological changes takes place within the solid waste. Some of these important changes as summarized by Tchobanoglous et al., (1977) are:

(1) the biological decay of organic putrescible material, either aerobically or anerobically, with the evolution of gases and liquids;

(2) the chemical oxidation of materials;

(3) the escape of gases from the fill and the lateral diffusion of gases through the fill;

(4) the movement of liquids caused by differential head;

(5) the dissolving and leaching of organic and inorganic materials by water and leachate moving through the fill;

(6) the movement of dissolved material by concentration gradient and osmosis; and

(7) the uneven settlement caused by consolidation of material into voids.

The decomposition and stabilization of waste depend on the composition of wastes, the degree of compaction, amount of moisture present, the presence of inhibiting materials, and the temperature. The overall rate at which the solid waste decomposes depends on their characteristics and to a large extent on the moisture content (Tchobanoglous et al., 1977).

The organic matter present in the solid waste can be divided into those containing cellulose or derivatives of cellulose and those not containing cellulose and its derivatives. Cellulose and hemicellulose are the major constituents of organic wastes and it comprises 45 – 60% of the dry unit weight of MSW (Barlaz et al., 1989). 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 processes occurring at each stage of decomposition is summarized by Hossain (2002) as follows. The conversion of cellulose to methane (CH_4) and carbon dioxide (CO_2) is described by Eq. (1).

$$(C_6H_{10}O_5)_n + n\ H_2O \longrightarrow 3n\ CH_4 + 3n\ CO_2 \quad (1)$$

Phase 1- Aerobic Phase: After the initial placement of the waste the 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 is 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 at 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.

2.2.1 pH

The pH is a good indicator of the particular stage of decomposition. The microorganism, which decomposes the MSW, was found to thrive well between the ranges of 6 to 9. When the pH goes below or above this range, the un-dissociated molecules of weak acid or bases can enter the cell and damage it (Tchobanoglous et al., 1977). However, the optimum pH range for anaerobic systems ranges between 6.5 and 7.6 (Parkin and Owen, 1986). Gas generation and decomposition rates have been reported to be highest at near neutral pH levels (Pohland et al., 1993). The leachate pH ranged between 4.7 - 8.8 for conventional landfills (USEPA, 2003; Kjeldsen et al., 2002; Chu et al., 1994; Krung and Ham, 1991) and from 5.4 - 8.6 for bioreactor landfills (EPA 2003; Pohland and Harper 1986).

The variations of pH in the leachate at different stage of decomposition are presented in Figure 2.1 (Barlaz et al., 1990). Initially the leachate pH may be neutral, however after the onset of anaerobic conditions the pH drops, especially during the acid forming phase. The pH drop is most likely caused by volatile fatty acid production and accumulation in the leachate (Tolaymat et al., 2004). The pH, however, will tend to move to neutrality as methanogens consume these acids.

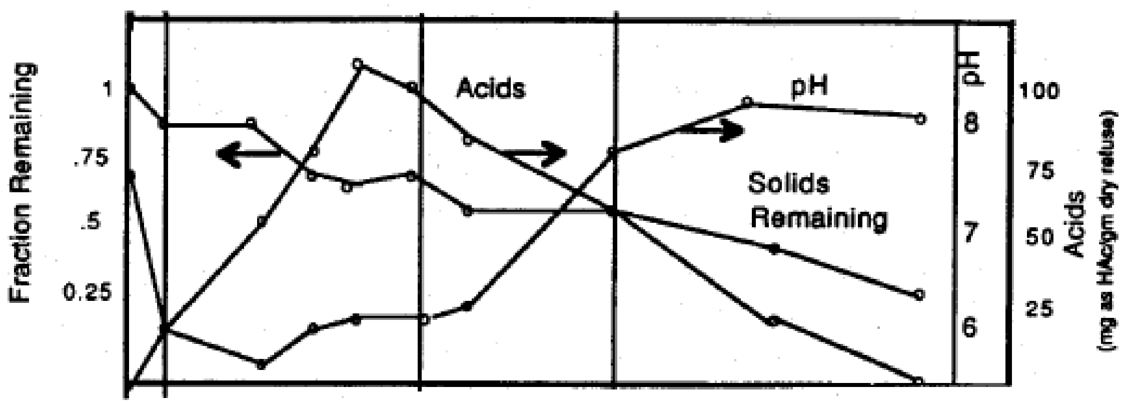


Figure 2.1 Variations of pH in the leachate at different stage of decomposition (Barlaz et al., 1990).

2.2.2 Temperature

The temperature range over which the microorganisms have been found to survive varies from -5 to 80°C. The anaerobic processes occur best within 30-38°C for mesophilic and 50 to 60°C for thermophilic organisms (McCarty 1964; Parkin and Owen 1986). Optimum methane generation from solid wastes, however, occurred at 41°C (Harts et al. 1982). Regardless of the operational temperatures, the maintenance of a uniform temperature is considered to be fundamental to anaerobic stabilization process efficiencies (USEPA, 2004). In the conventional landfills leachate temperature ranged from 7 to 25°C while bioreactor landfills leachate ranged from 6 to 37°C (USEPA, 2003).

Landfill temperature is not externally controlled; it reflects a combination of ambient temperature conditions and microbial activities (US EPA, 2004). In cold climates, leachate temperatures could be as low as 6°C, and soon after recirculation the leachate temperatures could steadily increase. US EPA (2003) reported that the leachate temperature at the Outer Loop landfill in Kentucky increased from around 7°C to 30°C within a few months of bioreactor operation. While an increase in leachate temperature is reflective of waste degradation in a landfill, it is not solely indicative of biological activity (US EPA, 2004).

2.3 Physical Characterization of MSW

The composition of the waste, moisture content, organic matter content, permeability, particle size distribution, and specific gravity are important MSW characteristics. These parameters greatly influence the geotechnical characteristics of the waste. Therefore, there is a need to understand the MSW characteristics with decomposition.

2.3.1 Composition of MSW

Municipal solid waste (MSW), commonly known as trash or garbage, is made up of the household type of waste ranging from package wrappings, food scraps, and grass clippings, computers, refrigerators, etc. however, it does not contain industrial, hazardous, or construction waste. Numerous reports have published the physical constituents of municipal solid waste (Barlaz et al., 1990; Tchobanoglous et al., 1977). Typical physical composition of municipal solid waste as reported by Tchobanoglous et al (1977) is presented in Table 2.2.

Table 2.2 Typical physical composition of municipal solid waste (Tchobanoglous et al., 1977)

MSW constituents	Range	Typical
Food wastes	6-26	15
Paper/	25-45	40
Cardboard	3-15	4
Plastic/	2-8	3
Textile	0-4	2
Rubber	0-2	0.5
Leather	0-2	0.5
Garden trimmings	0-20	12
Wood	1-4	2
Glass	4-16	8
Tin cans	2-8	6
Nonferrous metals	0-1	1
Ferrous metals	1-4	2
Dirt, ashes, brick, etc.	0-10	16

Due to the heterogeneous nature of the solid waste, the classification of waste is difficult. In the literature, few different approaches were adopted to classify MSW. The classification suggested by Landva and Clark (1990) based on their biodegradability is shown in Figure 2.2.

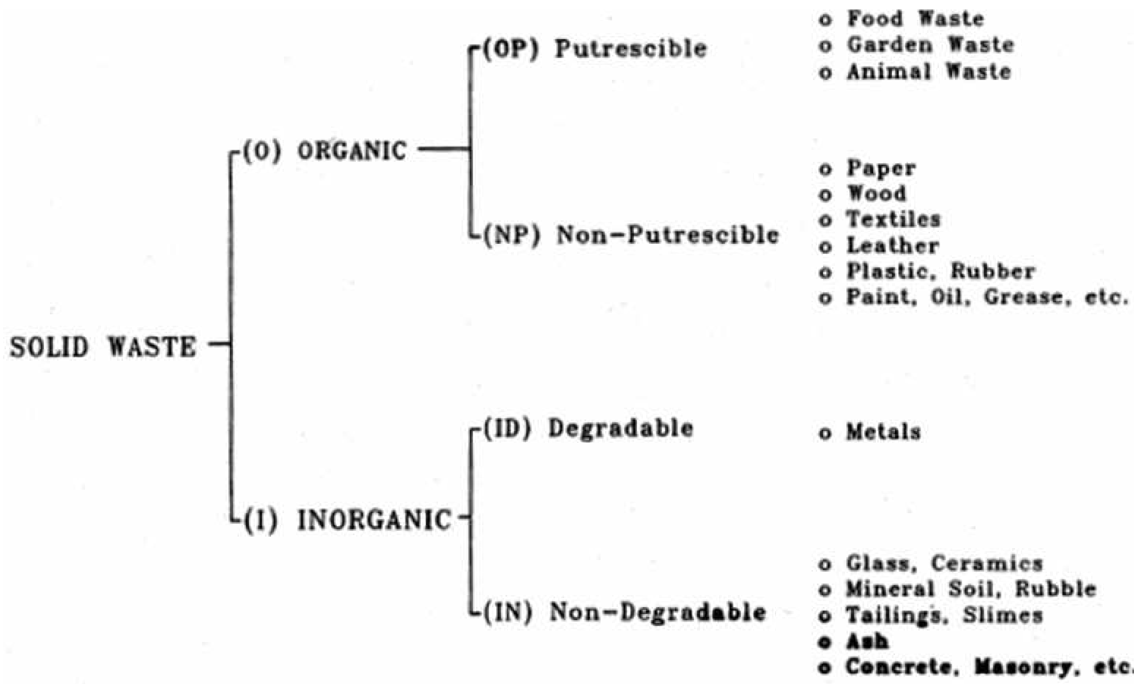


Figure 2.2 Solid waste classification based on their biodegradability (Landva and Clark, 1990)

2.3.2 Moisture Content

The moisture content of MSW is extremely important as it influences the decomposition behavior and all other engineering properties. Beaven and Powrie (1996) defined the moisture content of the waste as the ratio of the mass of water to the mass of dry solids present. After landfilling, the moisture content of the waste may increase through absorption of water by certain components of the waste such as paper, cardboard and textiles.

Zornberg et al. (1999) characterized the moisture content based on the amount and distribution of the liquids within the MSW. Figure 2.3 shows the mechanism of moisture retention within the waste mass. This mechanism of moisture retention within the waste mass was classified by Zornberg et al. (1999) as:

1. moisture within the waste (intra-particle voids);
2. moisture between particles (within inter-particle voids) held by capillary stress; and
3. moisture between particles, retained by low hydraulic conductivity.

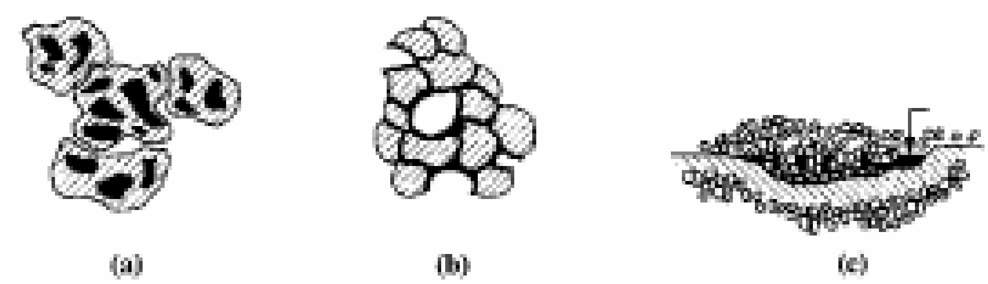


Figure 2.3 Mechanism of moisture retention in waste mass: (a) within particles; (b) between particles retained by capillary forces; (c) between particles retained by low hydraulic conductivity layers (Zornberg et al., 1999).

There is generally limited information regarding the in situ moisture distribution with depth in MSW landfill (Hossain, 2002). For most MSW the moisture content varies from 15 to 40 percent, depending on the composition of the wastes, the season of the year, humidity, and the weather conditions, particularly rain (Tchobanoglous et al., 1977). The wet weight moisture content is expressed as follows (Tchobanoglous et al., 1977):

$$\text{Moisture content (\%)} = \left(\frac{a-b}{a}\right)\times 100 \qquad (2)$$

Where, a = initial weight of the sample as delivered; and

b = weight of the sample after drying.

Moisture contents can also be determined based on the following relationship as proposed by Zornberg et al. (1999).

$$\text{Volumetric moisture content, } \theta = \left(\frac{\gamma_d}{\gamma_w}\right) w_w \qquad (3)$$

Where, γ_d = bulk dry unit weight of porous material;

γ_w = unit weight of water; and

w_w = gravimetric moisture content.

Based on the literature the moisture content varies between 15% and 130% (Gomes et al., 2002). The range of moisture content values presented by Hossain (2002) is presented in Table 2.3. Gabr and Valero (1995) reported increasing moisture content with age and organic content from the Pioneer Crossing Landfill, Pennsylvania. The authors observed 30% moisture content near the surface, and it increased to 130% at greater depth. Gomes et al. (2002) reported a similar behavior from their observation on Santo Tirso Landfill in Portugal. The moisture content ranged from 61% to 96% in newly collected waste, and it increased to about 117% for a 2 to 3 year old waste.

Table 2.3 Range of moisture contents as reported by various authors (Hossain, 2002)

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
Tchobanoglous et. al (1993)	15 - 45
Coumoulos et. al (1995)	20 - 125
Gabr and Valero (1995)	30 - 130

2.3.3 Organic Matter Content

The change in organic matter content in MSW with age greatly influences its mechanical characteristics and volume changes (Gomes et al., 2002). The organic matter content of MSW decreases with decomposition. At deeper depths, the MSW would be at an advanced stage of decomposition. Therefore at deeper depths the organic content in MSW will be lower, and it will be higher at surface level, where the MSW is at the initial stage of decomposition (Barlaz, 1988). Existing literature (Barlaz et al., 1990, Landva and Clark, 1990; Gifford et. al., 1990) had presented a range of organic matter content varying between 5 to 75 %. However, Gomes et al. (2002) reported that there is a direct relationship between moisture content and organic matter content, and a reduced influence on waste age. Their report is based on their observation from Santo Tirso Landfill in Portugal, where the organic content of the fresh waste was about 56%, and this waste was classified as very slow biodegradable material.

2.3.4 Hydraulic Gradient Effect

Proper assessment of hydraulic conductivity of waste is an important parameter because of the potential impact related to the uncontrolled leachate and stability problem (Hossain, 2002). Higher hydraulic gradient requires the application of larger effective stresses at the downstream end of the specimen. These stresses cause changes in the specimen volume and the structure of the void system (Oweis and Khera, 1990). Table 2.4 shows the summary of hydraulic conductivity reported by various authors using different methods on a domestic waste. In the materials of lower density the permeability decreases with increasing gradient this is shown in Figure 2.4 (Oweis and Khera, 1990). The permeability is also influenced by the degree of decomposition, aging, sample depth, etc (Penmethsa, 2007).

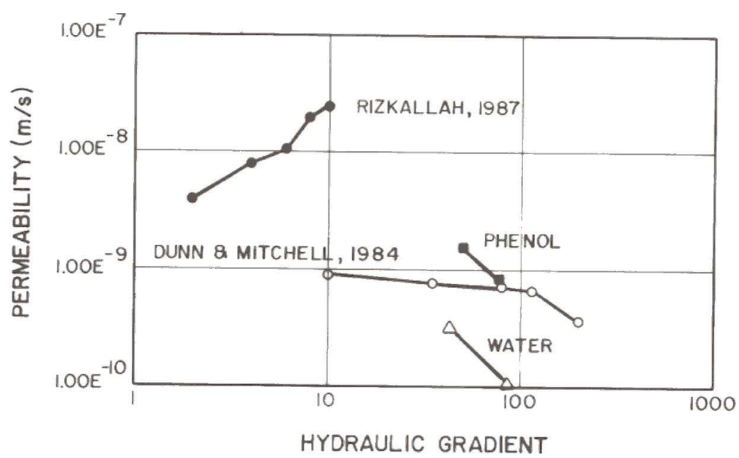


Figure 2.4 Effect of hydraulic gradient on permeability (Oweis and Khera, 1990).

Table 2.4 Hydraulic conductivity reported by various authors using different methods on a domestic waste (Hossain, 2002)

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

2.3.5 Particle Size Distribution

The mechanical behavior and decomposition of MSW are strongly influenced by the particle size distribution of the waste. Due to the presence of larger particles and heterogeneity of the waste, the grain size distribution of MSW is extremely difficult to determine. Gabr and Valero (1995) performed particle size determinations of MSW using mechanical sieve analysis and hydrometer analysis (Figure 2.5). The authors attributed the difference in grain size distribution to the higher degree of decomposition of MSW samples at deeper depth. Gomes et al. (2002) reported the same behavior for the waste collected from Santo Tirso landfill, Portugal as shown in Figure 2.6. The samples were at advanced stage of decomposition.

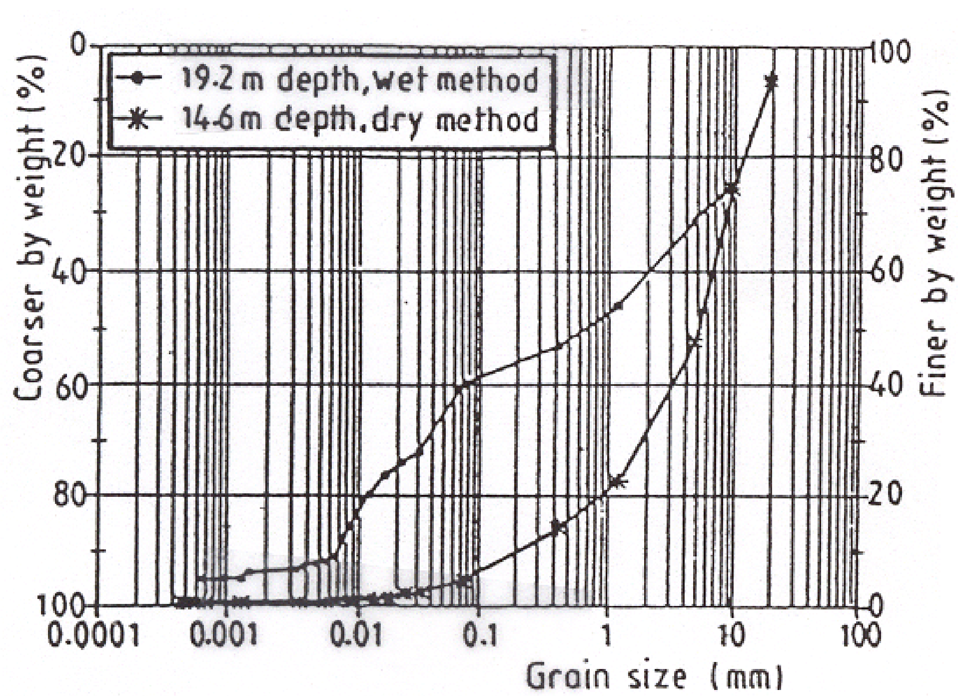


Figure 2.5 Particle size distribution from mechanical and hydrometer test analysis (Gabr and Valero, 1995)

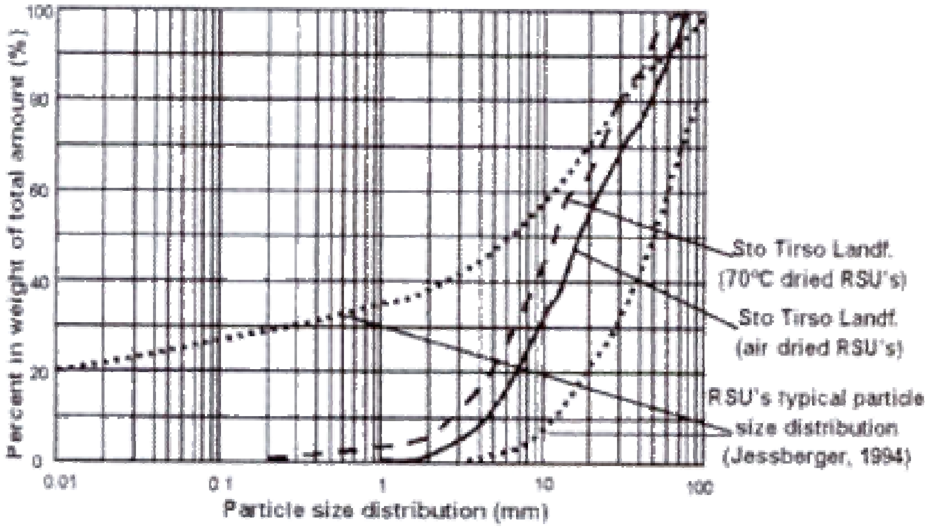


Figure 2.6 Particle size distribution of MSW from Santo Tirso Landfill
(Gomes et al., 2002)

2.3.6 Specific Gravity

Sowers (1972) indicated that due to the complex nature of MSW a precise determination of specific gravity may be not be possible. Gabr and Valero (1995) reported a mean specific gravity (G_s) equal to 2.0 with a variance of 0.0032 for the wastes entire grain-size distribution. Additionally, they have also performed measurements on only the fine fraction (<200 sieve), and reported a G_s of 2.4 with a variance of 0.0355. The authors were expecting the G_s value to be between 2.6 to 2.7. Gabr and Valero (1995) attributed the lower specific gravity value to the presence of decomposed organic matter, which had a specific gravity of 1(Hossain, 2002). Pelkey (1997) reported a G_s value of between 2.3 and 2.5 from their test results on fraction finer than 4.75 mm sieve. The sample predominantly consisted of cover soil with minor amounts of glass and organic material.

2.3.7 Atterberg Limits

Gabr and Valero (1995) conducted limited number of plastic and liquid limit tests on sample fraction finer than a standard US Sieve No. 40. Based on their test results, they found that the liquid limit increased with depth with no apparent increase in the value of plasticity index as shown in Figure 2.7. The plasticity index was found to be around 30%.

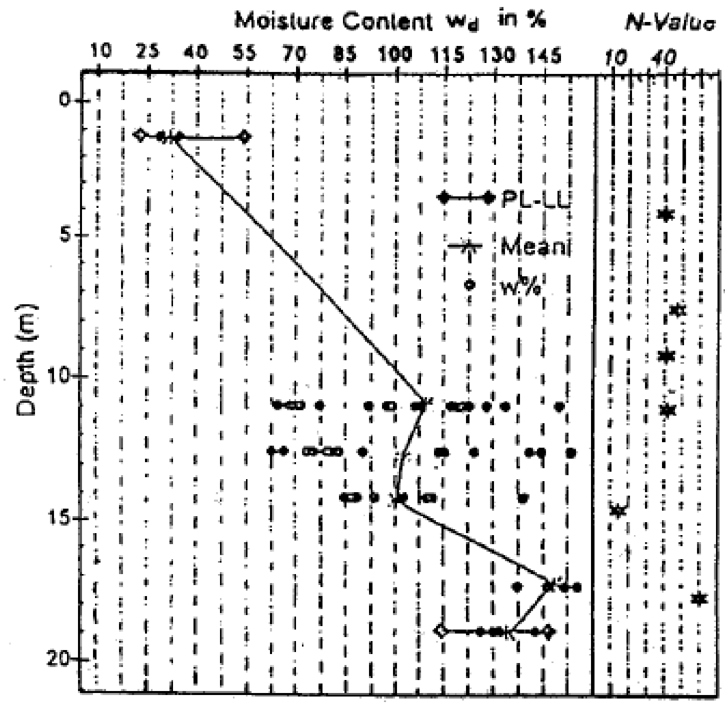


Figure 2.7 Variation of water content, liquid limit, and plastic limit with depth (Gabr and Valero, 1995)

<u>2.4 Geotechnical Characteristics of MSW</u>

The accelerated decomposition of the refuse in bioreactors considerably changes the geotechnical characteristics of the waste in the landfill, and thereby increases the concern for waste stability. Since many of the recent landfills are located in the vicinity of highly populated areas, this increases the potential hazard associated with the slope failure of a municipal solid waste (MSW) landfill. Due to this considerable attention has been focused on studying the shear strength characteristics of these landfills (Singh and Murphy, 1990; and Kavazanjian et al., 2001).

The strength characteristics of the MSW are intimately related to its heterogeneous composition, and its physical and chemical properties. These properties changes significantly not only with time, but also with the degree of decomposition (Gomes et al., 2002). Some of the important mechanical properties evaluated in this study are unit weight, shear strength, stiffness, and damping. Existing literature available on these properties are discussed in the following sections.

2.4.1 Unit Weight

Unit weight of solid waste is an important parameter for both static and seismic stability analyses of landfills. Unit weight of the waste is directly influenced by the type of waste, degree of decomposition, volume of daily cover, compaction degree, quantity of leachate produced, and the depth from which sample is taken. The combined effect of depth and age of the waste was investigated by Oweis and Khera, (1986) using 12 inch diameter bucket auger in a southern California landfill. The authors found that the unit weight increased with depth. The wet unit weight increased from 5 kN/m^3 at a depth of 5 m to about 13.8 kN/m^3 at 26 m. They also found that the wet unit weight of newer waste was slightly higher than that of older waste; but the dry unit weight of both the waste were approximately equal. Zornberg et al. (1999) had reported the same trend from his investigation of total unit weight profile from San Gabriel Valley landfill in

Los Angeles County, California. Their total unit weight value ranged from 10 kN/m^3 at 3m to 15 kN/m^3 at 55m below the landfill surface.

A method to determine the unit weight of solid waste was proposed by Landva and Clark (1990), which is given by Equation (4). This method takes into account the intra-particle and inter-particle void, porosity and degree of saturation.

$$\gamma_c = \frac{1}{\sum_1^n \frac{w_i}{w_c} \cdot \frac{1}{\gamma_i}} \qquad (4)$$

Where,

γ_c = average dry unit weight of a constituent;

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):

$$\gamma_c^{'} = \gamma_c \left[1 + \sum_1^n \frac{w_i}{w_c} \cdot \frac{\Delta\gamma_i}{\gamma_i} \right] \qquad (5)$$

Where, $\Delta\gamma_i$ = increase in unit weight of constituent *i*.

2.4.2 Shear Strength Characteristics

Shear strength is an important property of solid waste for stability analyses. A typical feature of the stress-strain behavior of MSW is that failure cannot be observed even at high sample compression (Singh & Murphy, 1990; Jesse-Berger & Kockel, 1993). In addition, if Mohr-Coulomb theory is used, the shear strength parameters cannot be adequately defined, unless they are considered strain dependent (Vilar and Carvalho, 2002). MSW shear strength parameters reported in literature varied widely, with a friction angle ranging from 10° to 53°, and cohesion varying from 0 to 67 kPa. Kavazanjian et al. (1995) proposed the lower bound MSW drained shear strength envelope as shown in Figure 2.8. The authors proposed cohesion of 24 kPa at low confining pressure (below 37 kPa) and a friction angle of 33 degrees at higher confining pressures (larger than 37 kPa). This strength envelope was confirmed by Mitchell (1996) using the back-calculated shear strength values from the Rumpke Landfill in Cincinnati, Ohio, USA.

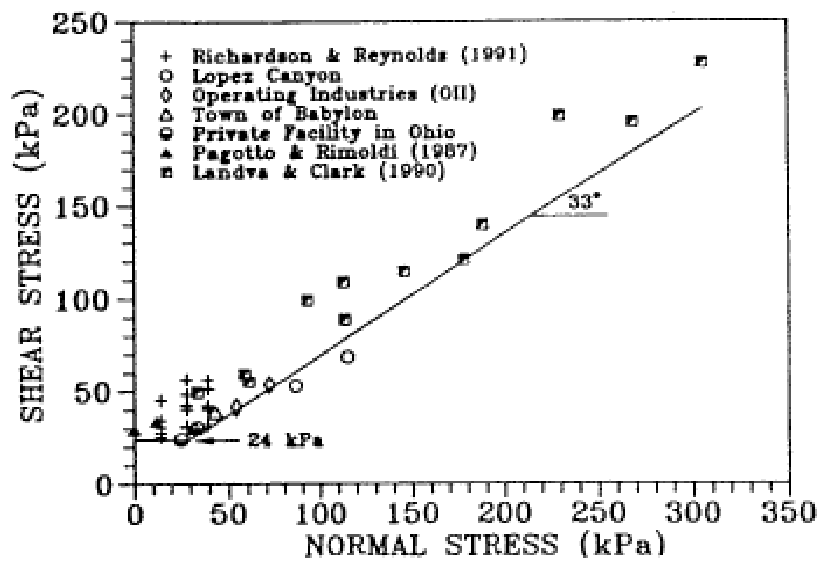


Figure 2.8 Lower bound MSW drained shear strength envelope (Kavazanjian, et al., 1995)

Paper and plastic are two major solid waste components. Paper, the degradable component decreases with degradation of MSW. However, plastic a non-degradable component remains constant (Hossain, 2002). Thomas et al. (2000) observed the same behavior of MSW in Torcy landfill, France. They reported a shearing angle of 29.6º and cohesion 23.4 kPa at 180 mm displacement. They have concluded that the shearing strength is greatly influenced by the presence of plastics content in the sample, and the shearing strength is less for the specimen with more plastic content.

According to Landva and Clark (1990), the concept of a linear relationship between shear strength and normal stress, as applied to conventional soils, cannot be applied to highly compressible MSW. Vilar and Carvalho (2002) reported a decrease in volumetric strain with an increase in confining stress. Taking into account this peculiar stress-strain behavior the authors concluded that the shear strength parameters based on Mohr-Coulomb criteria can only be determined if they are referred to some value of strain.

Vilar and Carvalho (2004) conducted consolidated undrained (CU) tests on a 15 year old saturated sample from Bandeirantes Sanitary Landfill, Sao Paulo, Brazil. From their test they found that the pore water pressures increased with strain until a maximum, and then it remained constant as strain increased. They also found a large angle of shearing strength than those measured in CD tests. For example, at 10% strain, they reported a friction angle of 29º, while in the CD test their corresponding value was 20º. Similarly, at 30%strain, their friction angle reached 57º, the corresponding CD value was 26º. Based on this observation the authors concluded that the effective stress-shear strength parameters from CU tests were misleading and did not agree with the parameters from CD tests, hence care must be exerted when trying to derive effective stress parameters from CU tests until more data are available. Vilar and Carvalho (2004) also tried to relate the undrained shear strength to effective confining pressure, as shown in Figure 2.9. Based on this observation the authors concluded that the undrained shear strength of MSW was proportional to the effective confining pressure and the relationship between these variables was larger than that usually observed in soils.

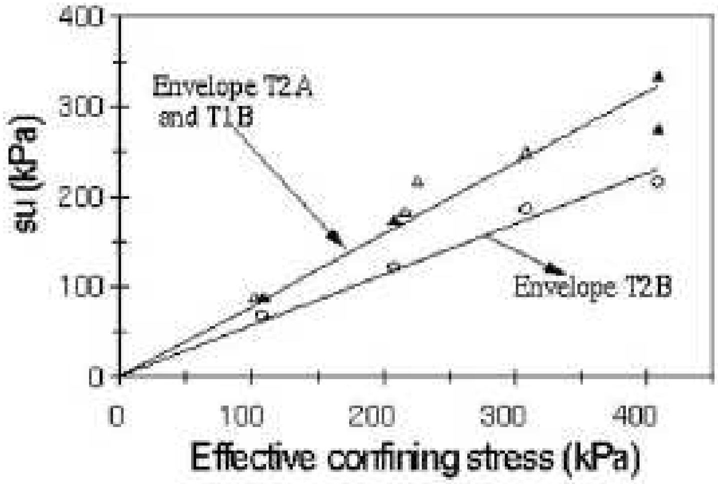


Figure 2.9 Relationship between undrained shear strength and effective confining pressure (Vilar and Carvalho, 2004).

Gabr and Valero (1995) conducted CU tests on reconstituted specimens having dry unit weight from 7.4 to 8.2 kN/m^3. They reported a decrease in cohesion values from 100 kPa at a water content of 55% to 40 kPa at 72%. The authors measured the water content at the end of the shearing stage of each CU test. Their results are shown in Figure 2.10. Additionally, at 20% strain level the authors had reported effective strength parameters of 34º for friction angle, and 16.8 kPa for cohesion. However the authors didn't report the CD shear strength parameters at any of the strain levels.

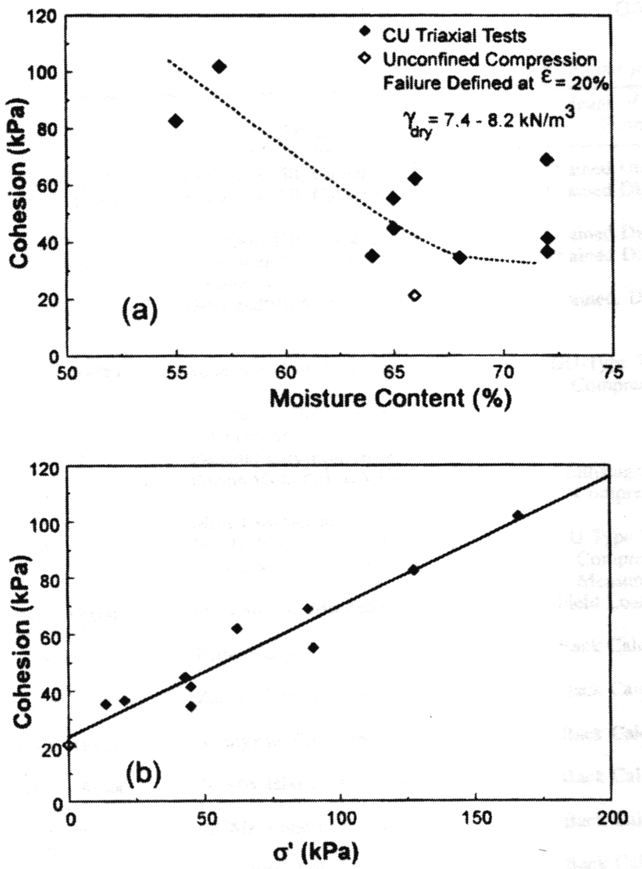


Figure 2.10 Variation of undrained cohesion: (a) as a function of moisture content, and (b) as a function of effective stress prior to shearing (Gabr and Valero, 1995).

2.4.2.1 Effect of Decomposition on Shear Strength

The shear strength parameters are dependent on variables such as age, composition, and moisture content of the waste. Hossain (2002) estimated the shear strength parameters based on the degree of decomposition using direct shear test. The author correlated the age of the waste to the ratio of (C+H)/L. Hossain (2002) found that at the initial stage of decomposition, when (C+H)/L ratio is 1.29 the friction angle was 32º. However at a fully decomposed state (i.e., when (C+H)/L is 0.25) the friction angle was 24º. The friction angle at different stage of decomposition is presented in Figure

2.11. From this observation the author concluded that the shearing strength decreases with decomposition.

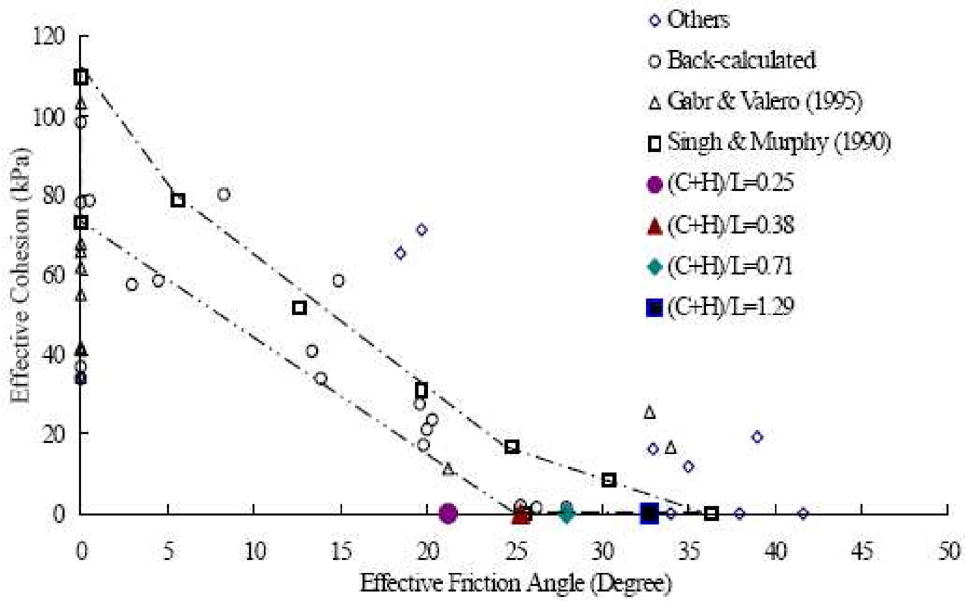


Figure 2.11 Rate of change in friction angle at different stage of decomposition (Hossain, 2002)

Landva and Clark (1986) estimated the drained shear strength parameters for old refuse sample. The authors reported a friction angles ranging from 38º to 42º and cohesion ranging from 16 to 19 kPa. The authors then stored the samples in plastic containers for one year. They found that the friction angle decreased to 33º after one year. The authors believed that the reduction in strength was due to decomposition. However, they did not have enough data to validate their results.

2.4.2.2 Effect of Displacement on Shear Strength

The increase in shear strength with displacement in MSW was observed by Gabr et al. (1995), Kavazanjian (2001); Pelky et al. (2001); Thomas et al. (2001); and Hossain (2002). Hossain (2002) reported an increase in shear strength with displacement for all the decomposition phases as shown in Figure 2.12. The author's mobilized friction angles increased from 13º at 2mm displacement to 24º at 10mm displacement at (C+H)/L of 0.25. Kavazanjian (2001) reported a friction angle of approximately 39º at a shear deformation of 25 mm for the waste from OII landfill in a 450 mm diameter shear box.

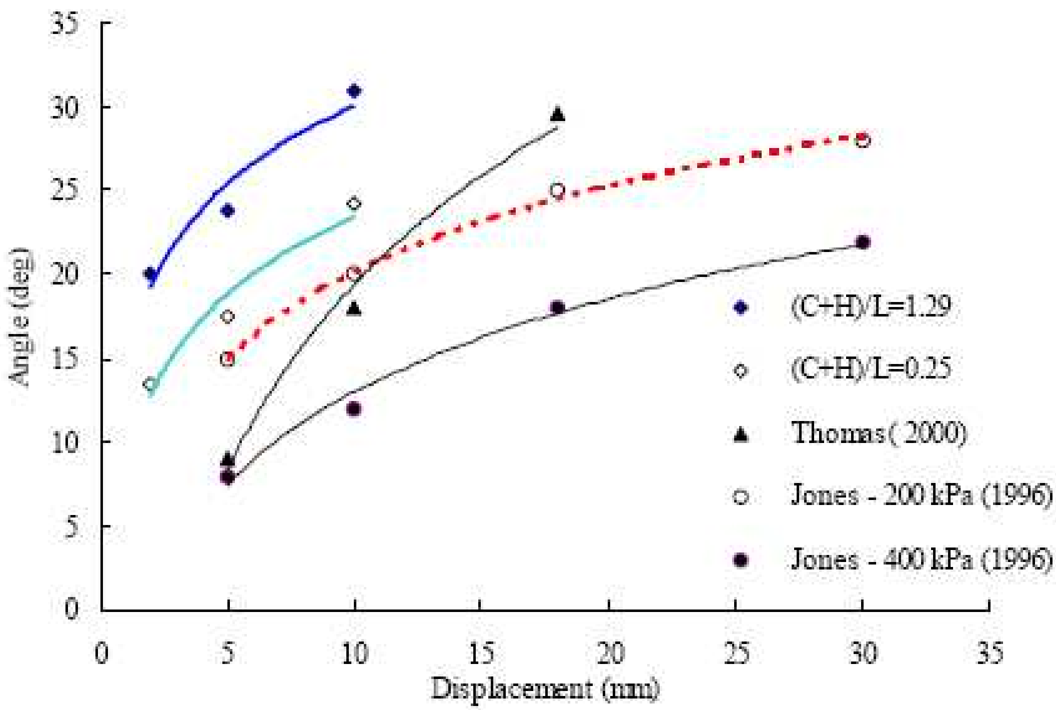


Figure 2.12 Increase in shear strength with displacement for all the decomposition phases (Hossain, 2002)

2.4.3 Dynamic Properties of MSW

In order to analyze the engineering behavior of refuse material to dynamic loadings it is essential to determine its dynamic modulus, poisons ratio, and strength. The shear modulus (G) is a key material property in the evaluation of dynamic response of MSW, since it relates shear stresses to shear strains. The dynamic shear modulus, modulus of elasticity, and poisons ratio can be estimated from its mass density and shear wave velocity. The shear modulus is simply related to the velocity of shear waves, hence measurements of shear wave velocity provides a convenient method for measuring stiffness An important advantage of the shear wave velocity is that the ground water level does not affect the measurements (Massarsch, 1998). The combination of shear wave and compression wave velocities are used to determine the poisons ratio (Sharma et al, 1990):

The dynamic properties of MSW landfills are highly site specific. However, most of the studies had revealed an increasing profile of shear wave velocity with depth of the landfill. Kavazanjian et al. (1996) measured the shear wave velocity profiles from six southern California MSW landfills. Figure 2.13 shows their shear wave velocity profile measured using a combination of Spectral Analysis of Surface Waves (SASW) and Continuous Surface Wave (CSW) techniques. Their values ranged from 80 m/s near the surface to 300 m/s at a depth of 30 m.

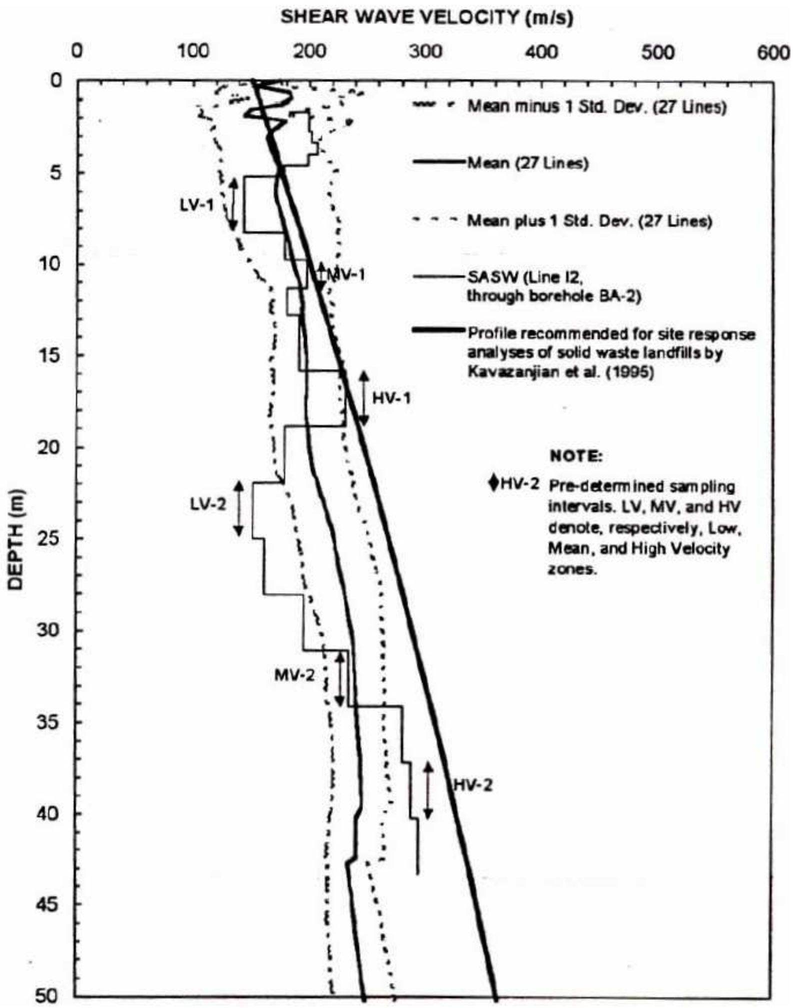


Figure 2.13 Shear wave velocity profile measured using surface wave testing from six southern Californian landfills (Kavazanjian et al., 1996).

Sharma et al. (1990) studied the characteristics of San Pablo Bay landfill, Richmond, California, and reported an average shear wave velocity of 198.3 m/s at a depth of 15.3 m. This value is within the range of recommended values by Kavazanjian et al. (1996). Carey et al. (1993) reported a shear wave velocity ranging between 185 to 478 m/s, though the depth at which these measurements were not reported. Based upon the maximum waste depth and the maximum depth for which the modulus data were reported, Kavazanjian et al. (1995) inferred Carey et al. (1993) shear wave velocity to a depth of between 24 and 37m.

2.4.3.1 Poisson’s Ratio

Matasovic and Kavazanjian (1998) used shear and compressional waves to calculate the Poisson’s ratio. Figure 2.14 shows their observation of Poissons ratio on OII solid waste. Due to the large variations along the profile, the authors adopted an average value of 0.33 for Poisons ratio. Similar value (0.36) of Poissons ratio for MSW was also reported by Abbiss (2001). According to the author this value of Poissons ratio indicates that the landfill was drained, with high permeability, even at dynamic frequencies. The assumption in Poisson’s ratio becomes a factor when it exceeds 0.4 and approaches 0.5, this occurs when the waste approaches saturation, as is the case of bioreactor landfills (Kavazanjian, 2003). Sharma et al. (1990) reported a poisons ratio of 0.49 from his studies on the San Pablo Bay landfill, Richmond, California. This landfill received both solid and liquid waste since 1950.

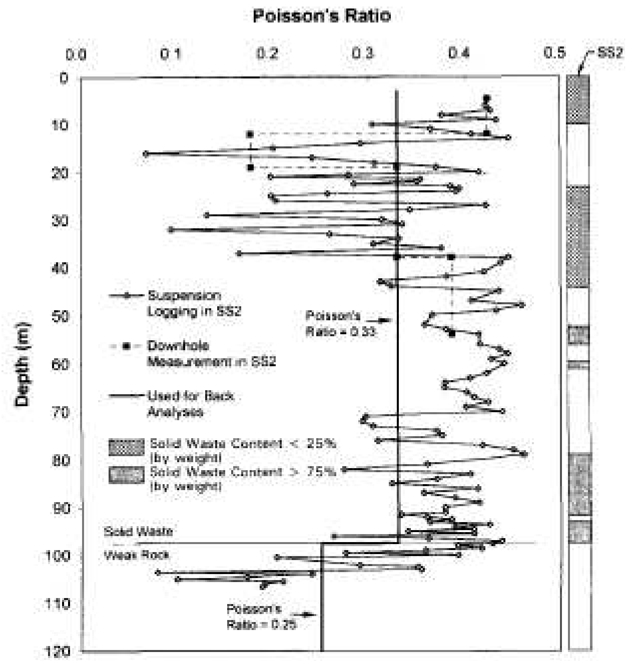


Figure 2.14 Poissons ratio for OII solid waste from in-hole and down-hole test data (Matasovic and Kavazanjian (1998)

2.4.3.2 Modulus Degradation and Damping

Landfills can be subjected to undrained cyclic loads due to earthquakes; the dynamic response under such loads depends to a large extent on the cyclic stress-strain characteristics of the MSW. Until recently, the shear modulus and damping curves developed for peat by Seed and Idriss (1970) was used for landfills. However recent studies suggested that the shear wave velocities of MSW are consistently higher than that of peat. Singh and Murphy (1990) assumed a shear modulus and damping curves to be some where in between that of clay and peat.

Back analysis of ground motion data from the magnitude 6.7 Northridge earthquake yielded invaluable data on strain dependent modulus degradation and damping at OII landfill (Kavazanjian, 2003). Augello et al (1998) developed the strain dependent modulus reduction and damping curves from the back-analysis of MSW dynamic properties from OII landfill in southern California. The authors used to 2D finite element (FE) analysis in two orthogonal horizontal directions using five recorded pairs of earthquake motion, initially six modulus reduction and damping curves, three shear wave velocity profiles, and four values of Poissons ratio. However they have cautioned the use of this curve above a dynamic shear strain of 0.2%. This is because the maximum shear strain induced by those earthquake events were on the order of 0.15%.

Matasovic and Kavazanjian (1998) used the 2D equivalent linear time domain response analysis to perform the back analysis. Based on their results the authors concluded that the back analysis indicated only a little modulus degradation within the waste for cyclic shear stains up to 0.08%. Therefore, laboratory testing of reconstituted samples was required to provide information on the large strain cyclic behavior of the OII waste mass. Matasovic and Kavazanjian (1998) conducted cyclic direct simple shear (CyDSS) on samples from OII landfill. The authors have also plotted their results from the direct simple shear (DSS). They have concluded that both the static and cyclic tests showed no understandable trends with respect to the waste composition. Figure 2.15 shows their strain dependent modulus degradation and damping curves for the solid waste at OII as determined from back analysis of Northridge earthquake ground motions recorded at OII combined with large scale cyclic laboratory tests on reconstituted specimens of MSW.

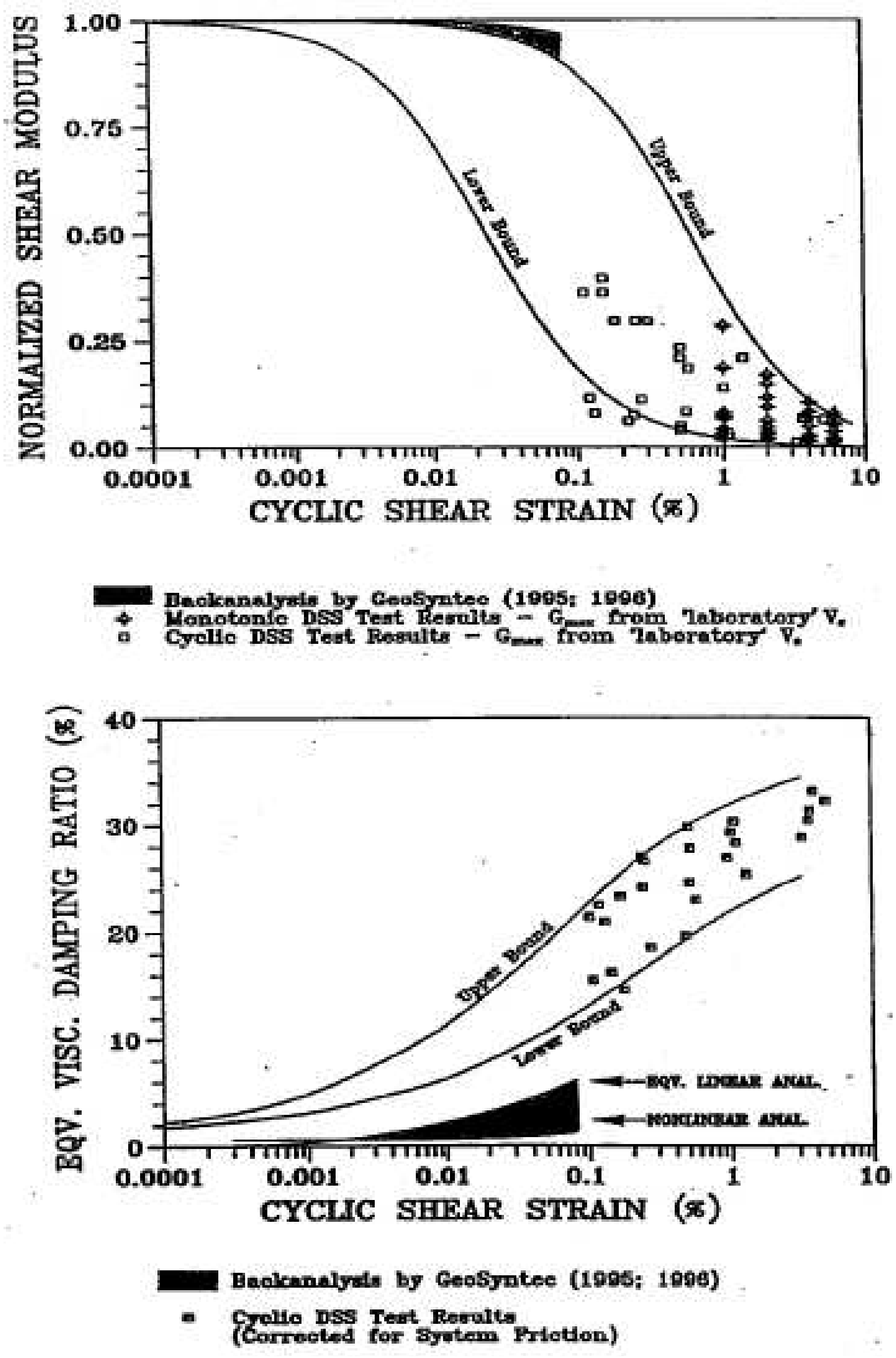


Figure 2.15 Strain dependent modulus degradation and damping curves for the solid waste at OII as determined from back analysis (Matasovic and Kavazanjian, 1998)

2.4.4 Back Calculation of Dynamic Properties

Back analyses are usually performed to develop the strain dependent modulus reduction and damping curves. Computer programs are used to develop this relationship using either one-dimensional (1D) non-linear analyses or a two-dimensional (2D) finite element (FE) analyses. Augello et al., (1998) performed a 2D FE analyses and examined the variations of shear wave velocity (V_s), unit weight (γ) and poisons ratio (υ). The authors have developed a set of shear modulus and damping curves which are intermediate between the clay PI = 30 and 100 at smaller strains and closer to PI = 30 curves at larger strain. Matasovic and Kavazanjian (1998) used the 2D equivalent linear time domain response analysis to perform the back analysis. Based on their results from back analysis, the authors developed modulus degradation and damping curves for the waste cyclic shear stains up to 0.08%.

2.4.5 Laboratory Determination of Dynamic Properties

Some of the commonly used laboratory procedures to evaluate the dynamic properties of solid waste are cyclic triaxial compression, cyclic simple shear, and resonant column tests. The principle, advantages, and disadvantages of some of the laboratory techniques are provided in the following Table 2.5, this is adapted in part from Sharma et al (1990).

Table 2.5 Description of some of the laboratory techniques are provided (Sharma et al, 1990).

Technique	Shear strain range	Description
Cyclic triaxial compression	10^{-3} - 1%	• Damping ratio is strain controlled It cannot measure shear modulus directly. • The major disadvantage of this test is that it doesn't simulate the field condition adequately. During actual earthquake loading, there is a cyclic reorientation of the principle stress direction through some angle relative to its initial position, while in the laboratory triaxial compression test; the major principle stress can act only in their vertical or horizontal directions. • The triaxial compression test apparatus cannot simulate plane-strain conditions which represent the actual field conditions.
Cyclic simple shear	10^{-3} - 5%	• They are more representative of field condition since specimens can be consolidated at K_o condition. • Wide range of strain amplitude can be conducted. • Pore water pressure can be measured at the boundary. • The simple shear test apparatus is preferred over the triaxial test apparatus.
Resonant column	10^{-5}%-10^{-3}%	• One of the most reliable and pragmatic test methods used for testing shear modulus (G) and material damping (D) of soils. • Analysis of resonant column tests is based on the assumption that the behavior of the soil is linear and elastic; analysis of the test data is strictly valid only in the region of very small-strain (Isenhower, 1979). • The difficulty with the resonant column test is that both driving apparatus used for the excitation of the soil specimen and motion monitoring instruments must be attached to the soil specimen. This alters the specimen boundary conditions so that the interpretation of the test is based on the assumption that the attachments are lumped into a mass which oscillates with the soil specimen.

2.5 Slope Stability Analysis

Stability analyses of landfills is one of the major tasks for landfill design and operation. Many of the landfills are located in the vicinity of highly populated areas, this increases the potential hazard associated with the slope failure of a municipal solid waste (MSW) landfill. Recently several heavy landslide events have occurred due to landfill failure (Kolsch and Ziehmann, 2004). The failure of Payatas landfill, Philippines in July 2000, Ano Liossia landfill, Greece in March 2003, and the most recent Leuwigajah dumpsite, Bandung, Indonesia in February 2005 increased the concern for landfill stability. Slope stability analysis performed using the solid waste properties from failed slopes, indicated that the reduction in waste strength properties as a reason for failure in most cases. Kolsch and Ziehmann (2004) carried out stability analysis by classic polygon sliding method (according to German DIN 4084), using waste properties estimated from lab testing results on Ihlenberg landfill waste in Germany. From the analysis, the authors found that the most unfavorable slip body was at the toe of the slope, where the solid waste properties used was typical of a decomposed or old refuse. Bogner et al. (2001) indicated that reductions in the shear strength of the waste, resulting from higher moisture contents, can significantly lower factors of safety for the waste and liner slopes during and after waste placement. Kolsch et al. (2005) conducted forensic analysis on failed Leuwigajah dumpsite, Bandung, Indonesia. Based on their results from the stability analysis on Leuwigajah dumpsite, they have concluded that the failure was due to the reduction in reinforcement particles due to smoldering landfill fire.

2.5.1 Seismic Stability Analysis

Substantial interest towards the analysis of seismic stability of landfills had been focused more recently. RCRA subtitle D regulations require that new landfills designed in seismic impact zones should resist maximum horizontal ground acceleration, with a 90 % probability that the selected acceleration will not be exceed in 250 years (Oweis and Khera, 1998). Seismic impact zones are defined by the U. S. Environmental Protection Agency (EPA) as areas with a 10% or greater probability that the maximum horizontal acceleration in lithified material will exceed 0.1 g in 250 yr (Bray et al., 1995). It can be observed from Figure 2.16 (Bray et al. 1995) that about 50 percent of the continental US are encompassed by this seismic impact zone. US EPA (2003) recommended factor of safety's to be used in solid waste landfills to be in the range of 1.2 to 1.7.

Seismic stability of solid waste landfills depends primarily on input ground motion, dynamic response characteristics, and strength characteristic. The input ground motion is characterized by three factors namely intensity, duration, and frequency (Rathje, 1997). The intensity (i.e., MHA) is predicted from an attenuation relationship, given the sites distance away from the fault generating a certain magnitude of earthquake (Bray et al., 1995). Similarly the duration is also related by the distance and magnitude. The frequency content of the input ground motion is controlled by the magnitude of earthquake, distance from the rupture plane and the site conditions. All these parameters are well documented by various researchers (Idriss 1995; Rathje 1997; Bray et al, 1995).

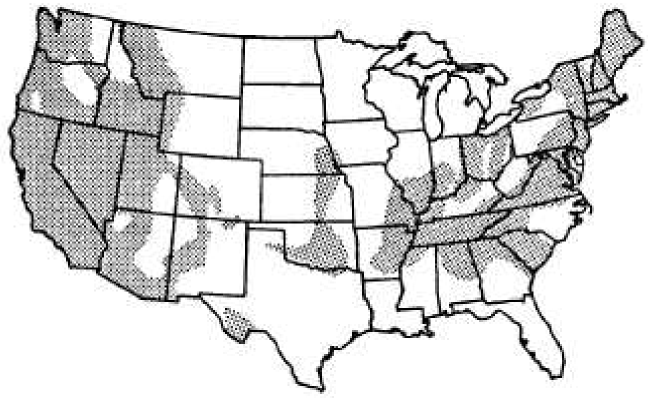


Figure 2.16 Seismic impact zones (Bray et al., 1995)

2.5.2 Recent Findings on Stability of Bioreactors Landfills

Bogner et al. (2001) developed a laboratory scale controlled decomposition bioreactor to study the dynamic changes occurring during accelerated decomposition. They analyzed the stability of slopes using the two-dimensional limit equilibrium analysis program PCSTABL4 developed by Lovell et al. (1983). Their result shows that the factor of safety reduces proportionally to the reduction in shear strength, and there was a significant reduction in shear strength due to the increase in moisture content. From their observation they have concluded that due to the reduced stiffness of the waste a significant increase in shear stress and shear displacement within the liner system was produced. However, the authors didn't determine the reduction in shear strength using any laboratory techniques. Their assumption was based on the existing studies made by Lamb and Whitman (1969) on clay and organic soils, where a 50 percent reduction in shear strength was reported possible due to the increased moisture content.

CHAPTER 3

MATERIALS AND METHODS

3.1 Introduction

Municipal solid waste (MSW) samples were collected from a transfer station in Burlington, Texas. The collected MSW was used to generate samples representing different stages of decomposition in a laboratory scale bioreactor. In this chapter a brief description on refuse collection, sample preparation for geotechnical testing, testing procedure, and stability modeling is presented.

3.2 Fresh Refuse Collection

Municipal solid waste (MSW) samples were collected from a transfer station in Burlington, Texas. Standard collection procedure was followed for obtaining a representative well mixed sample. Collected waste was placed on a platform and thoroughly mixed for several times. The refuse pile was then divided it into four parts as shown in Figure 3.1. One part was selected from this pile and three parts were discarded. The selected part of refuse pile was again mixed thoroughly, and divided into four parts. From this pile again one part was selected and the remaining three parts were discarded. The selected refuse pile was then filled into fourteen 3-mil thick plastic bags. The collected refuse from the transfer station in Burlington, Texas is presented in

Figure 3.2. The bags were then transported to the environmental engineering laboratory at UTA and stored at 4°C until the reactors were filled.

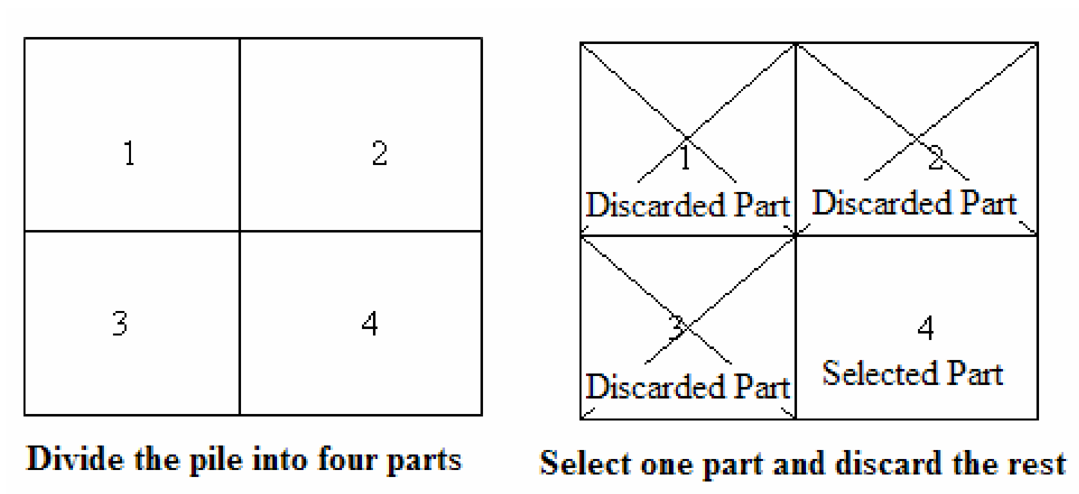


Figure 3.1 Procedure followed in fresh MSW collection

Figure 3.2 Collected MSW from a Transfer Station in Burlington, Texas

3.3 Characterization of Fresh Refuse

The collected waste sample was physically characterized before filling the reactors. The characterization includes visual inspection of refuse composition, weight percentage of each constituent, moisture content and volatile solids content determination. Weight percentages of MSW components present in each of the collected bag is presented in Figure 3.3. Paper constituted the major portion of MSW in all the bags. Paper constituted about 56% by weight of the total MSW. Food waste was about 13% by weight of the collected MSW. The average weight percentage plastic, textile, metal and glass are 16, 5, 3 and 6%, respectively. The average value of each of the constituent present in MSW is presented in Table 3.1. These values were within typical physical composition of residential MSW reported by Tchobanoglous et al. (1977). Similarly the physical volume composition of each of the constituent in MSW was also determined (Figure 3.4). The average volume percentage of textile, paper, plastic, food, and tin was 0.5, 50, 41, 4, 3, and 1.5 %, respectively. Volatile solids content (VOC) is often used as a measure of the biodegradability of the organic fraction of MSW. The percentages of VOC are presented in Figure 3.5.

Paper is the major degradable component in MSW and plastic is the major non-degradable component. Both paper and plastic has a significant impact on waste geotechnical characteristics (Gabr et al., 2007).

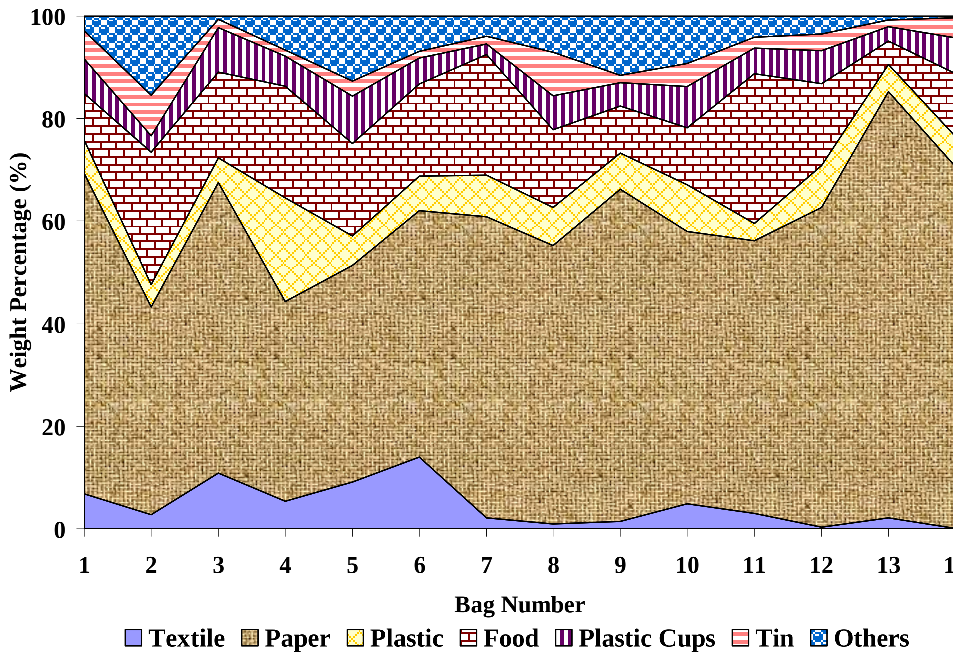


Figure 3.3 Weight percentages of MSW components in each bag

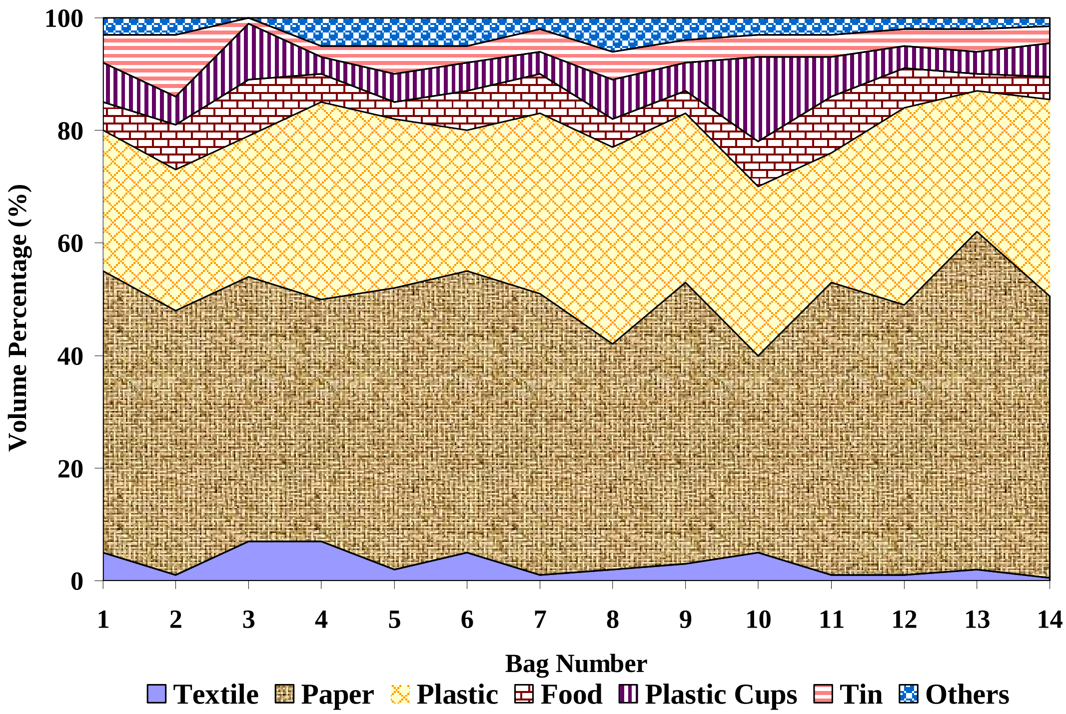


Figure 3.4 Volume percentages of MSW components in each bag

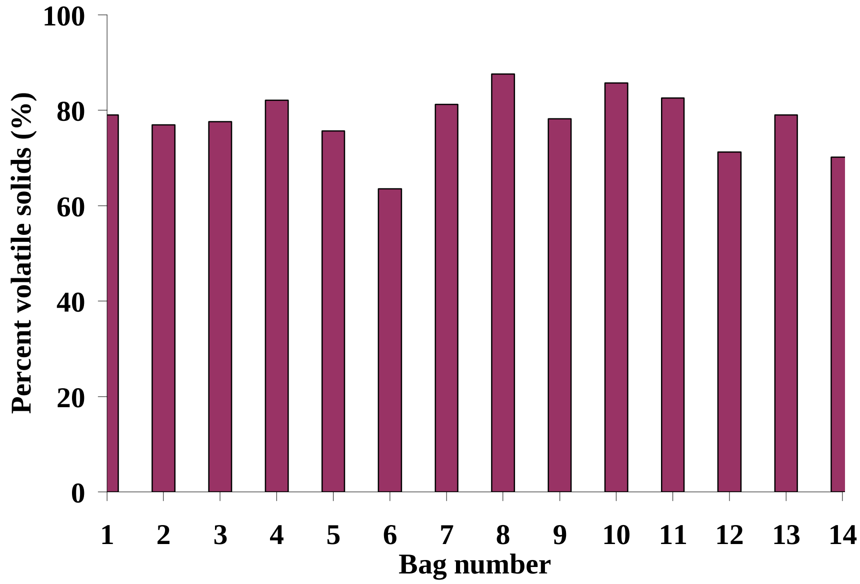


Figure 3.5 Percent volatile solids of MSW in each bag

Table 3.1 Comparison between typical and observed physical composition of residential MSW

MSW constituents	Typical MSW composition reported by Tchobanoglous et al. (1993)	MSW from Burlington transfer station
Wood	1-4	-
Paper/Cardboard	28-50	56
Plastic/Rubber	4-12	13
Textile	0-4	5
Metal	3-13	3
Glass	4-12	6
Dirt, ash, etc.	0-6	-
Food	6-18	16
Yard wastes	5-20	1

3.4 Reactor Building

Two sets of bioreactor cells were built in the laboratory as shown in Figure 3.6. Each set consists of four 16-gallon reactors to prepare samples at different stages of decomposition. The first sets of reactors were set up without soil, and the second sets of reactors were set with soil to simulate the intermediate covers. Before filling the reactors, each of the reactors was tested for leak as shown in Figure 3.7. The reactor was placed in its place and all the tubes leading to gas and leachate bags were connected. The leak test was conducted using a U-tube Manometer after sealing the reactor using O-ring and silicone sealant. To verify that the connector is not leaking, the head difference in Manometer was monitored for 48 hours. The initial and final head was recorded to verify the leak in the system. Results from the leak test indicated that the maximum head difference at the end of 12 hr was 0.5 in. of H_2O, and at the end of 48 hr was 3 in. of H_2O, these values were within the permissible limit.

Figure 3.6 Two sets of bioreactor cells with and without soil representing the four phases of decomposition

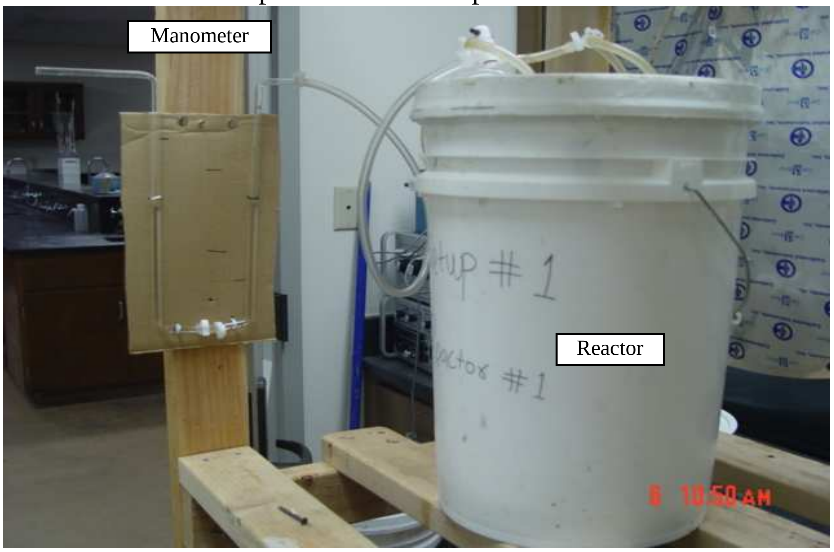


Figure 3.7 Leak test conducted on reactors

Once the leak test was completed in the reactors, their empty weight was measured. Prior filling the reactors, glass, tin and hard plastic bottles were removed and the refuse was thoroughly mixed. The reactors were then filled in equally distributed layers up to the marked volume with fresh refuse. The MSW was compacted by hand during filling operation. The steps involved during reactor filling operation are shown in Figure 3.8. In the second set of reactors intermediate soil layers were added to simulate the intermediate covers in landfills. The amount of soil to be added was calculated based on actual field data. The reactors were then numbered and weighed.

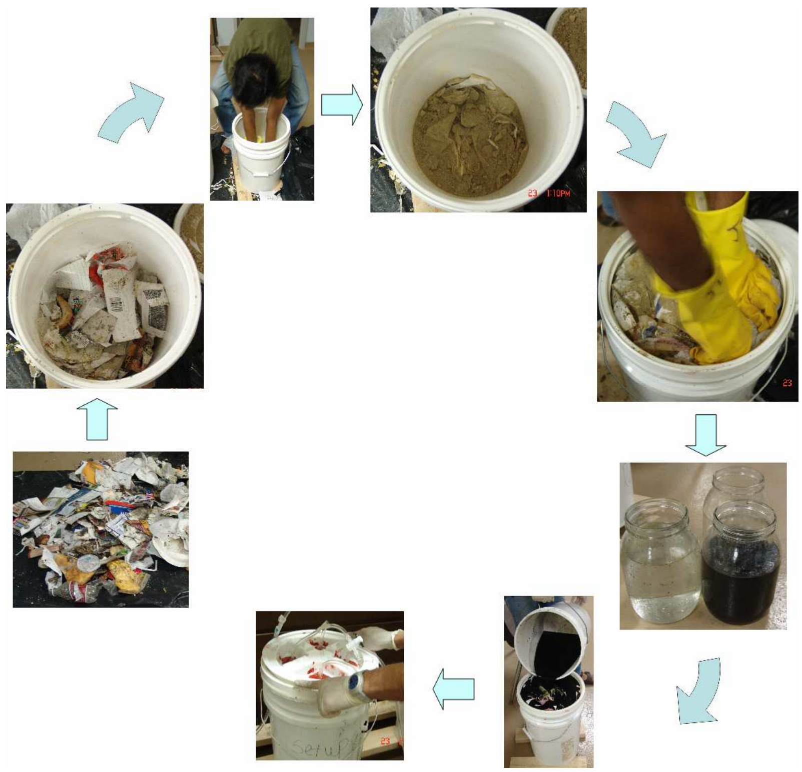


Figure 3.8 Steps involved during reactor filling operation

Reactors were operated under conditions designated to simulate a bioreactor, including: (a) the addition of sufficient moisture to induce leachate production; (b) leachate recirculation; and (c) the addition of an inoculum of anerobically digested sewage sludge. Therefore, sufficient quantity of deionized water and anaerobic digested sludge was added to produce 1500 ml of leachate to circulate daily. Quantity of moisture required to bring the sample to the optimum moisture is calculated based on the initial moisture content and wet weight of the sample filled in the reactor. Based on the initial moisture content, water was added to adjust the moisture content to 55% (wet weight basis), and to generate a leachate of 1.5 L. The reactors were then sealed, connected to gas & leachate bags and placed on their respective stand. The reactors were operated at a temperature of between 25 – 29 °C.

3.5 Sample Generation

Municipal solid waste (MSW) at different stages of degradation was generated in eight 16-gallon laboratory scale bioreactors with leachate recirculation, and under controlled conditions. A complete layout of a reactor under operation is shown in Figure 3.9. Each set of reactor consists of four 16-gallon reactors to generate samples at different stages of decomposition. At each phase of decomposition, (i.e., the anaerobic acidogenic phase, the accelerated methanogenic phase, and in the early and late decelerated methanogenic phase) the reactors were gently dismantled and destructively sampled. The stage of decomposition was determined from its gas generation, pH, and volatile solids composition. The procedure followed for estimating pH, gas generation, and volatile solids composition is discussed in the following sections.

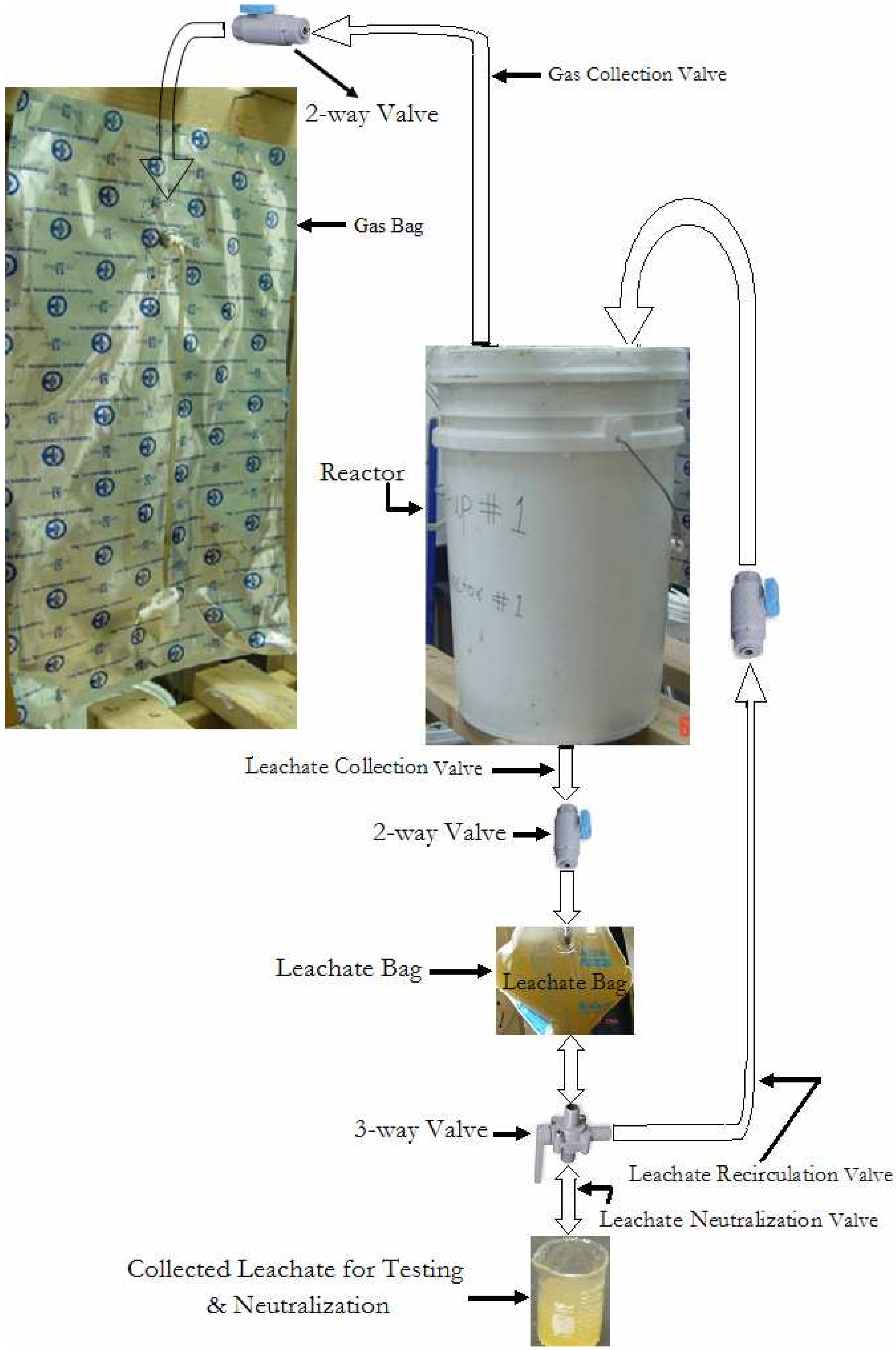


Figure 3.9 Layout of a reactor under operation

3.5.1 Leachate pH Measurement, Neutralization, and Recirculation

The degradation of MSW was accelerated by neutralization and recirculation of generated leachate. The generated leachate in the leachate collection bags were re-circulated on a daily basis. Loss in the quantity of leachate was compensated with the addition of deionized water. Before re-circulating, the leachate was neutralized with potassium hydroxide or sulfuric acid for acidic and alkaline conditions as necessary and recycled 4 days a week. The step by step process followed in pH measurement, and leachate neutralization and recirculation is shown in Figure 3.10.

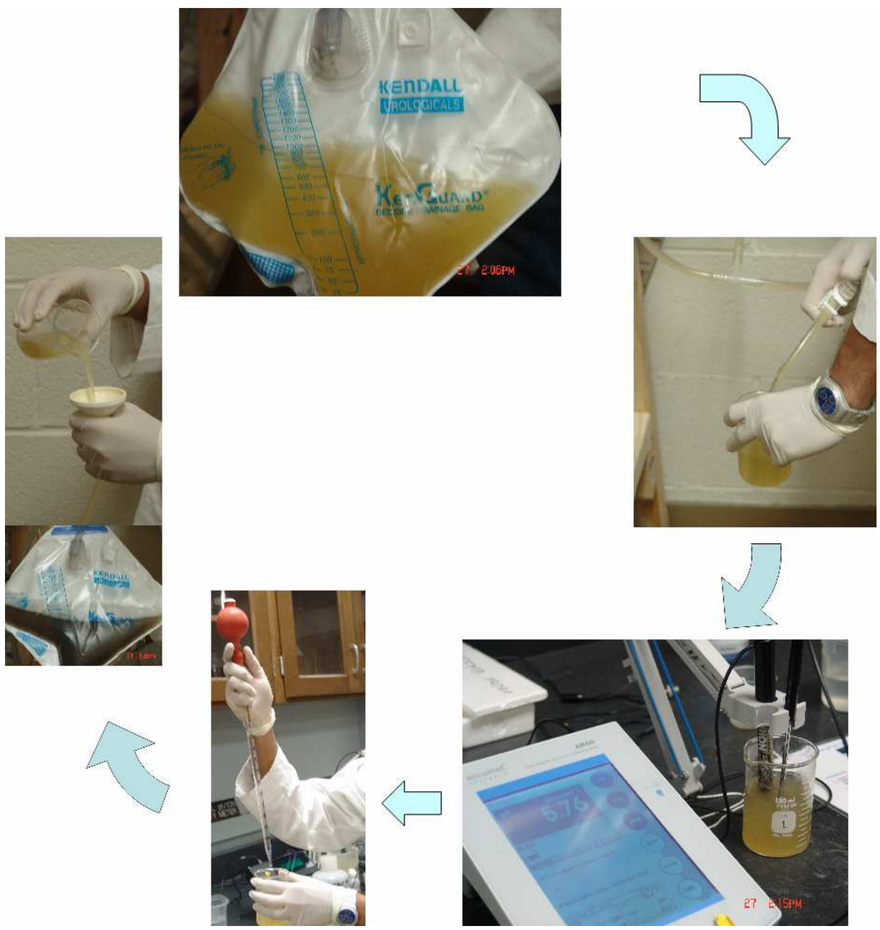


Figure 3.10 Leachate pH measurement, neutralization, and re-circulation

3.5.2 Gas Concentration and Volume Measurement

Gas was collected in five-layer gas bags and the volume was measured by pumping it out through a standard SKC air sampler, which pumps at a rate of 0.5 L/min. The Grab Air Sampler is a hand-held battery-operated sample pump designed to pump at a rate of 0.5 L/min efficiently and reliably. The SKC grab air sample pump is recommended for sample bags up to 10 liters. Methane gas concentration was measured using a gas chromatograph equipped with a thermal conductivity detector. The Model 8610C Gas Chromatograph used in this study is one of the most versatile and popular model. The 8610C can control up to 16 heated zones, three gas sampling valves, and up to six detectors. The thermal conductivity (TCD) detector used in the chromatograph consists of an electrically-heated wire. The temperature of the sensing element depends on the thermal conductivity of the gas flowing around it. Changes in thermal conductivity, such as when organic molecules displace some of the carrier gas, cause a temperature rise in the element which is sensed as a change in resistance. Measurement of gas composition and its volume measurement using gas chromatograph and SKC air sampler are shown in Figure 3.11.

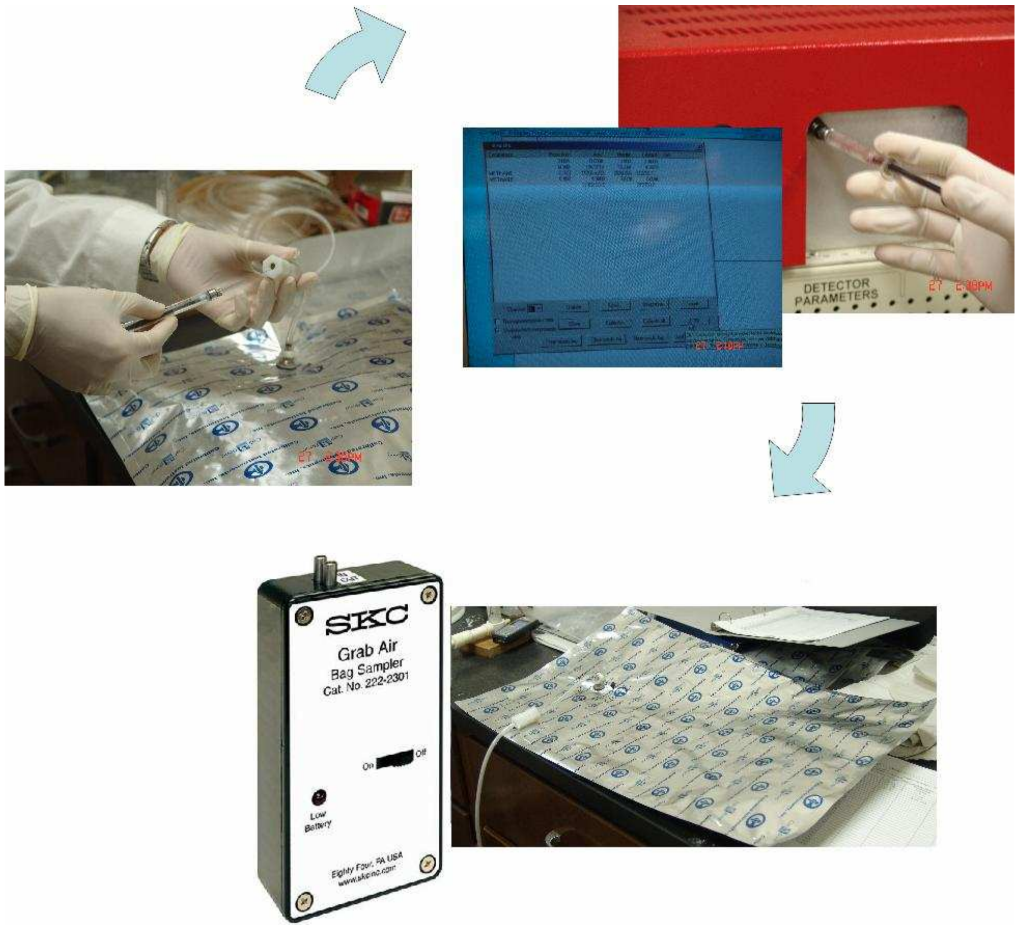


Figure 3.11 Gas composition and volume measurement

3.5.3 Volatile Solids Determination

The volatile solids were determined in accordance with Standard Methods APHA Method 2440-E. Samples were dried at 105 ˚C to a constant weight and held in a desiccator. Approximately 100 grams of this dried sample were then placed in ceramic dish and inserted into a muffle furnace at 550°C for 20 minutes. Samples were removed and allowed to cool in a desiccator to a constant weight. The percent weight loss from ignition yielded the total amount of volatile matter. The muffle furnace and solid waste samples used for determining the volatile solids is shown in Figure 3.12.

Figure 3.12 Volatile solids determining

3.5.4 Moisture Content

Moisture content of the samples on both dry and wet weight basis was determined in accordance with Standard Method 2540B. Samples were dried at 105 ˚C to a constant weight and held in a desiccator (Figure 3.13). Moisture content is determined by weight loss from the original sample and expressed as a percent.

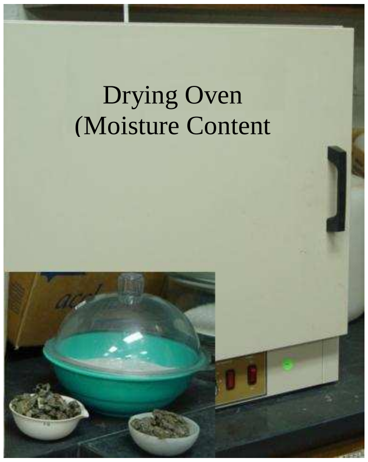


Figure 3.13 Moisture content determinations

3.6 Geotechnical Testing Program

Determination of engineering properties in MSW is difficult due to the heterogeneity of particles. An experimental program was developed to determine the engineering properties. The following sections present a brief description of different test procedures adopted in the current study. Some of the important tests performed are particle size analysis, CD triaxial test, and resonant column test. The tests were conducted in accordance with ASTM standards (Table 3.2). The procedure followed in remolding the specimen for CD triaxial test and resonant column test is also presented.

Table 3.2 Geotechnical test conducted on bioreactor waste

Test Method	Material	Variables	No. of Tests
Grain Size Distribution	Cover Soil	-	1
	MSW	4 phases	8
Moisture Content	MSW	4 phases	12
Triaxial (CD)	MSW	4 phases & 3 confinements (10, 20 and 30 psi)	12
	MSW + 20% Soil	2 setup, 4 phases & 3 confinements (10, 20 and 30 psi)	24
	MSW + 30% Soil	4 phases & 3 confinements (10, 20 and 30 psi)	12
Resonant Column	MSW	4 phases & 3 confinements (10, 20 and 30 psi)	8
	MSW + 20% Soil	4 phases & 3 confinements (10, 20 and 30 psi)	8
	MSW + 30% Soil	4 phases & 3 confinements (10, 20 and 30 psi)	8

3.6.1 Grain Size Distribution

Particle size analysis of MSW was done using wet sieve analysis and hydrometer analysis (Figure 3.14). The samples were prepared in accordance with ASTM D2217 and the analysis was conducted in accordance with ASTM D422-63. The analysis was repeated twice for the samples from each phase of decomposition and the average grain size distribution was plotted.

Two oven dried samples weighing approximately 250 grams from each of the reactors were quartered and washed through US sieve no. 200. The sample retained on #200 sieve was passed trough a series of sieves (1-in, 3/4-in, 3/8-in No.4, No.10, No. 20, No. 40, No. 60, No. 100 and No. 200). The particles retained on each sieve was collected, dried and weighed. The percentage passing through each sieve was then calculated by dividing the weight of sample retained on each sieve to the total weight of the sample. Hydrometer analysis was performed on the fraction passing through US sieve No. 200. The water collected during wet sieving through US sieve No 200 was oven dried to obtain approximately 750ml. The obtained solution was mixed with dispersing, and the mixture was stirred thoroughly. The prepared solution was then transferred to a 1000 mL graduated cylinder, and the test was done in accordance with ASTM D 422-63.

(a) (b)

Figure 3.14 Grain size distribution: (a) Sieve analysis; (b) Hydrometer analysis.

3.6.2 Specimen Preparation for Geotechnical Testing

Samples generated from the bioreactor cell at each phase of decomposition were compacted into a 71 mm diameter and 145 mm tall cylindrical specimens. Particles of length greater than 50 mm are cut into lengths of 50 mm. More than 48 samples were remolded using proctor test (Figure 3.15), and it was done in accordance with ASTM D1557. The samples were compacted in five lifts of 25 blows each using a 10 lb. hammer falling through 18 inches. In addition, in order to study the effect of soils present in solid waste, samples from the first set of reactors (only MSW) were remolded with 20 and 30% of soil. Samples from Setup 2 (reactors with soil) were directly remolded without adding any soil to it, since they already had 20% soil on it.

Figure 3.15 Specimen preparations in accordance with ASTM D1557

3.6.3 Consolidated Drained Triaxial Tests

Triaxial consolidated drained (CD) tests were performed using statically compacted specimens at their natural moisture content. More than 48 tests were conducted to estimate the strength properties at different stages of decomposition. Figure 3.16 shows the sample under test in a CD triaxial setup. The test was performed in conformance with American Society for Testing and Materials (ASTM) Test Method (WK3821). The triaxial compression test is used to measure the shear strength of a soil under controlled drainage conditions. The strain rate adopted was 0.7 mm/min, and the samples were tested at three different confinements (10, 20, and 30 psi), the confinements were applied until the sample consolidated completely, and then the loading was applied.

Figure 3.16 CD triaxial setup with sample

3.6.4 Resonant Column Testing

Resonant column (RC) test was performed in conformance with American Society for Testing and Materials (ASTM) Test Method (D4015) on remolded samples, and is presented in Figure 3.17. More than 24 RC tests were performed on the prepared sample to evaluate their dynamic characteristics. The RC is a device suitable for testing solid or hollow specimens with shearing strain amplitude of up to 0.4%. It is one of the most reliable, efficient, and pragmatic laboratory test methods used for testing shear modulus (G) and material damping (D). Resonant column was designed to be performed at very small-strains ($<10^{-3}$ percent), hence, the low strain shear modulus calculated using laboratory methods is more accurate as well as more reliable than most of the field methods. The MSW samples were tested at three different confinements (10, 20, and 30 psi), with each confinement being applied for at least 24 hours prior to testing. Tests were done at five different voltages (0.25, 0.5, 1, 2, 4, and 5 Vrms) through the driving mechanism to examine the behavior of MSW samples at different shear strain levels.

Figure 3.17 Resonant column test setup with a 71 mm diameter solid waste sample

3.7 Cover Soil

Soils are added into MSW landfills as an intermediate cover layer. Daily cover usually consists of 6 to 12 inches of native soil that are applied to the working face of the landfill at the end of each operating period. This daily cover soil layer mixes with the solid waste layer as time progresses. Typical percentage of cover soil in MSW reported in literature varied between 15 to 30%. Table 3.3 presents the typical composition of MSW with cover soil reported by Vilar & Carvalho (2002), and Gabr & Valero (1995). In addition, the results of physical composition of MSW samples collected from Arlington landfill are also presented. Sample composition results from Arlington landfill, and those reported by Gabr and Valero (1995) had approximately 30% soil. Vilar & Carvalho (2002) reported 10% soil content in their samples; however, they have also indicated that the paste had variable proportions of soil. Therefore based on these observations 20% and 30% cover soil content was selected to be used in the experimental program.

Table 3.3 Typical composition of MSW reported by Vilar & Carvalho (2002), Gabr & Valero (1995), and those from Arlington landfill

MSW constituents	Vilar & Carvalho (2002)	Gabr and Valero (1995)	MSW from Arlington landfill
Wood	4	9	14
Paper	2	2	23
Plastic/Rubber	19	13	6
Textile	3	23	2
Metal	5	10	3
Glass	2	10	16
Stone/Soil	**10**	**33**	**36**
Food	-	0	-
Garden	-	0	-
Paste	**55***	-	-

*Paste includes variable proportions of soil.

The effects of daily cover soil on shear strength and dynamic properties of MSW in bioreactor landfills were analyzed in this study. To study this effect 20% of cover soil by weight was added to a set of reactors. In addition, samples generated from first set of reactors (Only MSW) were also remolded with 20 and 30% soil by weight. Cover soil obtained from Arlington landfill was used for this purpose (Figure 3.18). This soil was classified as well graded sand with silt and gravel. The grain size distribution of the cover soil is presented in Figure 3.19. The soil had 9.52 % of particles passing through US sieve 200. The properties of cover soil are presented in Table 3.3.

Figure 3.18 Cover soil from Arlington landfill

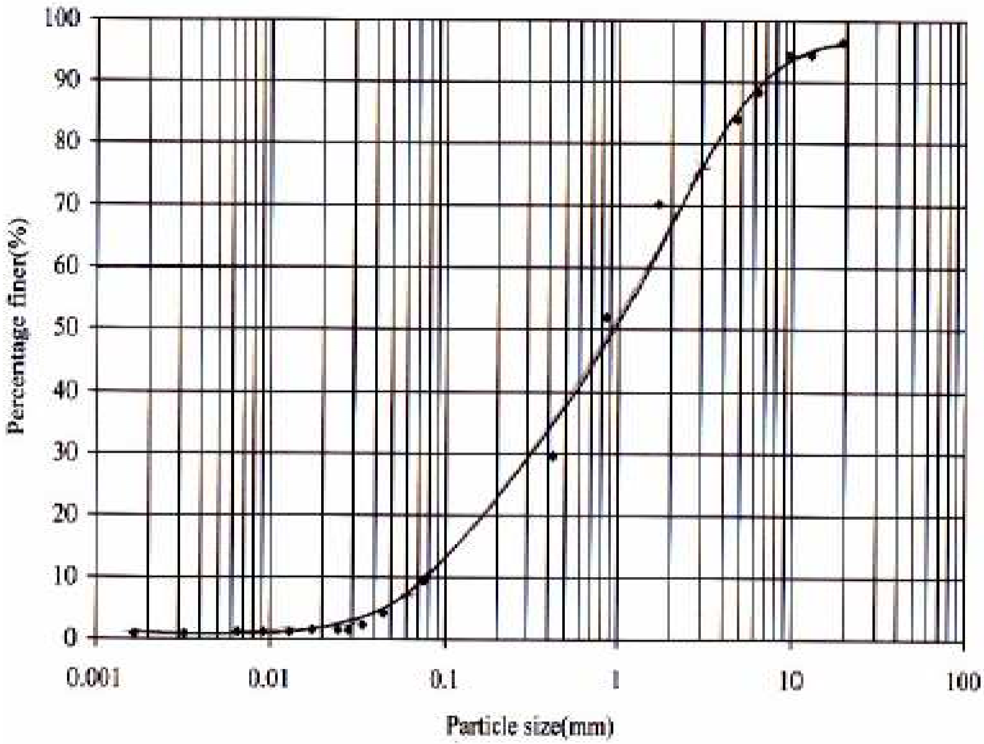


Figure 3.19 Grain size distribution of cover soil

Table 3.4 Properties of Cover soil

Description	Observation
Soil classification	SW-SM
Percent of particles passing through US sieve 200	9.52
Specific gravity	2.52
Coefficient of permeability (cm/s)	0.00081
Density (kg/m^3)	1742

3.8 Notations used

The notation followed in naming the samples is shown in Figure 3.20. The samples from first set of reactors (without soil) are referred to as RS1-I – RS1-IV, and those from second set of reactors are referred to as RS2-20%-I – RS2-20%-IV. Cover soil was also mixed at different percentage with the generated samples from first sets of reactors to study the effect of soil on solid waste shear strength. These samples are referred to as RS1-20%-I – RS1-20%-IV and RS1-30%-I – RS1-30%-IV for samples with 20% and 30% soils, respectively.

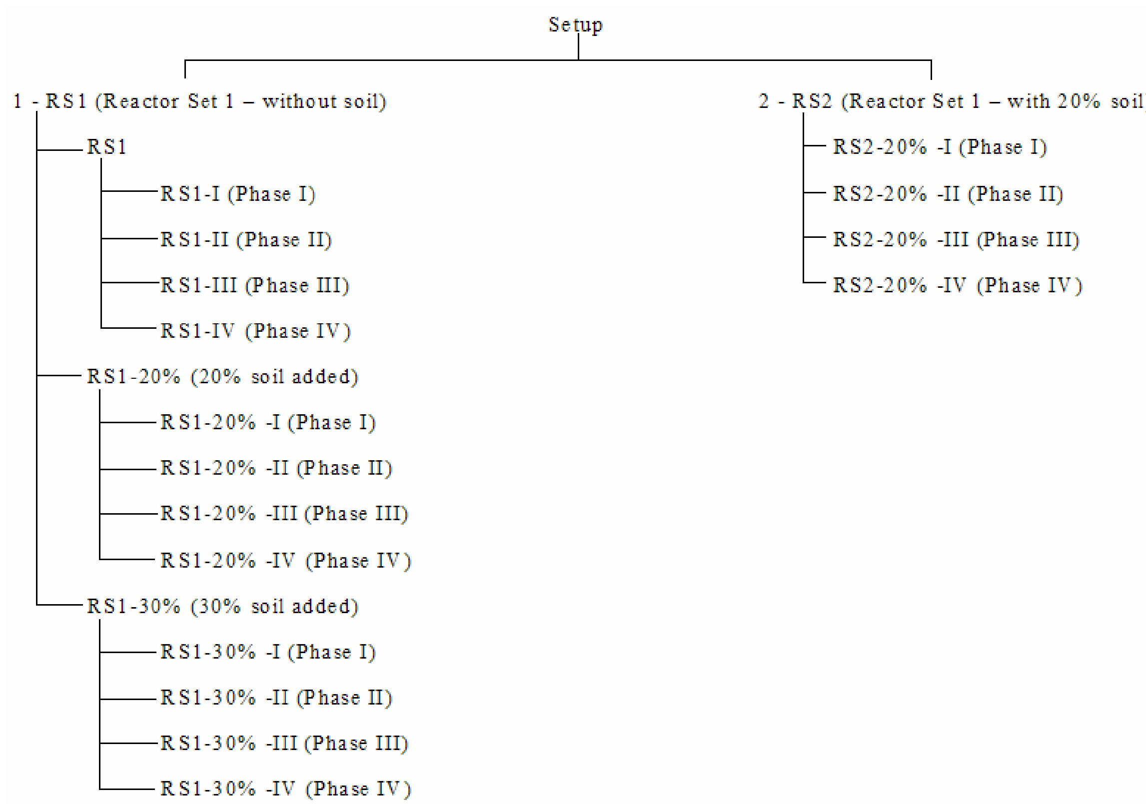


Figure 3.20 Notations used in naming samples

3.9 Slope Stability Analysis

Stability analysis of bioreactor landfills was performed using finite element program PLAXIS and limit equilibrium program GSTABL. PLAXIS V8 is a finite element package intended for the two dimensional analysis of deformation and stability in geotechnical engineering. The simple graphical input procedures enable a quick generation of complex finite element models, and the enhanced output facilities provide a detailed presentation of computational results. The factor of safety for slope stability analysis in PLAXIS was computed using *Phi-c reduction* calculation type at each case of decomposition. The strength parameters are reduced successively in each step until all the steps have been performed. The final step should result in a fully developed failure mechanism, if not the calculation must be repeated with a larger number of additional steps.

GSTABL with STEDwin is a powerful, comprehensive a 2-dimensional, limit equilibrium slope stability program. GSTABL performs all the slope stability analyses calculations, while the STEDwin provides an extremely user-friendly graphical user interface. The following are some of the few advantages of using GSTABL: (1) provides complete force and moment equilibrium; (2) robust search of multiple trial failure surfaces or individual user-specified failure surface. Any shape failure surface, including circular arc, block, wedge, and random, is supported. Up to 20 boxes may be used to generate block surfaces; (3) analysis by Modified Bishop and Simplified Janbu Method of Slices. Circular, random, and sliding block search routines are available for analysis. Use of the Janbu empirical coefficients with the Simplified Janbu method for multiple-surface searches or for a specified single surface; (4) up to 20 isotropic soil options may be included in the analysis; and (5) both a pore pressure ratio (r_u) and a pore pressure constant may be included for any soil.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, refuse decomposition results and the results from geotechnical testing program are presented. The methane production characteristics and solids composition of MSW samples used to evaluate the shear strength and dynamic parameters of MSW are described in the first part of this section, followed by the results from geotechnical testing program. The geotechnical test results include particle size analysis, unit weight, shear strength characteristics, and dynamic properties of MSW samples at each phase of degradation.

4.2 Refuse Decomposition Results

Methane production rates and the pH of the produced leachate are presented in Figure 4.1 and 4.2, respectively. The anaerobic digester sludge and leachate neutralization along with leachate recirculation enhanced the refuse decomposition. Each of these reactors were destructively sampled on days 25, 106, 225, and 253 in Setup 1; and at 22, 92, 167, and 235 days in Setup 2. Based on the methane presented in Figure 4.1 (a), and pH data in Figure 4.1 (b), at day 25 sample was in anaerobic acid phase (Phase I). At day 106, when the rate of methane production was at peak and pH was about neutral, the sample was in accelerated methane production phase (Phase II).

Finally, at days 225 and 253, the samples were in decelerated methane production (Phase III) and complete stabilization phases (Phase IV), respectively. Similarly for the second set (Setup 2) of reactors, samples at days 22, 92, 167, and 235 were at Phase I, II, III & IV stages of decomposition, respectively, and the results are presented in Figure 4.2. The methane production rates in reactors at different decomposition phases are presented in Table 4.1.

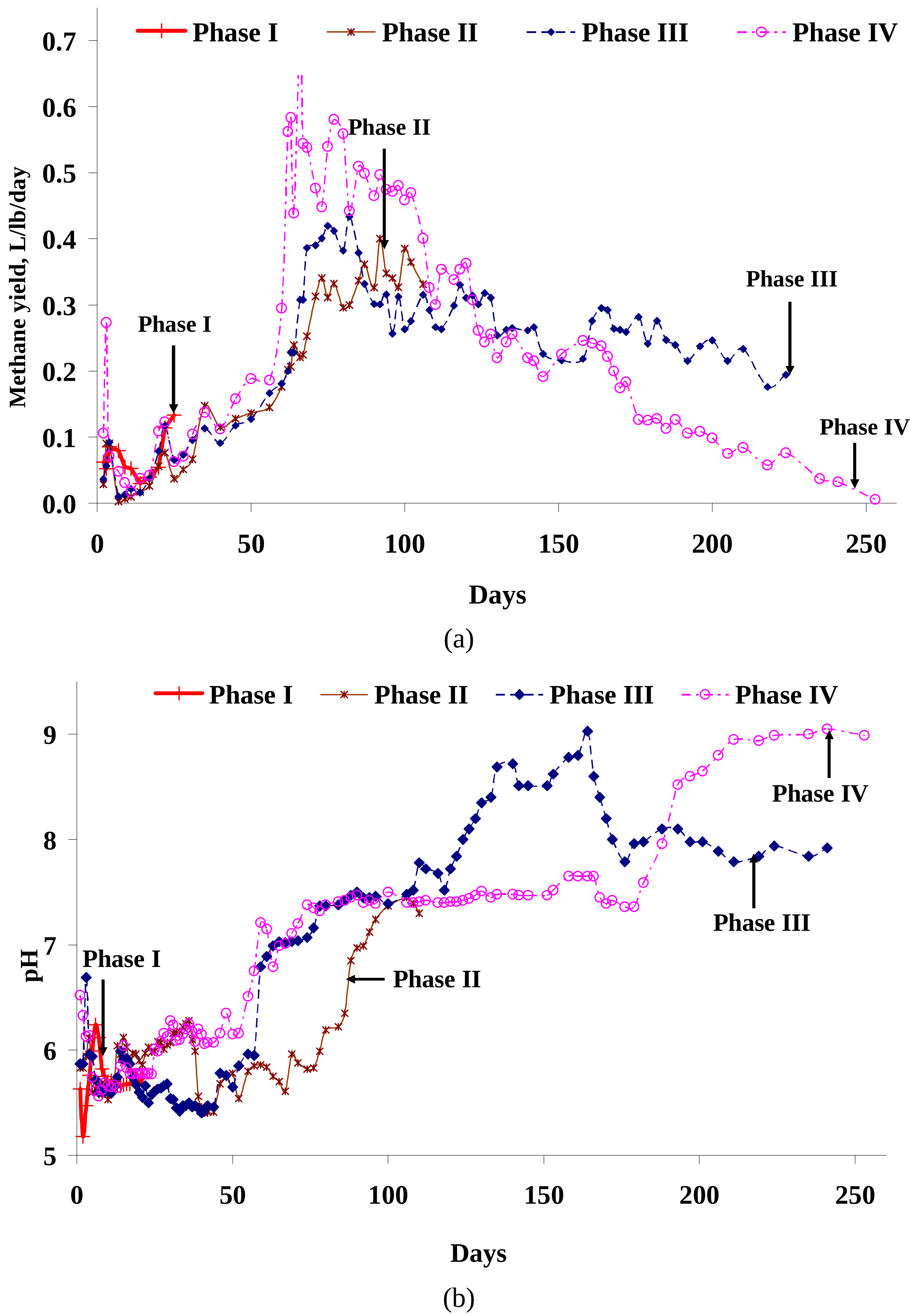
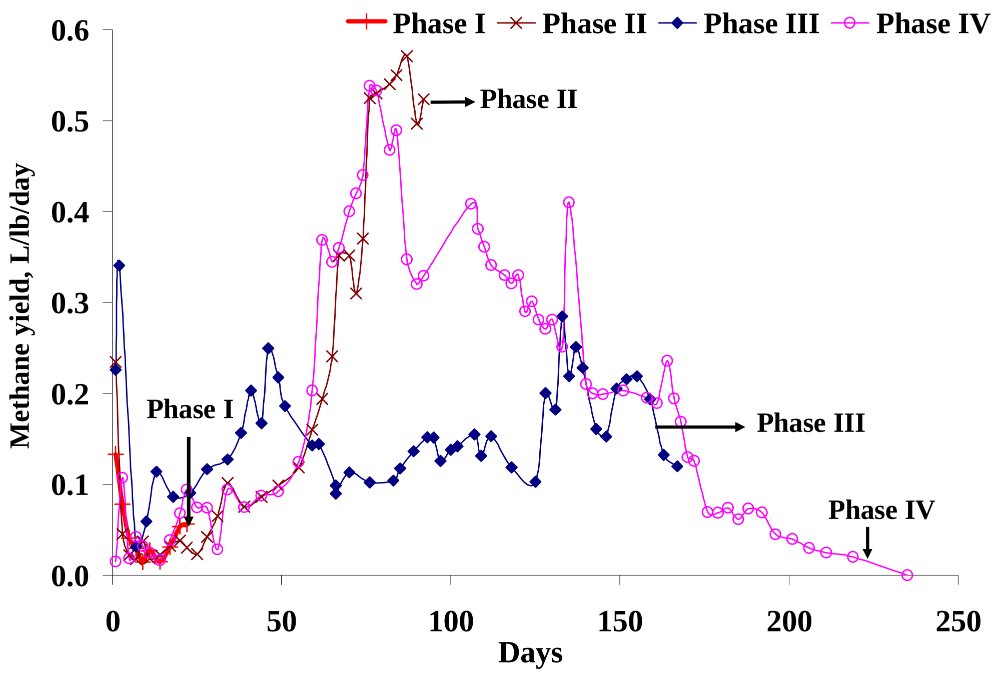
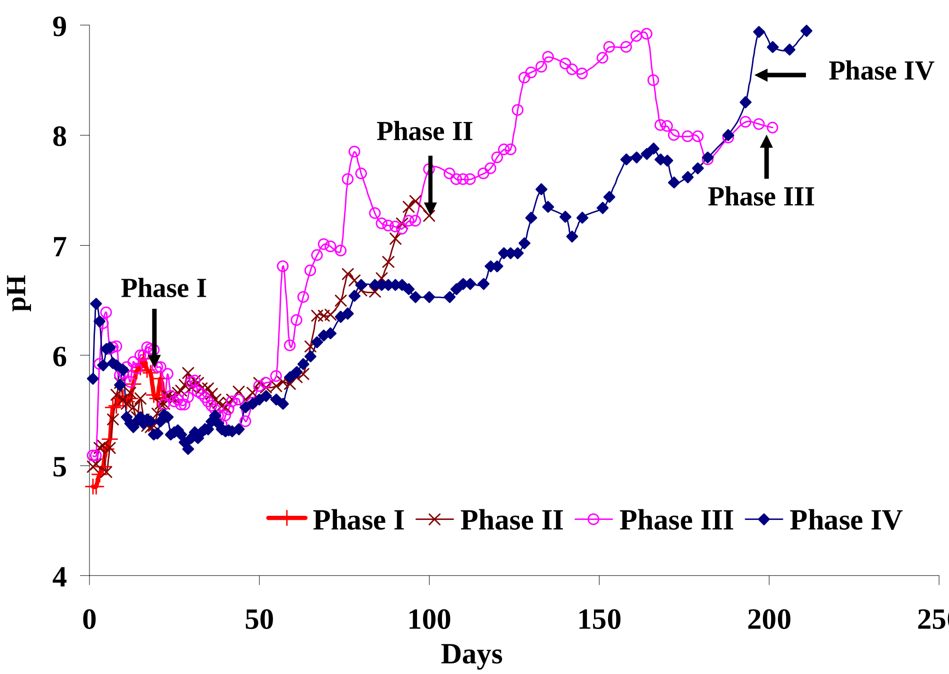


Figure 4.1 Rate of gas production and pH data from Setup 1 reactors at each phase of decomposition: (a) gas production data; and (b) pH data



(a)



(b)

Figure 4.2 Rate of gas production and pH data from Setup 2 reactors at each phase of decomposition: (a) gas production data; and (b) pH data

Table 4.1 Methane Production in Sampled Reactors

Phase	RS1 (without soil)		RS2 (with soil)	
	Time of Reactor Operation (days)	Cumulative Methane Production (L)	Time of Reactor Operation (days)	Cumulative Methane Production (L)
I	25	23.49	22	12.88
II	106	195.03	92	231.34
III	225	487.73	167	328.43
IV	253	515.41	235	563.80

4.2.1 Change in composition of MSW with degradation

The change in weight percentage of MSW constituents at each phase of decomposition are in Figure 4.3. The degradation of waste reduced the degradable component (paper and food) in MSW considerably, while the non degradable component (plastic) remained the same. The rate of decomposition also depended on the type of individual constituent. In Figure 4.3 it can be observed that the food wastes were completely consumed by the end of second phase, on the other hand only 28% percent of paper was degraded in this phase. However at the end of final phase of decomposition the degradation of paper was more. The paper present in the final phases of decomposition was more like a paste with higher moisture content. This is the reason for observing only a small decrease in percentage of paper at final phases of decomposition. Paper is a major degradable component of MSW, and it has a strong impact on geotechnical characteristics of MSW. As the waste degraded, the percentage of paper decreased, while the percentage of plastic increased. Figure 4.4 presents the percentage of paper and plastic at the end of each phase of decomposition.

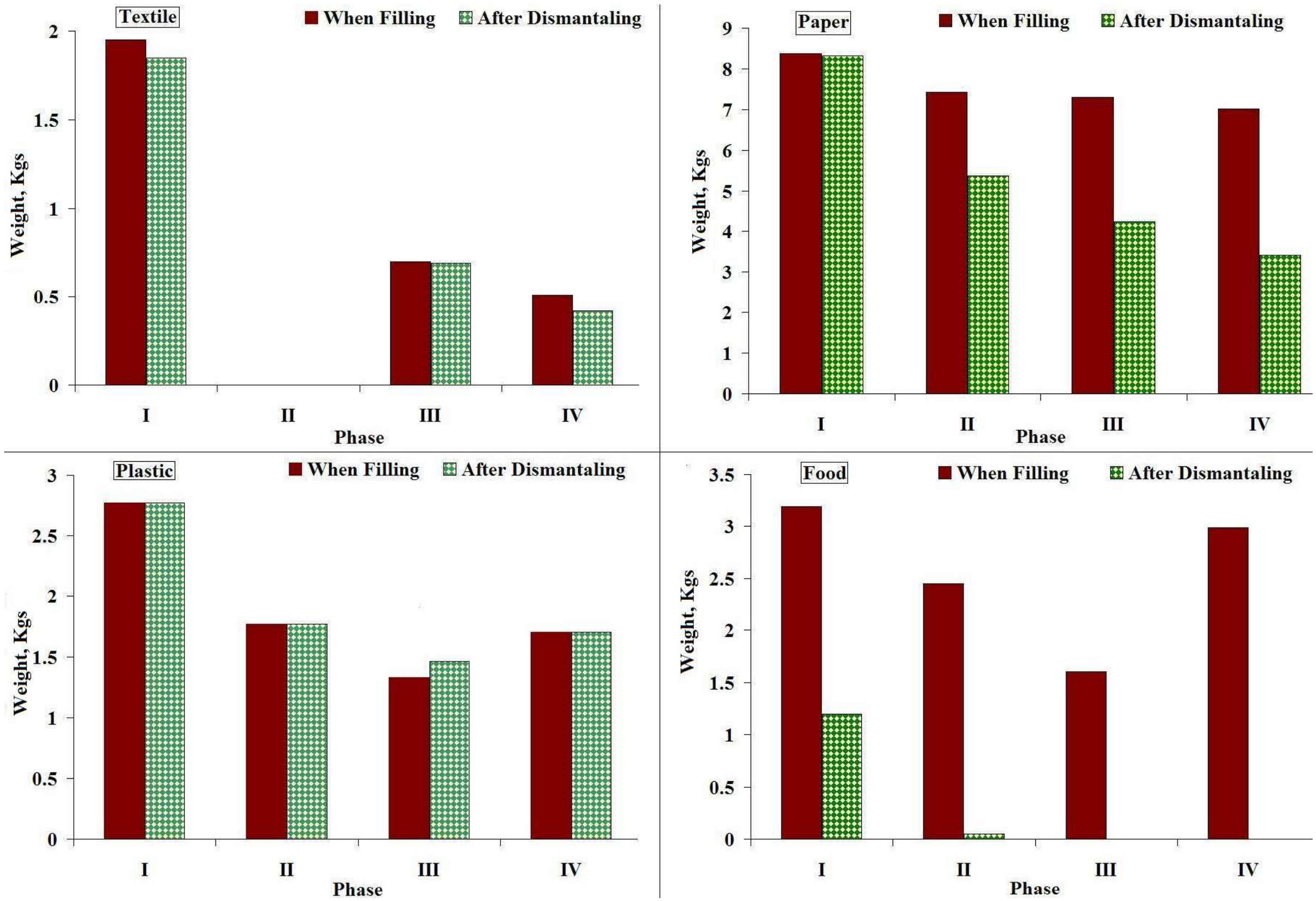


Figure 4.3 Change in weight percentage of MSW constituents with decomposition

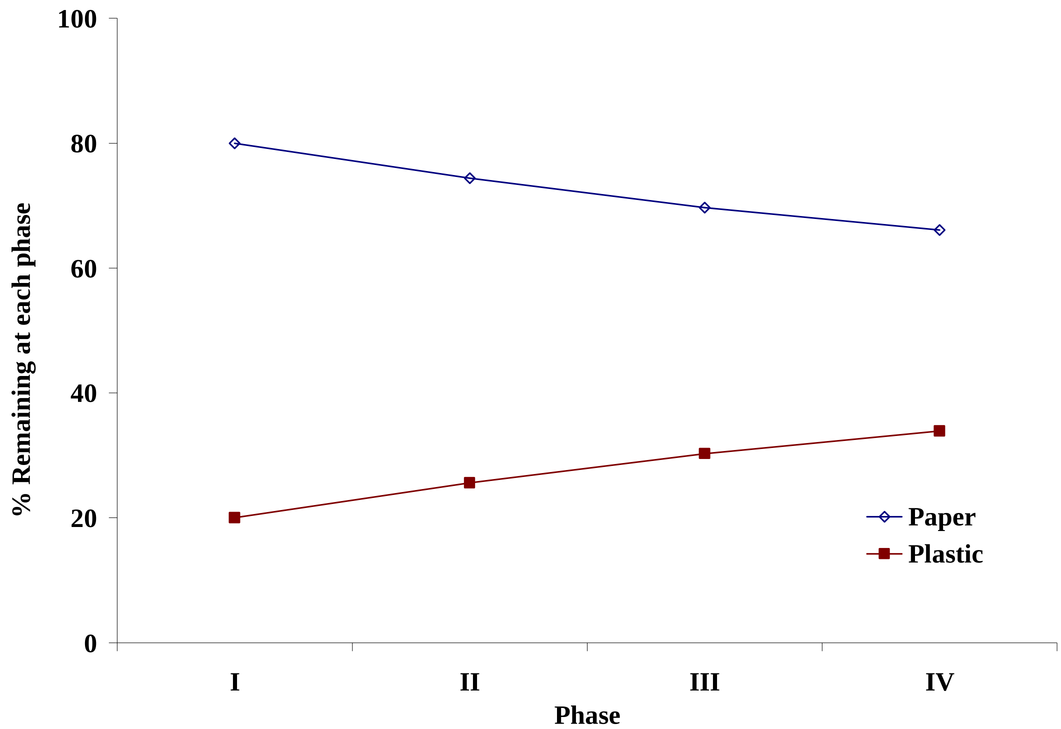


Figure 4.4 Percentage of paper and plastic at the end of each phase of decomposition

4.2.1.1 Change in Fabric Nature of Paper with Decomposition

Paper is a major degradable component of MSW, and it has a strong impact on shear strength. As the paper degraded with time, its fabric nature disintegrates considerably. Figure 4.5 shows the variation in papers fabric nature with decomposition. At the end of Phase I the fabric nature of paper did not change. However, as the degradation continued to the end of Phase III, the fabric was partly destroyed, and the paper became a soft material. With further degradation at the end of Phase IV the fabric was completely destroyed, and it was like a paste.

Figure 4.5 Variations in the fabric nature of paper with decomposition

4.2.2 Moisture Content

The average moisture content of MSW increased with the degree of decomposition. The results of moisture content of MSW are reported in Table 4.2. In Setup 1, the moisture content increased from 59.5% in Phase I to 64.7% in Phase IV. Similarly in Setup 2, it increased from 55.3% in Phase I to 69.6% in Phase IV. The observed increase in moisture content can be attributed to the disintegration of MSW constituents (mainly paper) with degradation. Degradation of MSW particles resulted in a decrease in pore spaces, and thus allowing the MSW (mainly paper) to retain its moisture.

Table 4.2 Moisture Content of MSW with Decomposition

Phase	Setup 1	Setup 2
I	59.5	55.3
II	59.7	59.9
III	63.3	68.9
IV	64.7	69.6

4.2.3 Volatile Solids

The composition of solids remaining at the end of each phase of decomposition is presented in Figure 4.6. Leachate recirculation had a significant effect on the degradation of the waste. The accelerated decomposition is indicated by the significant decrease in volatile solids. The percent of volatile solids remaining at the end of each phase of decomposition decreased from 94% in Phase I, to 41 % in Phase IV on Setup 1 samples, and it decreased from 89% in Phase I to 51% in Phase IV on Setup 2 samples (Table 4.3). As expected, the cumulative methane production increased as the waste degraded with time.

Table 4.3 Percent volatile solids consumed due to degradation at different phases of decomposition in Setup 1 & 2

Phase	RS1 (without soil)		RS2 (with soil)	
	Time of Reactor Operation	% Volatile Solids Consumed	Time of Reactor Operation	% Volatile Solids Consumed
I	25	6	22	11
II	106	26	92	22
III	225	38	167	41
IV	253	59	235	49

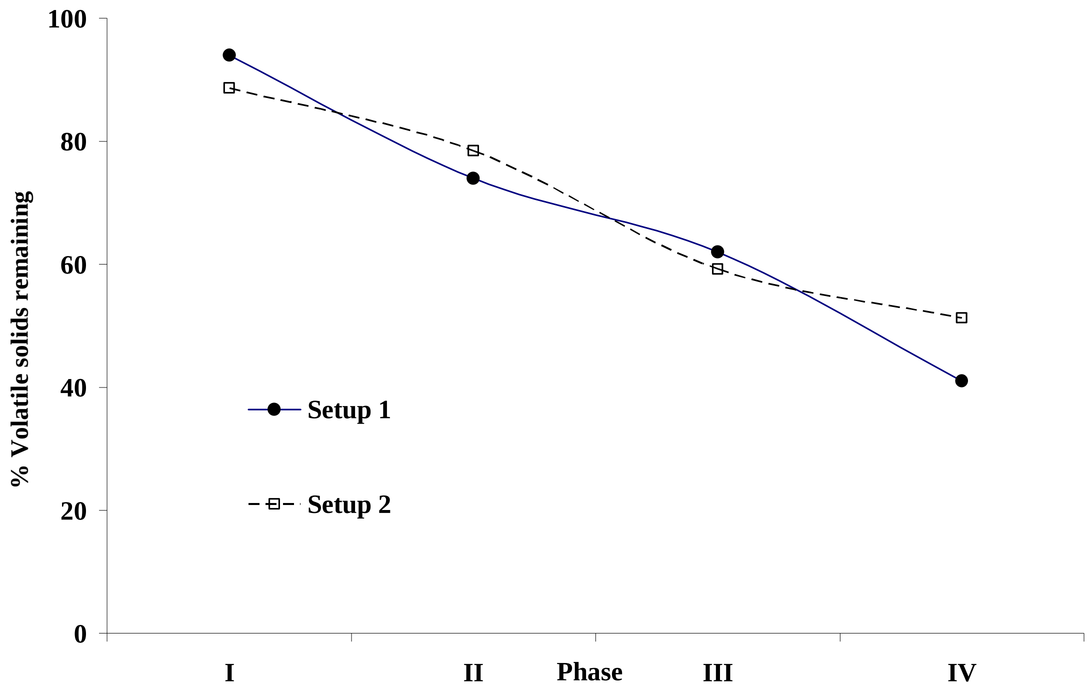


Figure 4.6 Percent volatile solids remaining at the end of each phase of decomposition

4.3 Geotechnical Testing

Geotechnical tests were performed on the generated samples at the end of each phase of decomposition. The results from the geotechnical testing program are presented in the following sections. Results from particle size analysis of MSW are discussed in the first part of this section, followed by the results of shear strength and dynamic properties of MSW.

4.3.1 Particle Size Analysis

Results from the wet sieve analysis conducted on the fraction retained on US sieve No. 200 indicated the disintegration of MSW particles with decomposition. Grain size distribution curves for MSW at different stages of decomposition in Setup 1 and 2 are presented Figure 4.7, and Figure 4.8, respectively. The particle size distribution curves indicate an increase in percent of fraction passing US sieve No. 200 with degradation. The MSW particles were relatively larger during the initial stages of decomposition. However, as the degradation progressed, the matrix structure of paper and other degradable constituents of MSW were broken down into smaller particles and the particle size decreased. The result from hydrometer analysis shown in Figure 4.9 clearly indicates an overall increase in the percentage of finer fraction with decomposition. The percent fines in MSW samples increased from 10% in Phase I to 39% in Phase IV.

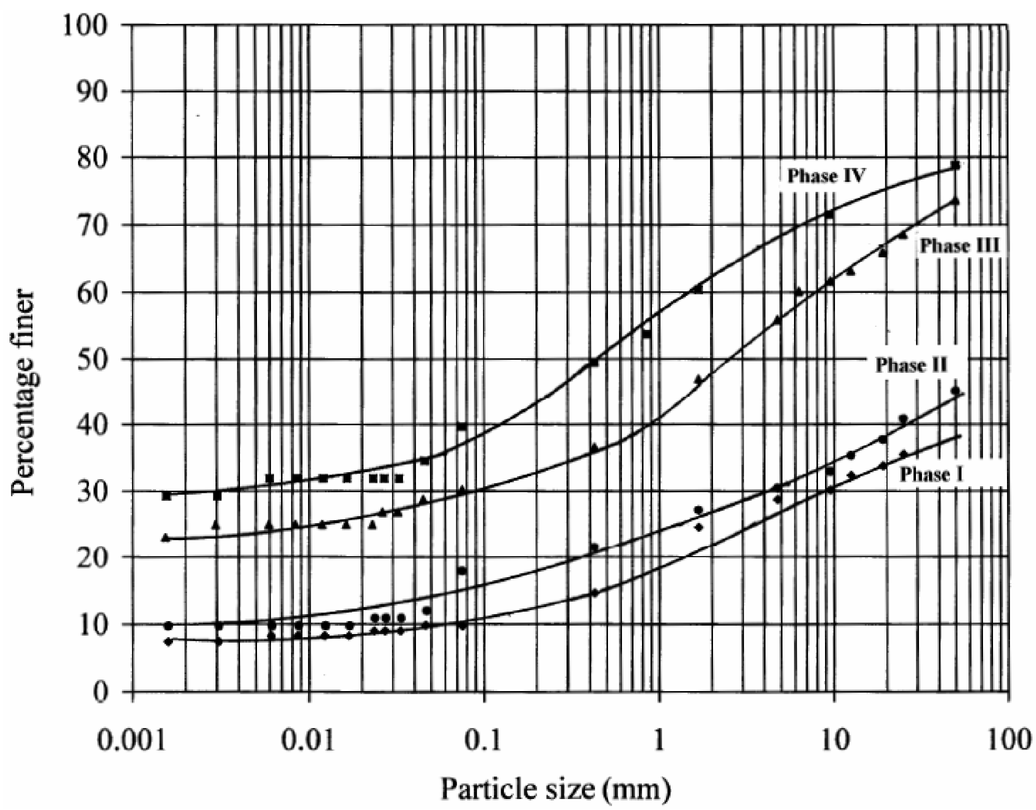


Figure 4.7 Particle size distribution of MSW samples from Setup 1 with decomposition

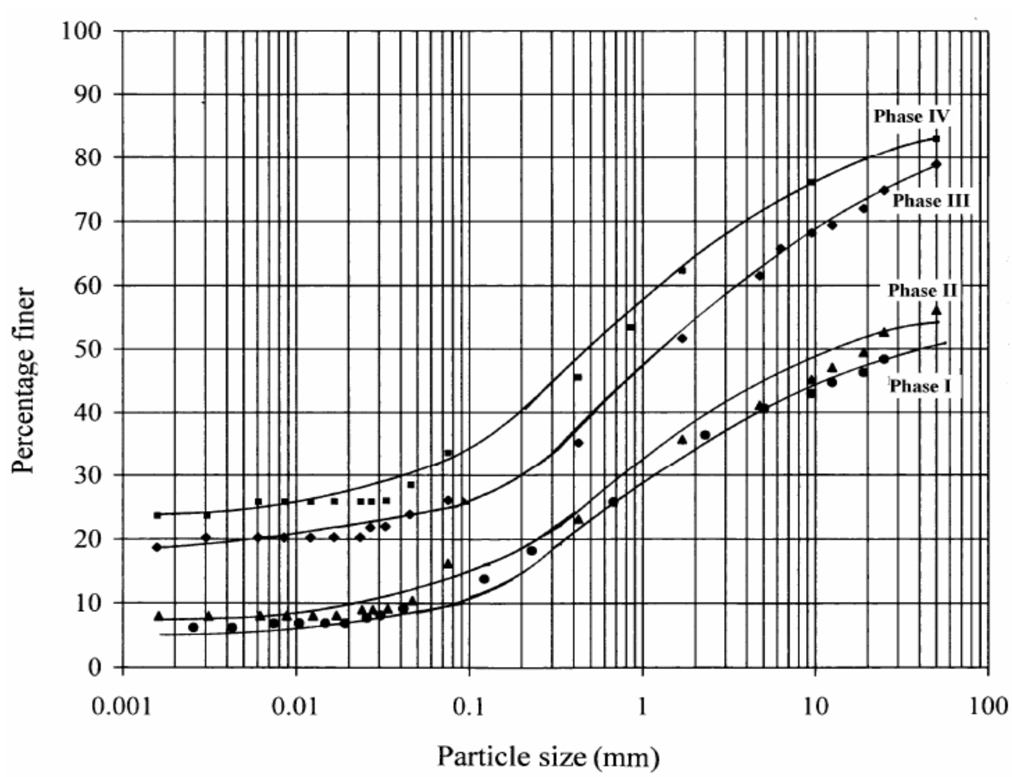


Figure 4.8 Particle size distribution of MSW samples from Setup 2 with decomposition

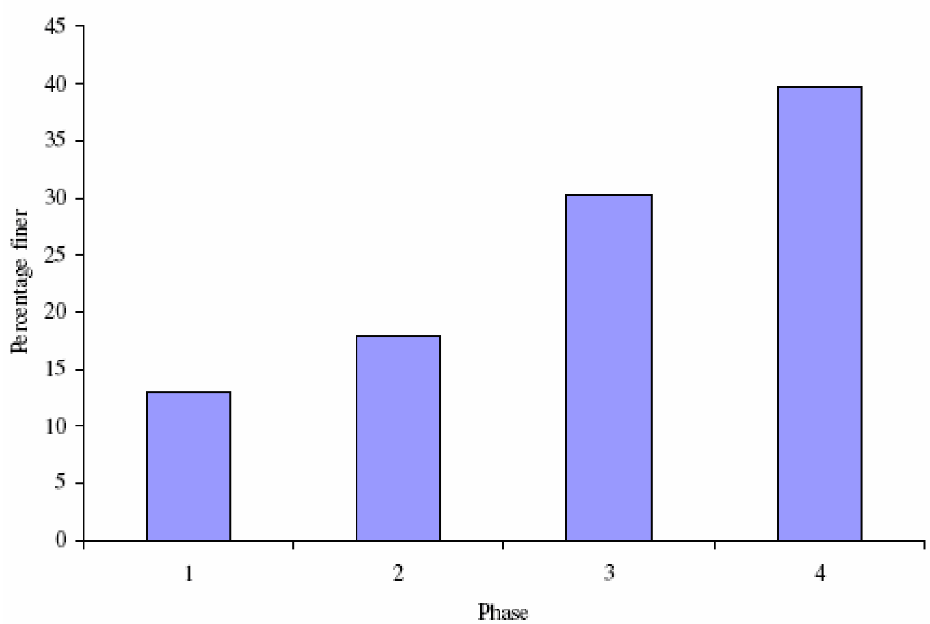


Figure 4.9 Results from Hydrometer analysis at different phases of decomposition

4.3.2 Unit Weight

Unit weight of solid waste is considered to be an important factor in estimating the stability of landfills. It is directly influenced by the type of waste, degree of decomposition, degree of compaction, volume of daily cover, compaction degree, quantity of leachate produced, and the depth from which sample is taken. The unit weight values increased with the degree of decomposition, and also with the addition of cover soil. The average unit weight values at different decomposition phases are presented in Figure 4.10. As the waste degraded, larger particles in the MSW are broken down into smaller ones; this reduced the voids and increased the mass of the solid waste per unit volume. In Phase I sample the unit weight ranged between 8.5 – 9.1 kN/m^3, and in Phase IV samples it was between 10.7 – 11.2 kN/m^3 (Table 4.4).

Table 4.4 Unit weight values at different decomposition phases

Phase	Unit weight values kN/m3		
	Only MSW	MSW with 20% Soil	MSW with 30% Soil
I	8.5 - 9.1	10.0 - 10.6	10.9 - 11.9
II	9.2 - 9.8	10.2 - 11.0	11.3 - 11.9
III	10.1 - 10.3	10.6 - 11.4	12.0 - 12.2
IV	10.7 - 11.2	11.5 - 11.9	11.5 - 12.5

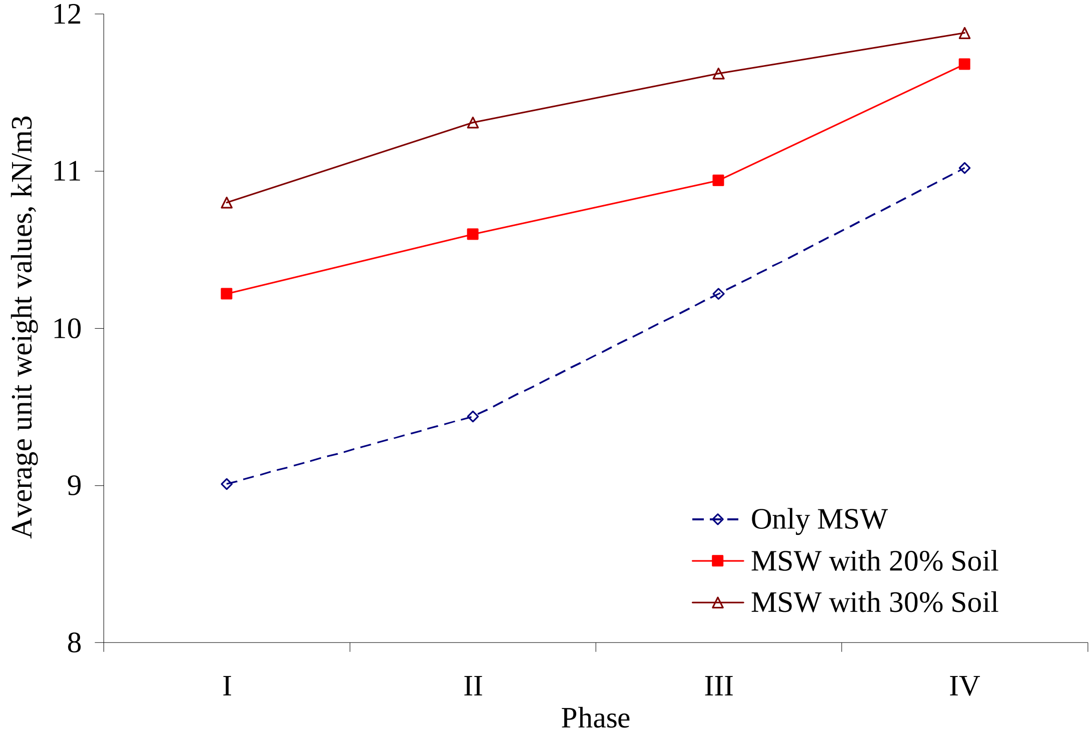


Figure 4.10 Average unit weight values with soil addition and decomposition

4.3.3 Shear Strength Properties

Shear strength parameters of MSW estimated at each phase of decomposition using static triaxial consolidated drained tests (CD) are presented in the following sections. The effect of increase in axial strain and cover soil addition was also discussed in later sections. Remolded sample before and after failure in CD triaxial tests is shown in Figure 4.11. The triaxial tests results indicated that the deviator stress increased almost continuously with axial strain, without reaching any ultimate value as shown in Figure 4.12. At large strains an upward inflection was produced, suggesting that the material is stiffening. Therefore the shear strength parameters can be estimated only by referring it to some percent of strain. The results from this study are presented in the form of stress paths followed in the drained tests (Figure 4.13). The shear strength envelopes were drawn for all the four phases at 10, 15, and 20% axial strain. In the figures,

$$s = \frac{\sigma_1^{'} + \sigma_3^{'}}{2}\text{; and } t = \frac{\sigma_1^{'} - \sigma_3^{'}}{2}$$

Where,

$\sigma_1^{'}$ = stress at failure or at a particular percent strain

$\sigma_3^{'}$ = confining stress

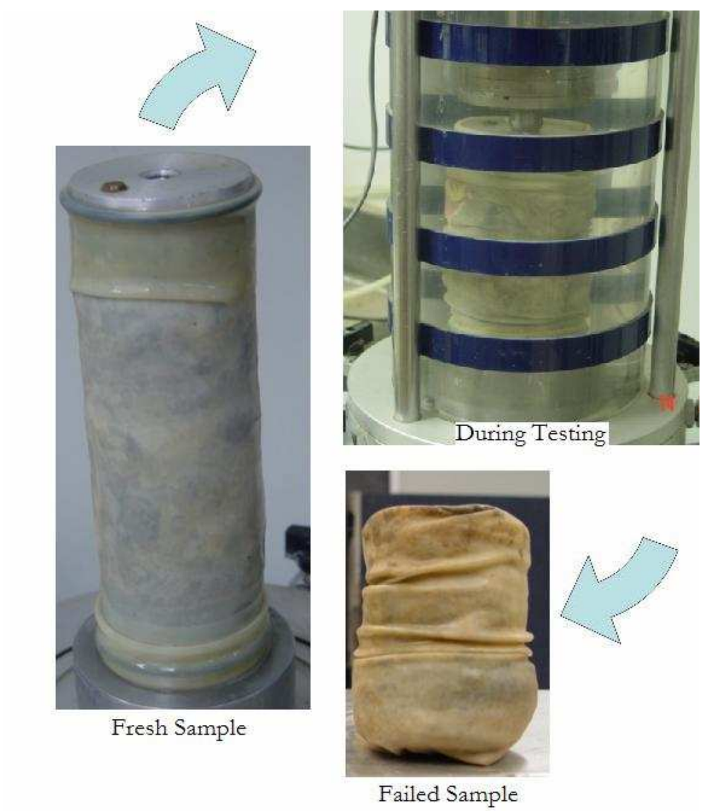


Figure 4.11 Fresh and failed sample from CD triaxial test

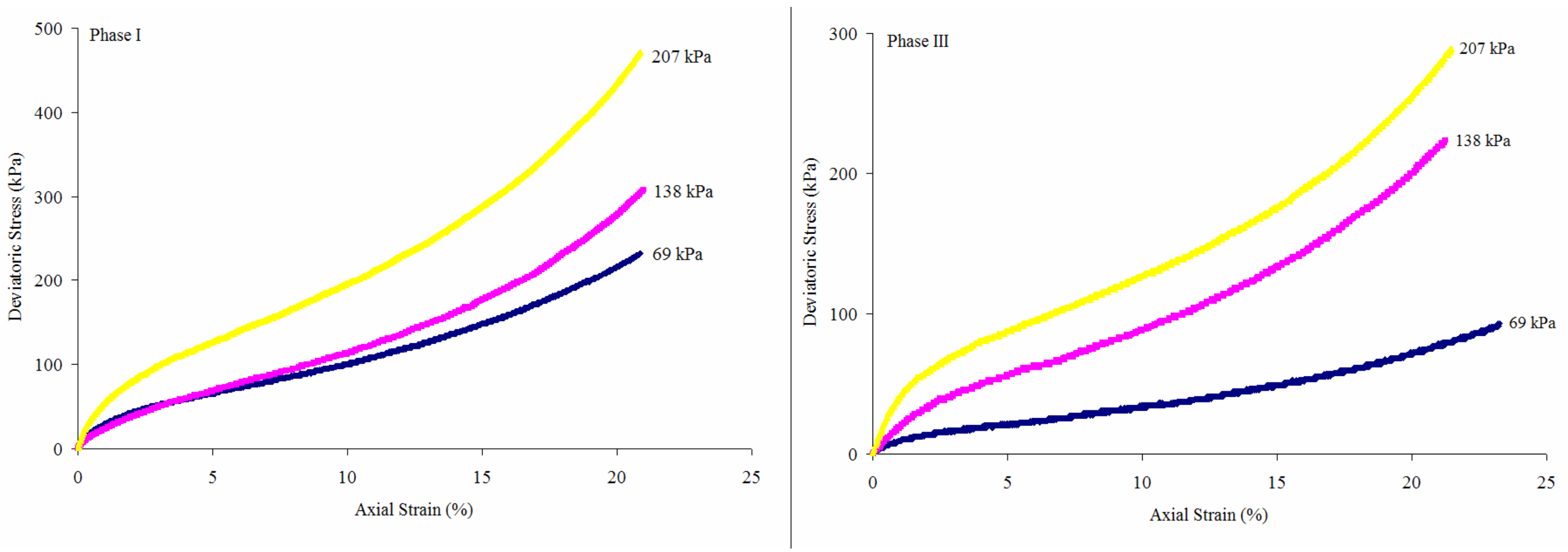


Figure 4.12 Results from CD Triaxial tests with deviator stress increasing almost continuously with axial strain

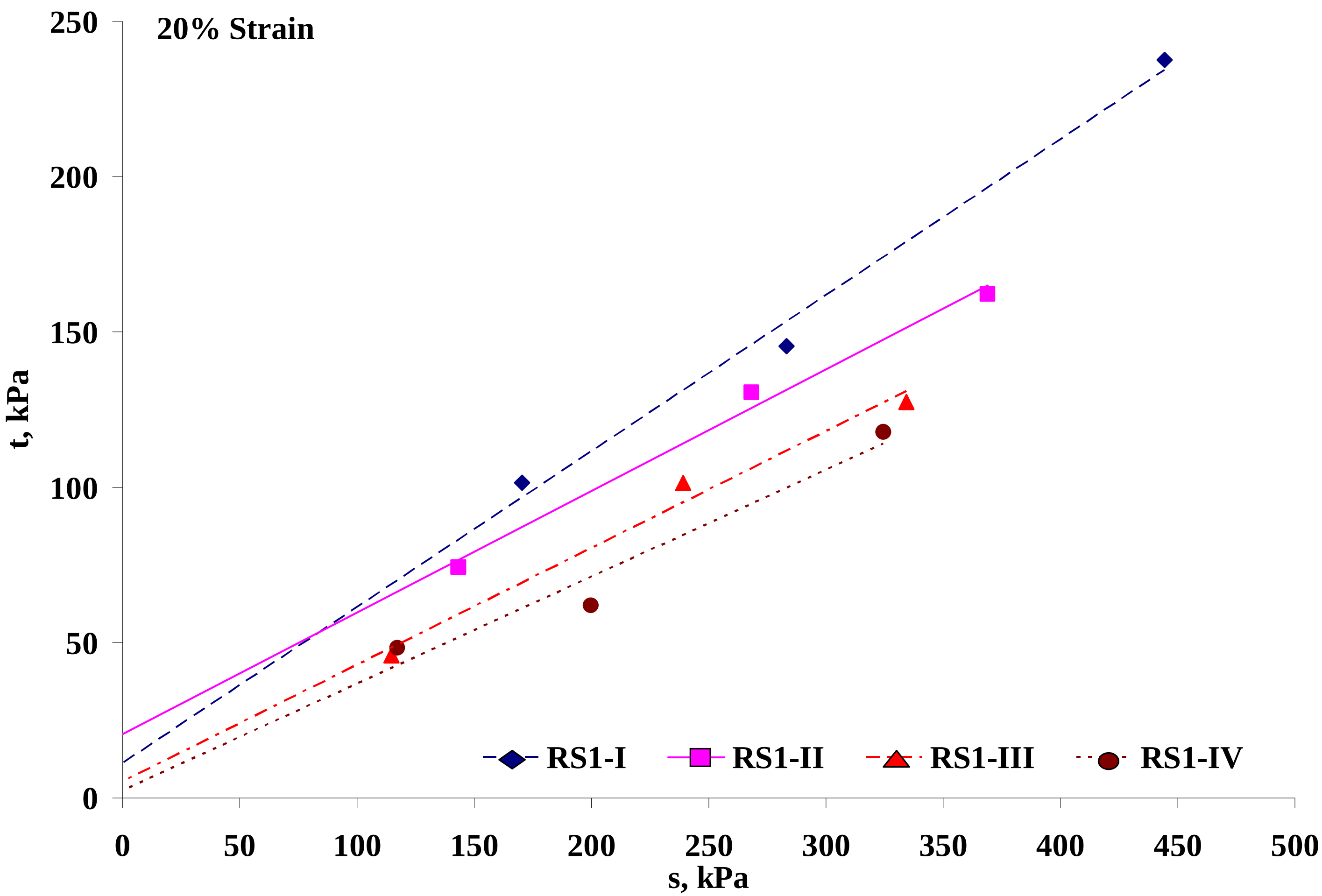


Figure 4.13 Shear strength envelopes at different phases of decomposition for RS1 samples at 20% strain.

4.3.3.1 Effect of Decomposition on Shear Strength Parameters

Degradation of MSW with time affected its shearing strength considerably. Figure 4.14 shows the changes in friction angle at different phases of decomposition. The results of triaxial tests conducted on RS1 (without soil) samples are presented. The test results showed a remarkable decrease in friction angle with decomposition. At 20% strain level the friction angle decreased from 26.7° in Phase I, to 19° in Phase IV. The rate of increase in shear strength with shear displacement for fresh paper is higher than that for plastics (Gabr et al., 2007). However as the matrix structure of the paper gets broken down with time, its strength will decrease. As decomposition proceeded the percentage of paper in MSW decreased, while the percentage of plastic increased. The increased percentage of plastic present in the final stages of decomposition created more potential sliding surfaces, and decreased its shear strength. Landva and Clark (1986) and Thomas et al. (2000) had also indicated a decrease in shear strength in MSW with an increasing plastic content. Therefore, the test results suggest that the degradation of solid waste decreased the percentage of paper and increased the percentage of plastic, causing reduction in shearing strength of MSW with degradation.

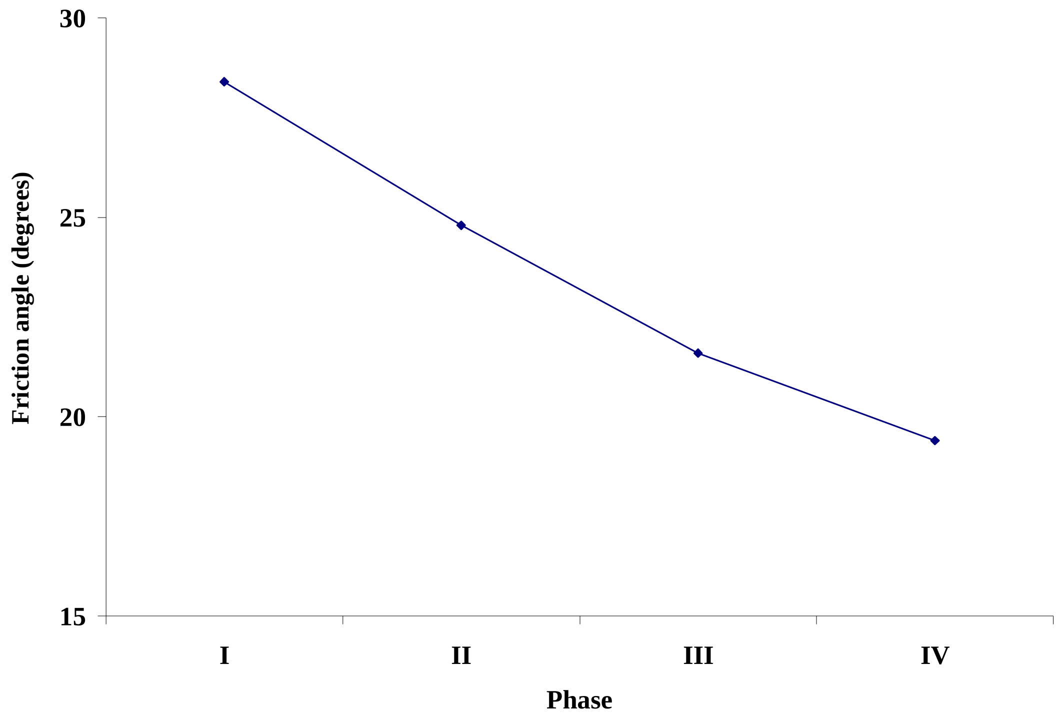


Figure 4.14 Decrease in friction angle with decomposition

4.3.3.2 Effect of Strain on Shear Strength

The shear strength parameters increased with an increase in strain for all the phases of decomposition. Similar observations were previously reported by Thomas et al. (2001), Gabr and Valero (1995), and Jones et al. (1997) as presented in Figure 4.15. The friction angles increased from 17.7° at 10% strain, to 24.7° at 15% strain, and finally to 28.4° at 20% stain for Phase I samples. These results indicate that shear strength of MSW is a function of shear strain in addition to the degree of decomposition. As the mobilized strength varies with deformation, strain compatibility becomes an important design issue for stability analysis.

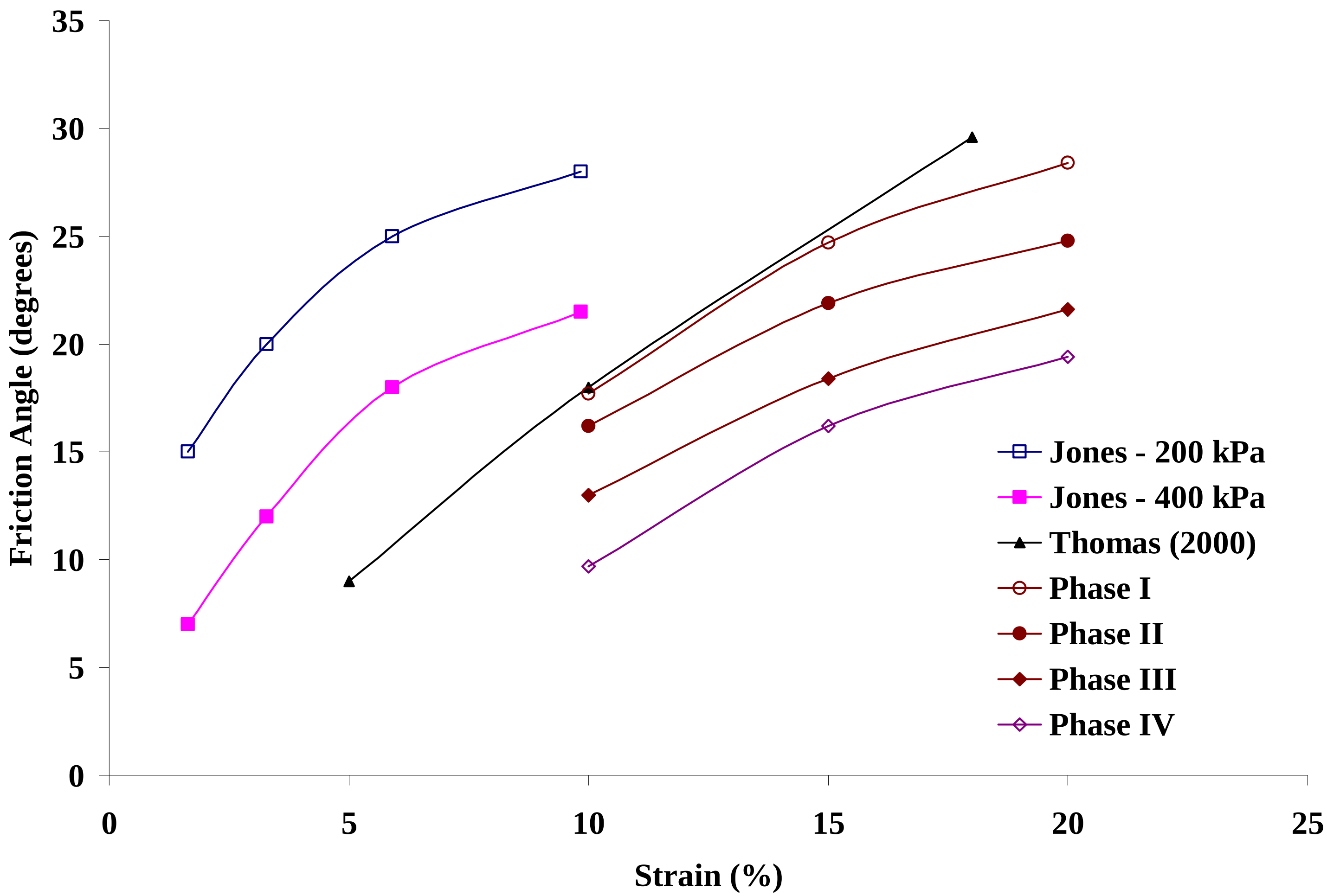


Figure 4.15 Change in friction angle of MSW with strain and decomposition

4.3.3.3 Effects of Cover Soil on MSW Shear Strength

Shear strength envelope for the samples from four different phases of decomposition at 20% strain are presented in Figure 4.16. The shear strength envelope shifted up with an increase in soil percentage in all the four phases of decomposition. The samples without soil had the least strength, and those with 30% soil content by weight had the highest strength. The changes in friction angle in samples without soil and those with 20% and 30% soil are shown in Figure 4.17. The friction angle of Phase I samples at 20% strain level were 26.7°, 29° and 33.1° for samples without soil, samples with 20% soil, and samples with 30% soil, respectively. Same trend was observed in all four phases of decomposition, and is reported in Table 4.5. The cohesion also increased with increasing soil percentage; at 20% strain level cohesion was 11.2, 22.3, and 24.5 kPa in only MSW, MSW with 20% soil, and MSW with 30% soil samples, respectively. The soil added to the samples entered the inter-particle voids, acted as a reinforcing agent, and increased its strength in all phases of decomposition.

Table 4.5 Changes in Shear Strength Parameters with Cover Soil Content

Phase	Only MSW (RS1)		MSW with 20% Soil (RS1-20%)		MSW with 30% Soil (RS1-30%)	
	C, kPa	Φ	C, kPa	Φ	C, kPa	Φ
I	11.2	26.7	22.3	29	24.5	33.1
II	20.5	21.5	30.7	24.9	34	29.4
III	5.3	20.6	13.7	23.2	13.1	26.4
IV	2.4	19	9.1	21.8	12.9	23.7

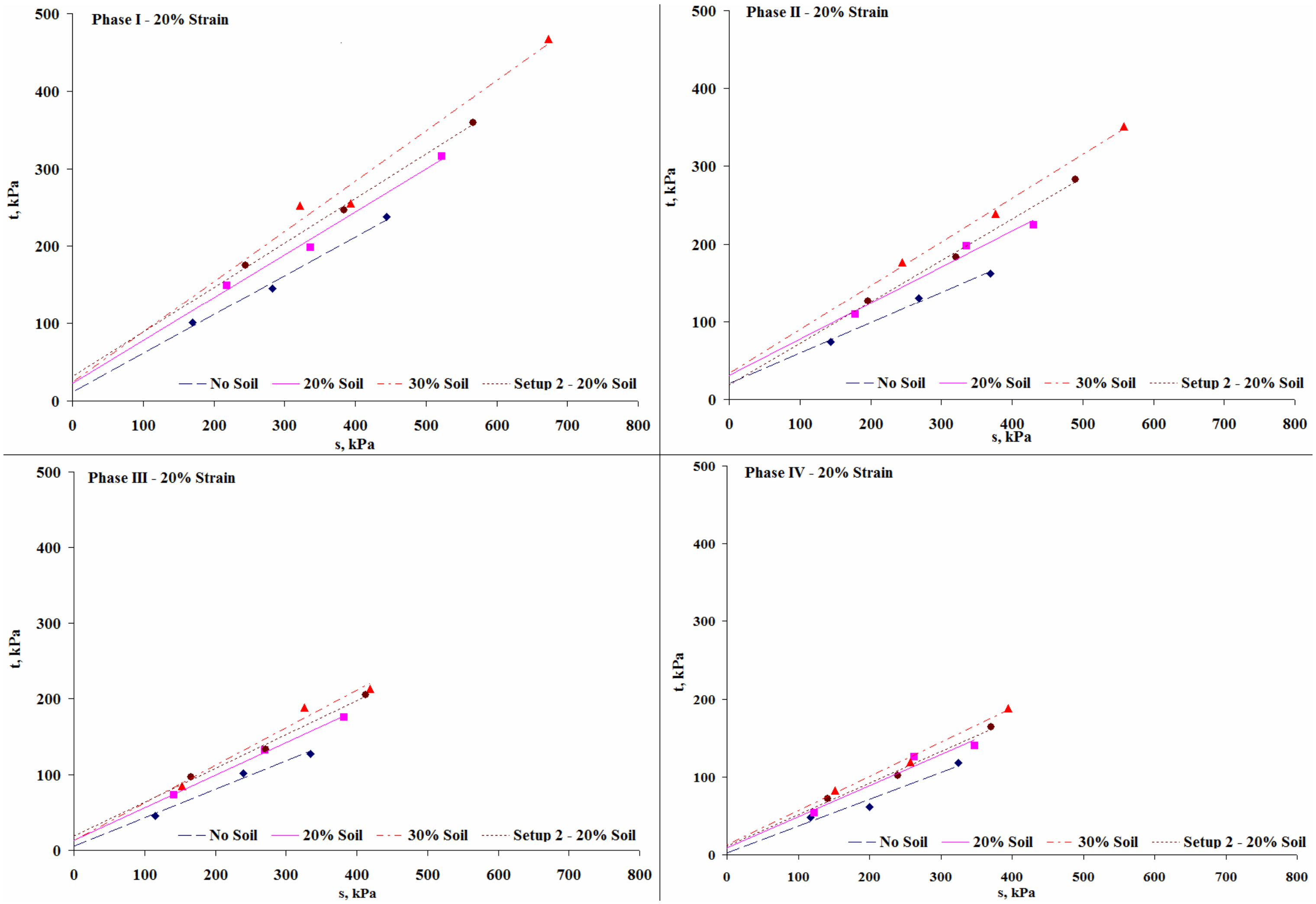


Figure 4.16 Strength envelopes at 20% strain for different phases of decomposition

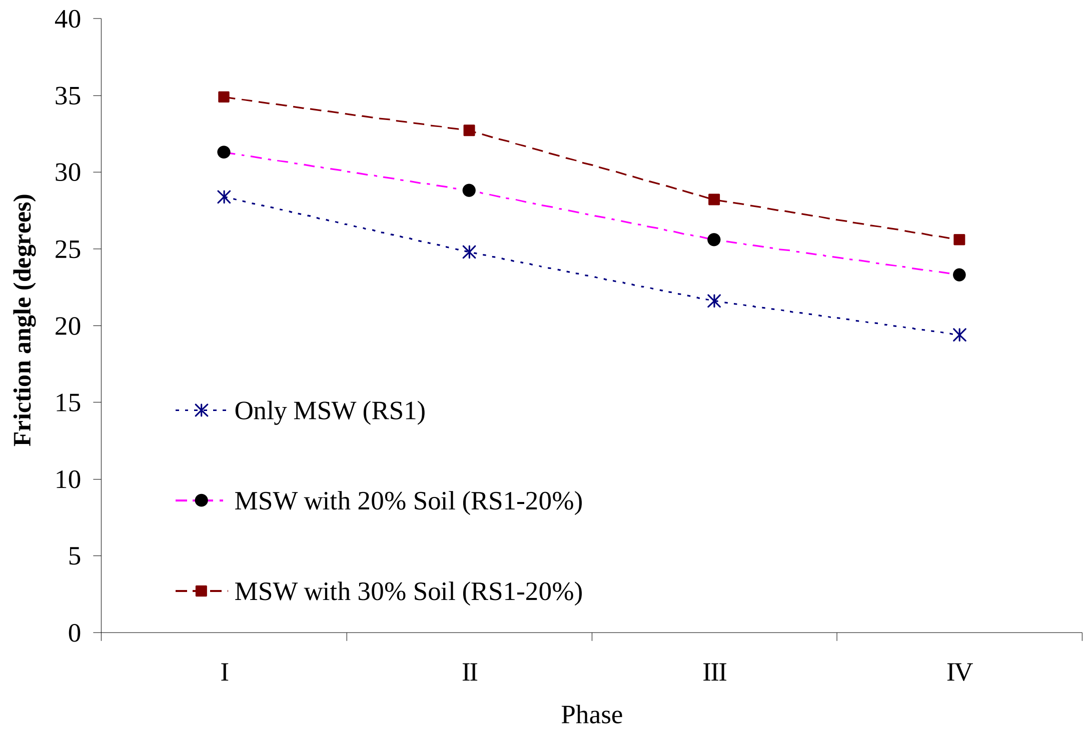


Figure 4.17 Increase in friction angle with an increase in cover soil content in all phases of decomposition

4.3.3.4 Effect of Cover Soil Addition at the End of Decomposition Phases

Results of friction angle estimated from Setup 1 and Setup 2 samples are presented in Table 4.6. The computed friction angles for Phase I samples in Setup 1and Setup 2 are 31.3° and 33°. Accordingly, friction angles of 28.8° and 30.2° in Phase II, 25.6° and 26.8° in Phase III, and finally 23.3° and 23.9° in Phase IV were observed in the samples from Setup 1 and Setup 2 samples. Based on these results, there was only a 5% variation in friction angles estimated from the sets of reactors. Therefore, from the results it can be said that the addition of soil with MSW during reactor building or at the end of decomposition phases did not make any significant difference.

Table 4.6 Friction Angle in RS1 & RS2 Samples at Different Phases of Decomposition

Phase	RS1-20%	RS2-20%	Percent variation in RS1 & RS2 Friction Angles
	Φ	Φ	
I	31.3	33	5.2
II	28.8	30.2	4.6
III	25.6	26.8	4.5
IV	23.3	23.9	2.5

4.3.3.5 Repeatability of Shear Strength Parameters

Municipal solid waste samples are extremely heterogeneous in nature. Due to its heterogeneity, the variation in samples within the same reactor can be an issue for testing. Results from tests conducted on specimens from the same reactor can vary due to sampling and experimental errors. Three triaxial tests were conducted at 157.8 kPa confinement, and the results presented are at 20% strain level. Table 4.7 presents triaxial test data's conducted on Phase II & IV samples. A statistical analysis was conducted on the results obtained from triaxial tests. The analysis gave a standard deviation in deviatoric stress of 27 kPa in Phase II samples, and 11 kPa in Phase IV samples. Using normal distribution the standard error in test data's at 90% confidence interval was estimated. The standard error was 11% in Phase II and 9% in Phase IV, in other words, the results from the Phase II samples are 89% repeatable, and those from Phase IV are 91% repeatable. Therefore, the result from the statistical analysis indicates that the tests conducted on specimens from the same reactor are quiet repeatable.

Table 4.7 Repeatability of Test Data at 157.8 kPa and 20% Strain in Phase II & IV

Phase	Deviator Stress ($\sigma_3 - \sigma_1$) kPa	Mean kPa	Standard Deviation kPa	Percent Standard Error at 90% Confidence Interval
II	261	237	27	11
	208			
	242			
IV	103	115	11	9
	124			
	119			

4.3.3.6 Comparison of Shear Strength Parameter with Existing Results

Shear strength parameters for municipal solid waste obtained from laboratory, in-situ tests, and back-analysis of observed failures are presented in Figure 4.18. The large scatter observed in the existing results can be attributed to the heterogeneity of waste, and decomposition of waste with time. With a few exception most of the results obtained from the current research falls within the region recommended by Singh & Murphy (1990). Results from Phase I & II samples with 20 and 30% soil, and those from Phase III & IV without soil lie outside this recommended region. Region for shear strength parameters suggested by Singh and Murphy (1990) are estimated using samples with little degradation. In our case the Phase I samples are at the initial stage of decomposition, while the Phase III & IV samples are in advanced stage of decomposition. In addition, the data from triaxial laboratory tests conducted by Vilar & Carvalho (2002) on a 15 year old sample from Bandeirantes landfill was also located above the Singh & Murphy (1990) recommended region. However, Singh & Murphy (1990) did not considered the effect of decomposition on shear strength parameters.

Therefore their recommended region for strength needs to be revised. In addition, the results also suggest that the stability of bioreactors should be evaluated using the strength characteristics as a function of time and decomposition rather than using average values.

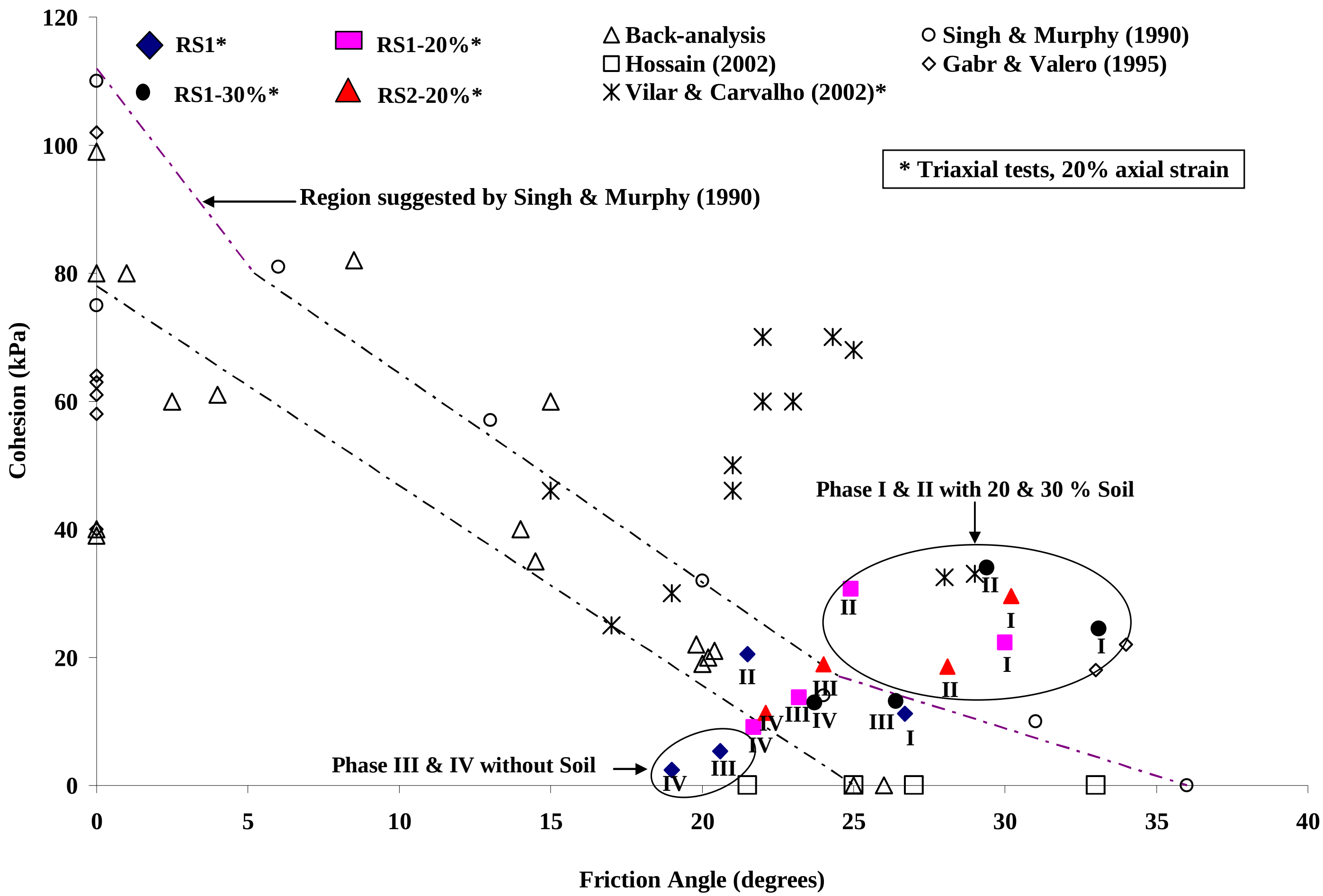


Figure 4.18 Effective shear strength parameter of municipal solid waste with decomposition

4.3.4 Dynamic Properties of MSW

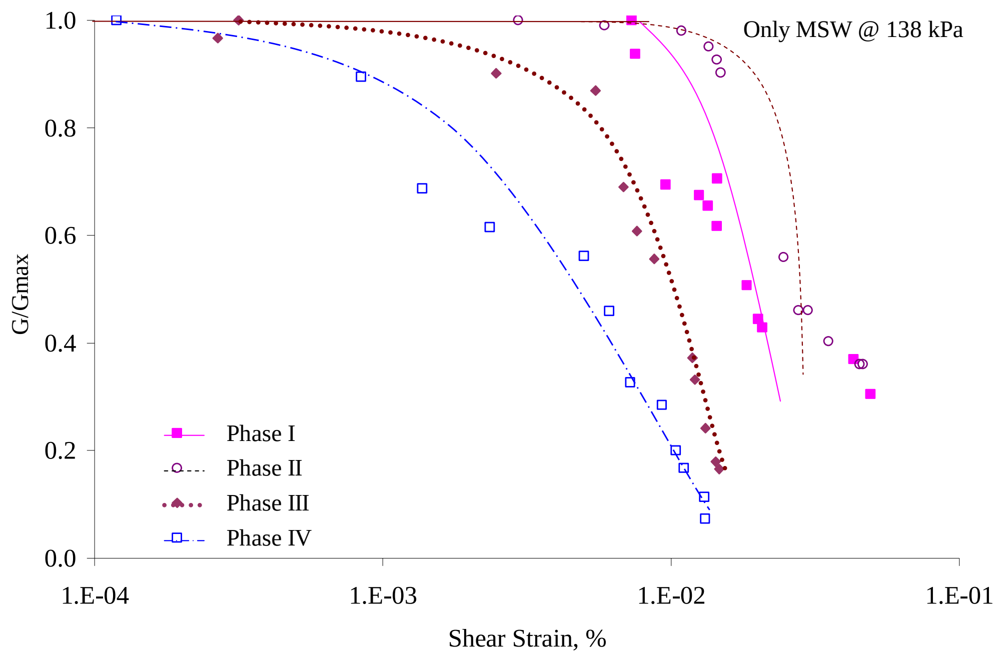
The dynamic properties of MSW estimated using a series of Resonant Column (RC) tests are presented in the following sections. The tests were performed at each phase of decomposition. From the RC results normalized shear modulus and material damping curves, as a function of shear strain was plotted for the first and final phases of decomposition. In addition, the effect of presence of soil in MSW was also evaluated.

4.3.4.1 Effect of Decomposition on Shear Modulus and Damping

The degradation of MSW with time affected the modulus degradation and damping curves considerably. The threshold strain of MSW decreased and small-strain shear modulus increased with time and decomposition. The results are presented and discussed in the following sections.

(a) Decrease in Threshold Strain with Decomposition

Results from the resonant column tests at different phases of decomposition are shown in Figure 4.19. As the material degraded, the shear modulus reduction and damping curves shifted to the left and the threshold strain decreased (Figure 4.20). This shift can be attributed to the breakdown of fibrous nature of solid waste particles as it degrades. The degradation of waste considerably reduced the degradable component (paper and food) in MSW, while the non degradable component (plastic) remained the same. As the paper degraded with time, its fabric nature disintegrates considerably. Therefore, Phase I samples required higher shear strains to induce plastic deformation, whereas the highly degraded Phase IV samples required lesser shear strain to induce plastic deformation. At higher shear strains, the material becomes highly deformable as it enters into plastic behavior, and the changes in shear modulus and damping will be drastic. The samples from Phase III & IV showed more drastic change in modulus reduction and damping at larger strains, than the samples from Phase I & II (Figure 4.19). This further confirms that the decomposition has a strong influence on modulus degradation and damping curves.



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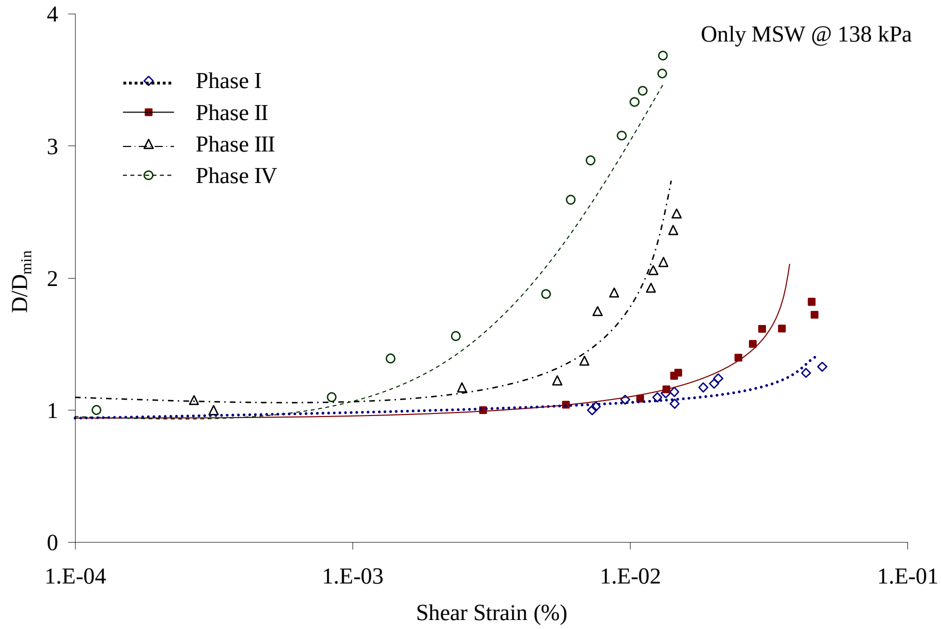


(b)

Figure 4.19 Modulus degradation and damping curves for only MSW at 138 kPa confinement at different phases of decomposition: (a) shear modulus reduction; (b) material damping.

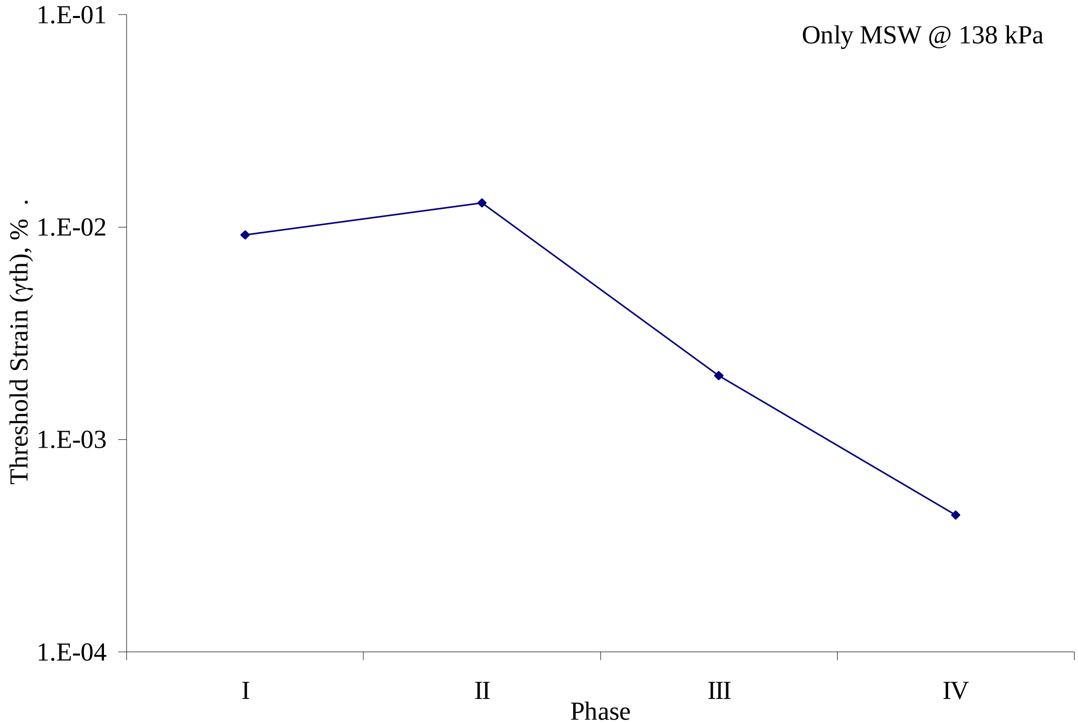


Figure 4.20 Variation in threshold strain with decomposition

(b) Changes in Shear Modulus and Damping with Decomposition

The experimental results also showed an increase in small-strain shear modulus with decomposition. The change in shear modulus with decomposition is presented in Table 4.8. The shear modulus increased from 2.41 MPa in Phase I to 17.88 MPa in Phase IV at a constant confinement of 69 kPa (10 psi). The increase in shear modulus can be attributed to the decrease in particle size of MSW with decomposition. The particle size distribution curve indicated an increase in percent of fraction passing US sieve No. 200 with degradation. The MSW particles were relatively larger during the initial stages of degradation and with degradation, the matrix structure of paper, textile, and other degradable constituents were broken down into smaller particles. These resulted in an overall increase in percentage of finer fraction passing US sieve 200. The percentage of particles finer than 75μm (US sieve No 200) for phase I is only 10% when compared to 39% in Phase IV. Hence, the denser samples in the final stages of decomposition increased the shear modulus of MSW accordingly.

Conversely, at smaller strains (below 10^{-3}%) the material damping ratio is not significantly reduced by strain, and it remained roughly constant at values of about 6 - 8 %. However, as the strain level increases beyond 10^{-3}%, the material damping ratio increased with decomposition. The damping ratio increased from 12% in Phase I to 21% in Phase IV specimens (Table 4.8). Fibrous materials tend to provide a reinforcement effect in the specimen, resulting in smaller modulus reduction and lower damping (Zekkos, 2005). Therefore, at larger strain the fibrous nature of Phase I samples would have decreased the material damping, whereas, the degraded Phase IV samples with a minimal reinforcement would have increased the damping in them.

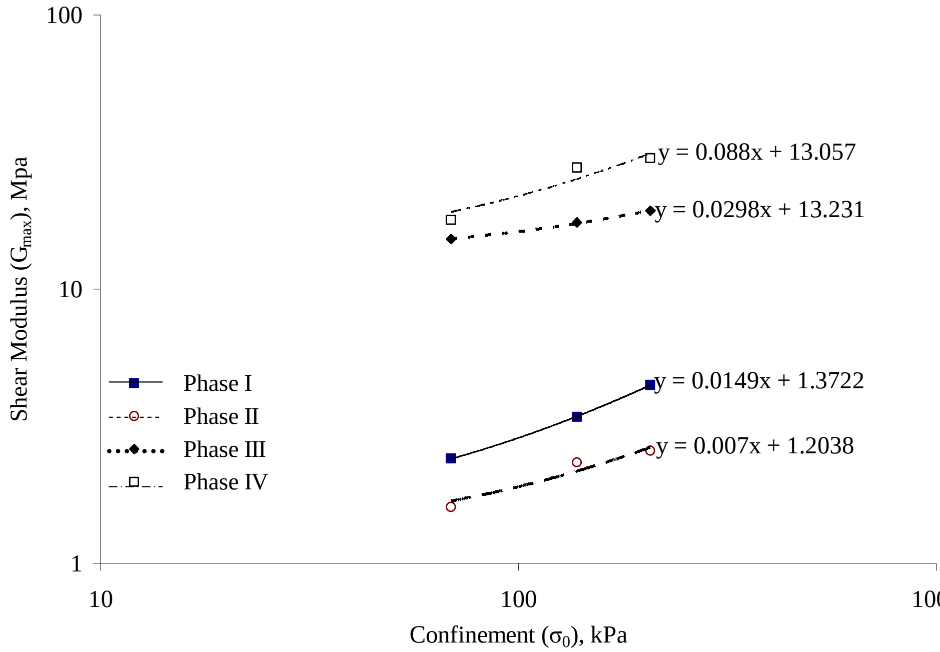
Table 4.8 Change in shear modulus and damping with decomposition at 69 kPa confinement

Phase	Small Strain (< 10^{-3} %)		Large Strain (> 10^{-3} %)	
	G_{max}, MPa	D_{min}, %	G_{min}, MPa	D_{max}, %
I	2.41	8.97	1.36	12.01
II	1.60	8.02	0.71	15.01
III	15.21	7.83	0.99	16.14
IV	17.88	5.12	2.01	21.02

4.3.4.2 Effect of Confinement on Shear Modulus and Damping

The experimental results showed that the effect of confinement on small-strain shear modulus was less pronounced in Phase I & II samples than in Phase III & IV.

Figure 4.21 (a) shows the variation in small-strain shear modulus at different confinement for different phases of decomposition. In Figure 4.21 (a) the slope of the Phase IV samples was maximum, and it was least in Phase II samples. The steep slope in Phase IV indicates that these samples are more susceptible to changes in confinement. The shear modulus in Phase I samples increased from 2.41 MPa at 69 kPa confinement to 4.47 MPa at 207 kPa confinement, whereas in Phase IV it increased from 17.88 MPa (69 kPa) to 30.02 MPa (207 kPa). The fibrous materials in Phase I samples did not allow the sample to get denser with an increase in confinement, resulting in smaller increase in shear modulus values. While the highly degraded waste samples in final phase of decomposition readily became denser with an increase in confinement, and hence the increase in shear modulus with confinement was quiet significant. Damping ratio was not quiet affected with an increase in confinement, and it followed the same trend in all phases of decomposition (Figure 4.21 (b)). It only increased marginally with an increase in confinement.



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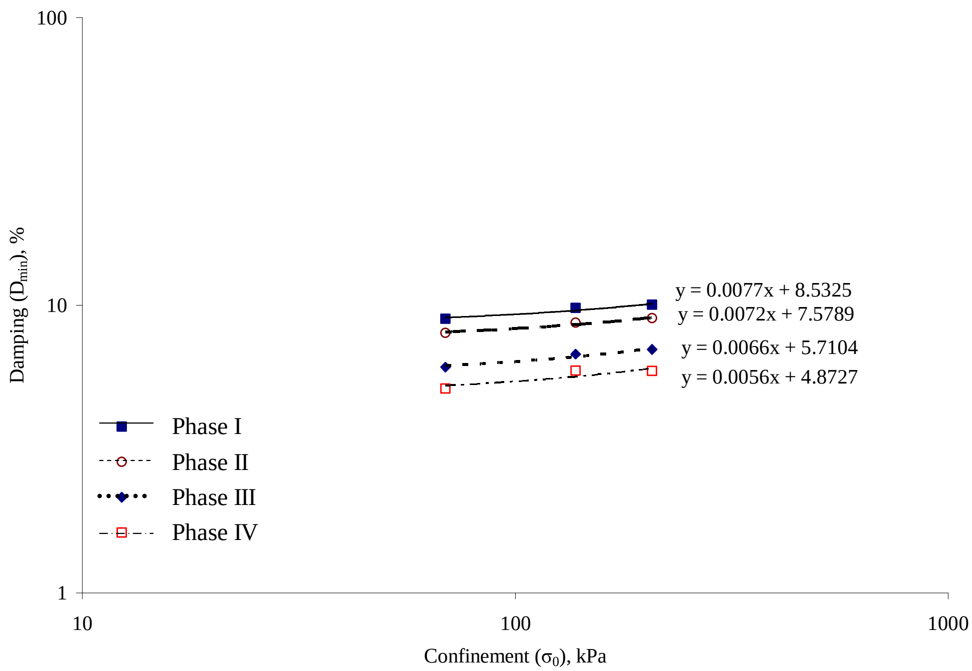


(b)

Figure 4.21 Variation in dynamic properties at different phases of decomposition: (a) shear modulus (G_{max}); (b) material damping ratio (D_{min})

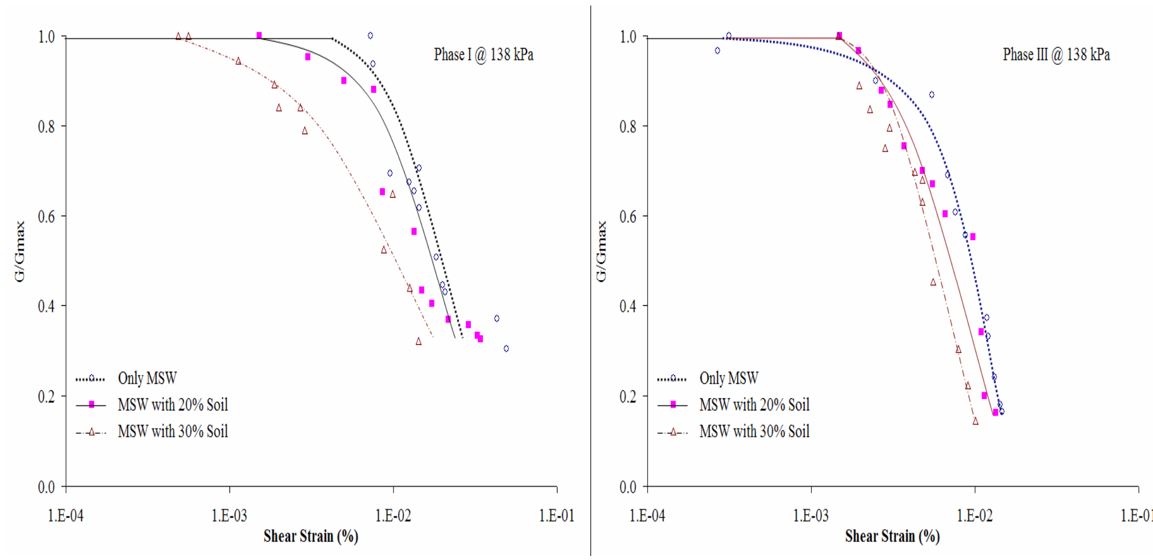
4.3.4.3 Effect of Cover Soil Addition on Shear Modulus

Dynamic properties of MSW samples with and without cover soil at different phases of decomposition are presented in Figures 4.22 and 4.23. The shear modulus reduction curve shifted to the left and the threshold strain decreased with an increase in soil content, which is shown in Figure 4.22 (a). The increase in percentage finer particles in the samples with the addition of cover soil decreased the threshold strain. However, a peculiar behavior was observed in the variation of small-strain shear modulus with cover soil addition. With the addition of cover soil the small-strain shear modulus increased in the initial stages of decomposition and decreased in the final stages of decomposition (Table 4.9). The shear modulus in Phase I increased from 3.42 MPa in samples without soil to 8.10 MPa in samples with 30% soil, whereas in Phase III it decreased from 17.5 MPa in samples without soil to 8.67 MPa in samples with 30% soil. In addition, the slope of Phase I & II samples in Figure 4.23 (a) indicates that these samples are more susceptible to changes in cover soil addition. The addition of cover soil in Phase I & II samples increased the overall percentage of particles finer than 75µm (US sieve No 200), whereas it decreased the overall percentage of particles finer than 75µm in Phase III & IV. Therefore, with an increase in overall percentage of particles finer than 75µm size, Phase I & II samples would have become denser and thereby an increase in its shear modulus. On the contrary, the decrease in overall particle finer than 75µm size in Phase III & IV samples would have decreased its denseness, and thus a decrease in its shear modulus.

Damping curves were also affected by cover soil addition. The damping ratio decreased with an increase in soil content at smaller strain, and it increased with an increase in soil content at larger strains. The damping in Phase I samples at strain less than 10^{-3} % decreased from 9.77 % in samples without cover soil (RS1) to 3.97 % in samples with 30% soil (RS1-30%). However, as shown in Figure 4.22 (b), the effect of cover soil addition was more pronounced in Phase III (decomposed samples) samples than in Phase I samples (fresh). This might be only due to effect of finer particles present in the samples. This effect can be clearly observed from Figure 4.23 (b), in this figure, the steep slope of Phase III & IV samples indicate that these samples are more susceptible to cover soil addition than the samples from initial stages of decomposition. From the observation it can be said that the increase in cover soil content in the final stages of decomposition, increased the overall particle size of the samples, and thereby decreased its material damping considerably. Whereas, the increase in cover soil content in the initial stages of decomposition, decreased the overall particle size of the samples, and hence the decrease in material damping was minimal.

Table 4.9 Variation in dynamic properties with soil content and decomposition

Phase	G_{max}, MPa			D_{min}, %		
	Only MSW	MSW with 20% Soil	MSW with 30% Soil	Only MSW	MSW with 20% Soil	MSW with 30% Soil
I	3.42	5.26	8.10	9.77	4.02	3.97
II	2.33	3.18	6.38	8.68	5.82	4.67
III	17.50	10.99	8.67	6.76	3.94	2.43
IV	27.69	17.08	13.17	5.92	2.73	2.01



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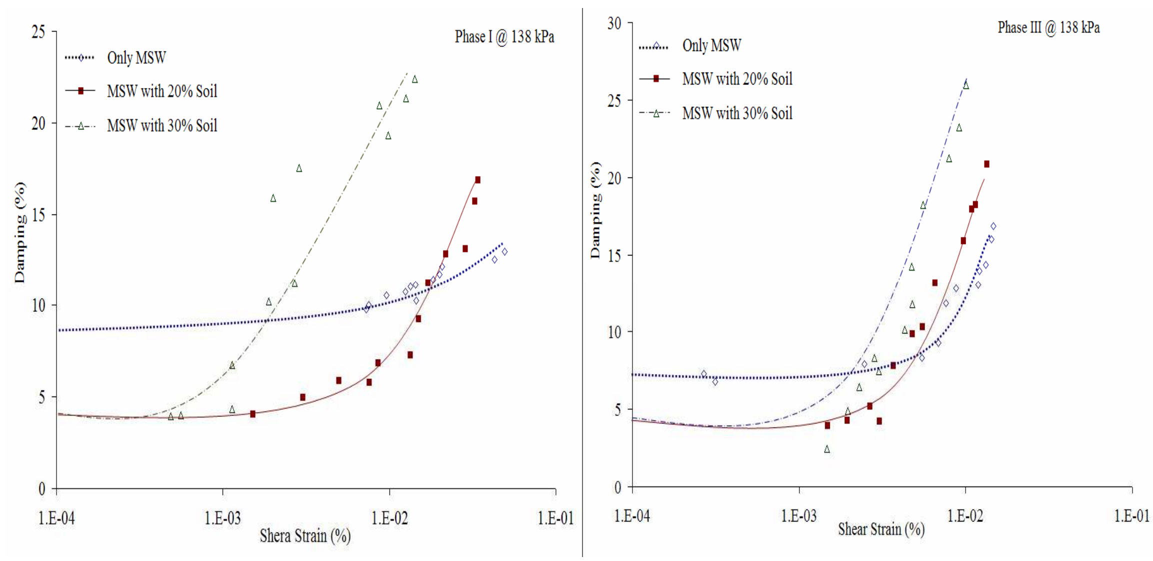

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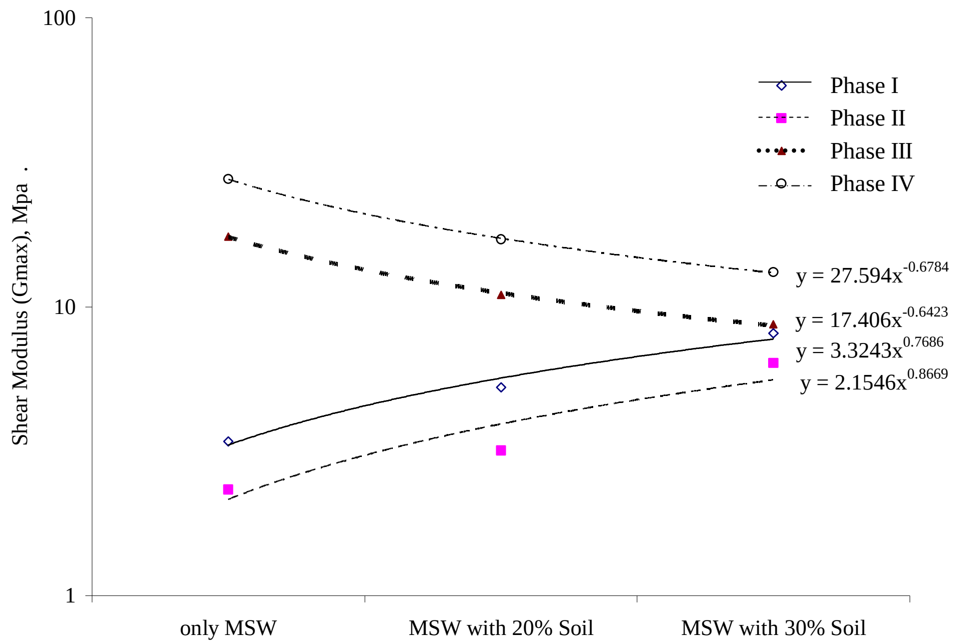
Figure 4.22 Modulus reduction and damping curves in MSW samples (Phase I & III) with and without soil at 138 kPa confinement: (a) shear modulus reduction; (b) material damping



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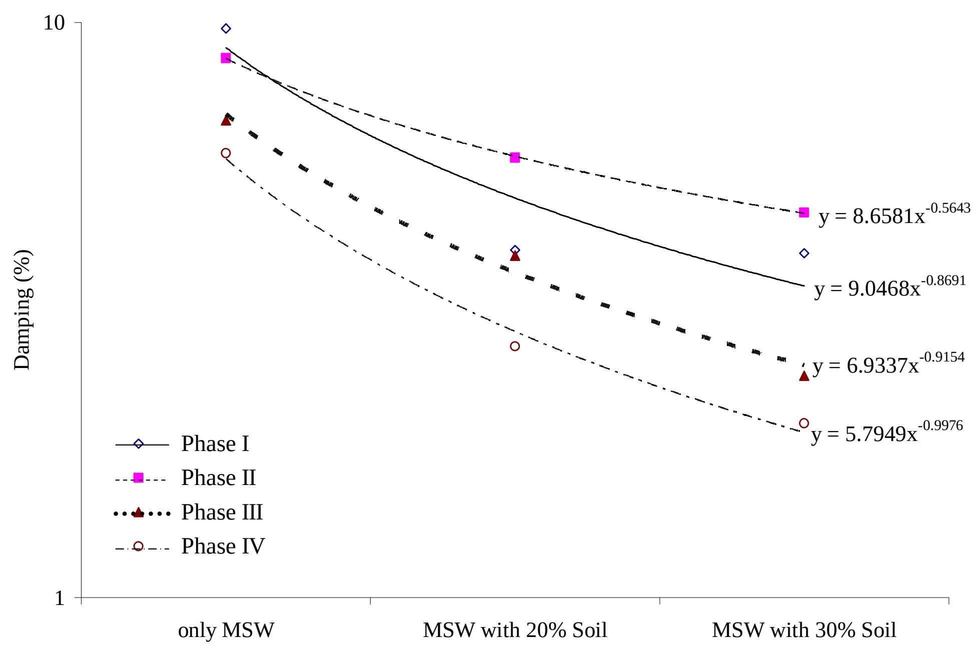
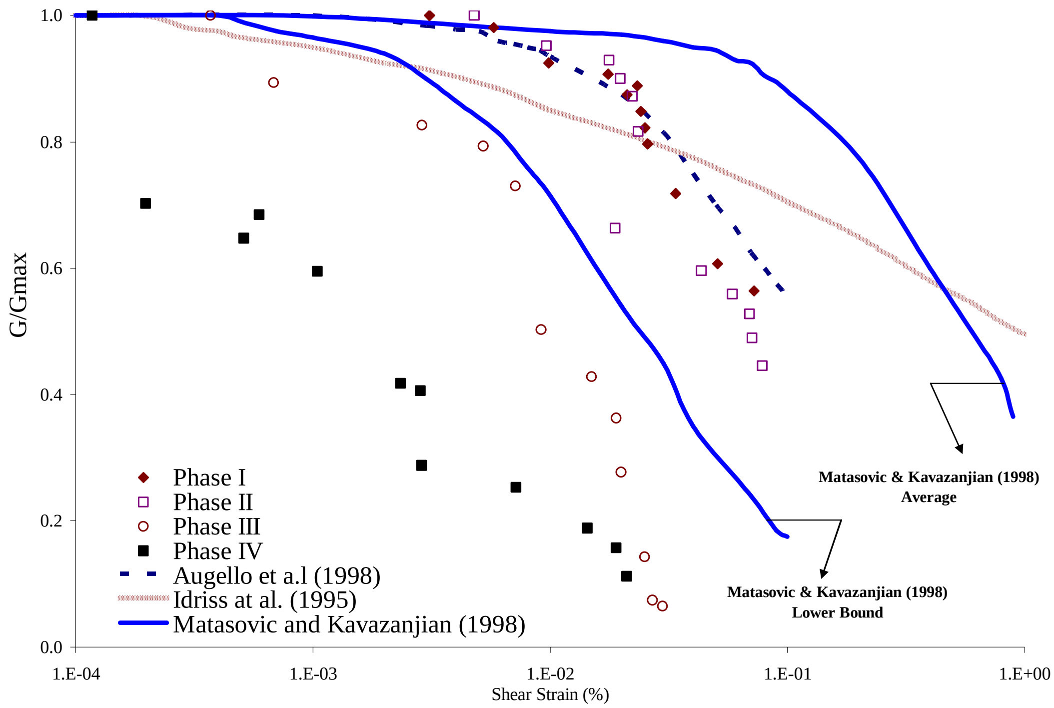


(b)

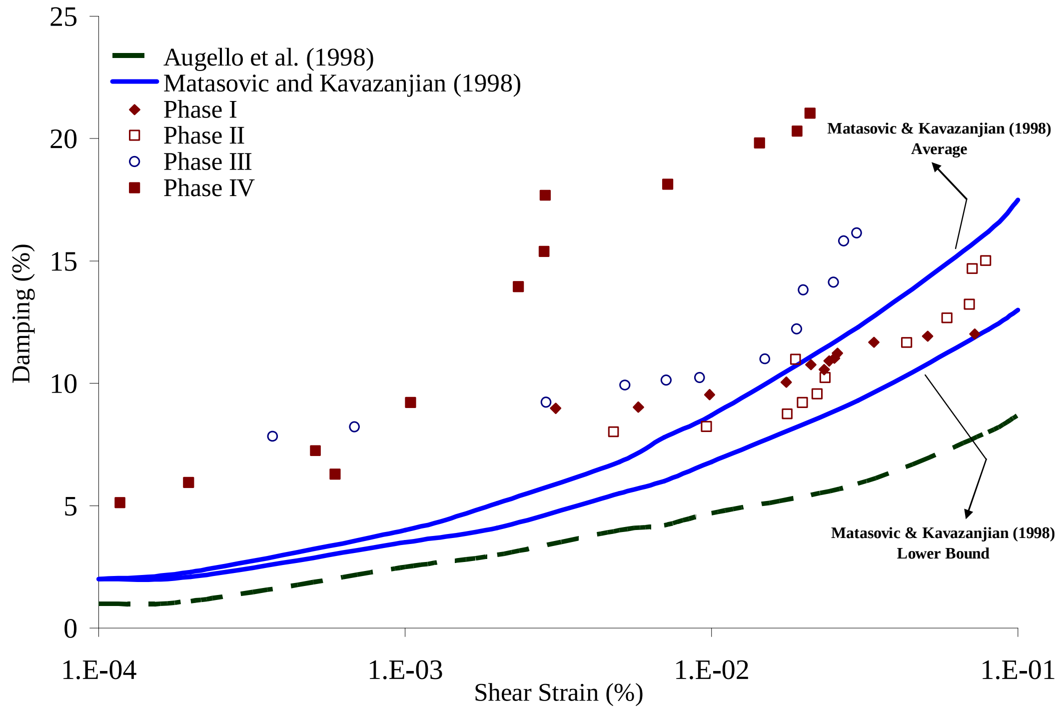
Figure 4.23 Effect of cover soil addition and degradation on modulus reduction and damping curves at 138 kPa confinement: (a) shear modulus reduction; (b) material damping curves

4.3.4.4 Comparison with Existing Results

Dynamic properties of municipal solid waste obtained from laboratory, and back-analysis of observed failures are presented in Figure 4.24. The large scatter observed in the existing results can be attributed to the heterogeneity of waste, and decomposition of waste with time. Idriss et al. (1995) back-calculated the strain-dependent shear modulus reduction and material damping curves using the time histories recorded on top of OII landfill from four earthquakes. Augello et al. (1998) also back calculated the curves from the response of accelerometer for five different earthquake events at the top of OII landfill. The results of shear modulus reduction curves for Phase I & II samples in this study were similar to that of Augello et al. (1998) curve, and are shown in Figure 4.24 (a). Conversely the damping curve for Phase I & II samples shown in Figure 4.24 (b) was not similar to that of Augello et al. (1998) curve. However, the shear modulus reduction and damping curves for Phase I & II samples were within the region recommended by Matasovic and Kavazanjian (1998). The region was developed using the results from large cyclic simple shear tests performed on reconstituted specimens from OII landfill. In addition, Augello et al. (1998), and Idriss et al. (1995) results were also within the region recommended by Matasovic and Kavazanjian (1998). It should be noted that the region suggested by Augello et al. (1998), Idriss et al. (1995), and Matasovic and Kavazanjian (1998) is for the samples from the top of OII landfill, where the waste would be in the initial stage of decomposition. Therefore as the MSW degrades with time its shear modulus and damping ratio are expected to change. However, existing researches (Augello et al., 1998; Idriss et al., 1995; and Matasovic and Kavazanjian, 1998) did not consider the effect of decomposition on dynamic parameters, therefore their recommended region for these parameters need to be revised. In addition, the results also suggest that the seismic stability of bioreactors should be evaluated using the dynamic characteristics as a function of time and decomposition rather than using average values.



(a)



(b)

Figure 4.24 Comparison of Resonant Column results with literature: (a) shear modulus reduction; (b) material damping curves

CHAPTER 5

SLOPE STABILITY ANALYSIS

5.1 Introduction

Landfilling is the primary source of disposal of solid waste in United States. About 54% of the generated solid waste goes in to the landfills (US EPA, 2005). Many of the landfills are located in the vicinity of highly populated areas, this increases the potential hazard associated with the slope failure of a municipal solid waste (MSW) landfill. Stability of landfills is one of the major geotechnical tasks in landfill design and operation. In this chapter, considering the different stages of decomposition, the stability of bioreactor landfill was analyzed. The analyses were performed using two-dimensional FEM PLAXIS program and limit equilibrium program STABL. In the first part the results from the slope stability analysis performed under static condition are presented, followed by the results from the stability analysis performed under dynamic conditions.

5.2 Static Slope Stability Analysis

The stability of bioreactor landfill under normal condition, and as a function of decomposition was performed, and the results are presented in the following sections. The effect of cover soil on slope stability of MSW in bioreactor landfill was also analyzed. Finally, the slope stability results from the finite element program PLAXIS were compared with the results obtained from GSTABL.

5.2.1 Finite Element Modeling

The finite element program PLAXIS has been used to evaluate the stability of bioreactor landfill. The cross-section utilized for the numerical model is presented in Figure 5.1. Four layers of solid waste were considered for the bioreactor landfill. Each layer of solid waste represents different stages of decomposition in the beginning, and with time the decomposition of each layer are expected to change. Accordingly, the solid waste properties need to be adjusted. The bioreactor landfill is modeled as a two dimensional plane strain model. The slope stability analysis was performed for a slope of 3H:1V.

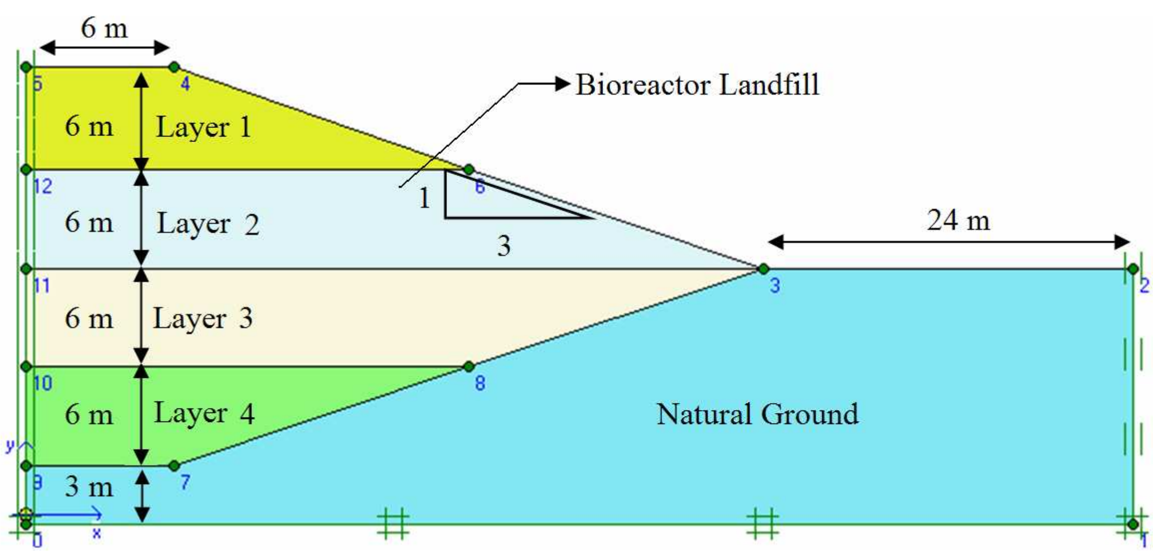


Figure 5.1 Cross-section of the numerical model

5.2.1.1 Mesh Generation and Boundary Conditions

The 15 nodded triangle elements were used in the modeling (Figure 5.2). The mesh generation of PLAXIS version 8.0 used here follows a robust triangulation procedure to form ‘unstructured meshes’. These meshes are considered to be numerically efficient when compared to regular ‘structured meshes’. The powerful 15-node element provides an accurate calculation of stresses and failure loads (PLAXIS, 2002). The two vertical boundaries are free to move, whereas the horizontal boundary is considered to be fixed as presented in Figure 5.3. The foundation soil was considered to be stiff soil and its stability is not considered in this analysis, therefore the bottom boundary is fixed.

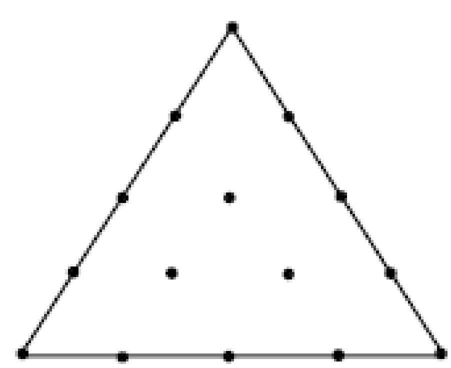


Figure 5.2 15-nodded triangle elements were used in the modeling

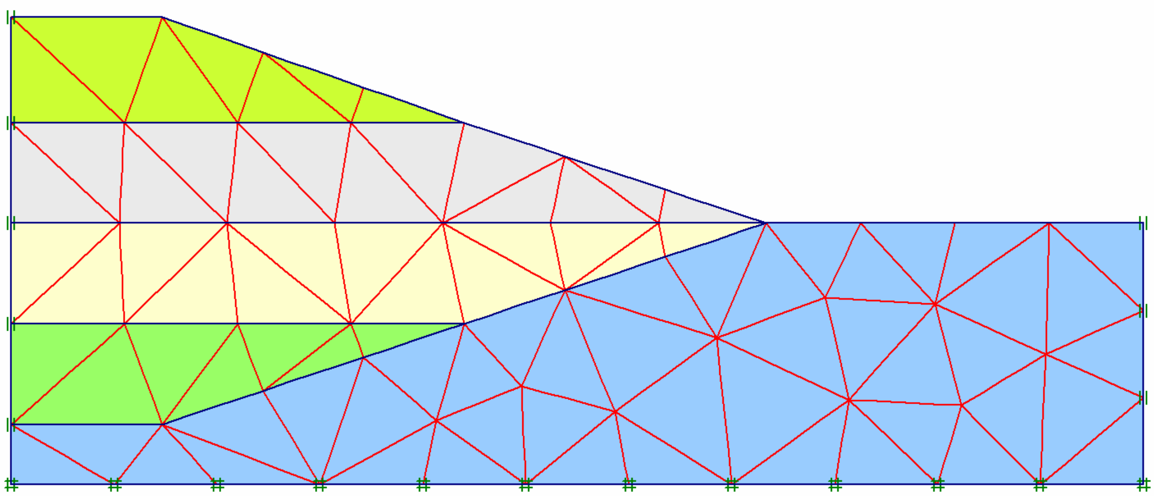


Figure 5.3 Cross-section of generated mesh

5.2.1.2 Material Model

The Mohr-Coulomb model was used for this analysis. This model involves five parameters, namely Young's modulus, E, Poisson's ratio, υ, the cohesion, *c*, the friction angle, ϕ, and the dilatancy angle, ψ. In this case dilatancy angle was assumed to be zero, since it is close to zero for clay and for sands with friction angle less than 30°.

5.2.1.3 Material Parameters

The parameters used in the FEM analysis for the different phases of decomposition are presented in Table 5.1. Some of the important waste properties required for the analyses are unit weight, shear strength, stiffness, and permeability. These parameters are obtained from the extensive laboratory studies performed on MSW samples. The MSW samples at each phase of decomposition were obtained from the simulated bioreactor landfills in the laboratory.

Table 5.1 Parameters for M-C Model in FEM analysis

	Material Set	Drainage Condition	Unit Weight γ_{moist}, kN/m^3	Permeability, m/day $\times 10^{-3}$	Poisons Ratio*	Shear wave velocity v_s, m/sec	Cohesion c, kN/m^2	Friction Angle Φ°
Only MSW	Phase I	Drained	9.01	190	0.25	15.7	11.2	26.7
	Phase II	Drained	9.44	173	0.4	19.5	20.5	21.5
	Phase III	Drained	10.22	130	0.42	41.4	5.3	20.6
	Phase IV	Drained	11.02	86	0.45	50.1	2.4	19
	Natural ground	Drained	15.90	1	0.35	11.8	9.6	30
MSW with 20% Soil	Phase I	Drained	10.22	130	0.25	17.3	22.3	29.0
	Phase II	Drained	10.60	86	0.4	22.7	30.7	24.9
	Phase III	Drained	10.94	78	0.42	31.7	13.7	23.2
	Phase IV	Drained	11.68	60	0.45	38.2	9.1	21.8
	Natural ground	Drained	15.90	1	0.35	11.8	9.6	30
MSW with 30% Soil	Phase I	Drained	10.80	78	0.25	23.8	24.5	33.1
	Phase II	Drained	11.31	69	0.4	27.4	34	29.4
	Phase III	Drained	11.62	35	0.42	27.3	13.1	26.4
	Phase IV	Drained	11.88	9	0.45	33.3	12.9	23.7
	Natural ground	Drained	15.90	1	0.35	11.8	9.6	30

* Obtained from Zekkos et al. (2006)

Unit weight of solid waste is considered to be an important factor in estimating the stability of landfills. It is directly influenced by the type of waste, degree of decomposition, degree of compaction, volume of daily cover, compaction degree, quantity of leachate produced, and the depth from which sample is taken. The unit weight values to be used in the analysis are presented in Table 5.1. The unit weight values increased with the degree of decomposition, and also with the addition of cover soil. As the waste degraded, larger particles in the MSW are broken down into smaller pieces, and accordingly, reduced the voids and increased the mass of the solid waste. A same trend was observed by Kavazanjian (2003).

The shear strength parameters are dependent on variables such as age, composition, and moisture content of the waste. The results from CD Triaxial test in this study confirmed that the shear strength parameters are strongly influenced by the degree of decomposition of MSW. The shear strength parameters of solid waste estimated at each of the four phase of decomposition using CD triaxial test are presented in Table 5.1.

PLAXIS uses alternative stiffness moduli, such as shear modulus, G, and the oedometer modulus, E_{oed}. These stiffness moduli relate to Young's modulus according to Hooke's law of isotropic elasticity, which involves Poisson's ratio. The shear modulus values estimated from this study was used in the analysis. Poisson's ratio was assumed to be higher at advanced stage of decomposition and lower for fresh waste. The Poisson's ratio values estimated using this assumption was found to be in agreement with those observed by Zekkos et al. (2006) at Tri-Cities landfill in

California. Zekkos et al. (2006) also observed an increase in unit weight and the small-strain shear modulus on specimens with increasing amounts of finer particles (decomposed waste).

5.2.1.4 Analyses Type

The factor of safety in PLAXIS was computed using *Phi-c reduction* method at each stage of decomposition. This method follows the load advancement number of steps. The incremental multiplier is used to specify the increment of the strength reduction of the first calculation step. The strength parameters are reduced successively in each step until all the steps have been performed. The final step should result in a fully developed failure mechanism, if not the calculation must be repeated with a larger number of additional steps. Once the failure mechanism is reached, the factor of safety is given by (PLAXIS, 2002):

$$SF = \frac{available}{strength} \frac{strength}{atfailure} = \text{value of } \Sigma Msf \text{ at failure}$$

5.2.1.5 Analyses Cases

A closed MSW landfill may not have a single waste age, but rather have different ages associated with various cells within the landfill and their respective stabilization stages (Pohland et al., 1993). The age of waste in MSW landfill can be divided into four stages: aerobic phase, anaerobic phase, accelerated methane production phase, and decelerated methane production phase. Layers 1 – 4 were assumed to represent the stages of landfilling, and each of these layers is at different stage of decomposition. It is assumed that immediately after landfill closure layer 1 is at initial phase of decomposition, at the same time, it is possible that layer 2, 3, and 4 would be at second, third, and fourth phases of decomposition, respectively. With time solid waste layers may advance to next phases of decomposition. Finally after complete stabilization, all the layers would be at the final stage of decomposition. Table 5.2 shows the phases of decomposition at different cases (i.e., different time periods). In addition, the slope stability analysis for the bioreactor landfill was also evaluated at three different conditions, namely, MSW without soil, MSW with 20% cover soil, and MSW with 30% cover soil.

Table 5.2 Phases of decomposition at different stages

	Layer 1	Layer 2	Layer 3	Layer 4
Stage 1	Phase I	Phase II	Phase III	Phase IV
Stage 2	Phase II	Phase III	Phase IV	Phase IV
Stage 3	Phase III	Phase IV	Phase IV	Phase IV
Stage 4	Phase IV	Phase IV	Phase IV	Phase IV

5.2.2. Limit Equilibrium GSTABL Slope Stability Analysis

The solid waste parameters used in the analysis are shown in Table 5.3. The solid waste parameters, dimensions, and the procedure followed to compute the stability at each case of decomposition in the bioreactor landfill are same as that used in FEM analysis.

Table 5.3 Parameters used in GSTABL analysis

	Material Set	Unit Weight γ_{moist}, kN/m^3	Cohesion c, kN/m^2	Friction Angle Φ°
Only MSW	Phase I	9.01	11.2	26.7
	Phase II	9.44	20.5	21.5
	Phase III	10.22	5.3	20.6
	Phase IV	11.02	2.4	19
	Natural ground	15.90	9.6	30
MSW with 20% Soil	Phase I	10.22	22.3	29.0
	Phase II	10.60	30.7	24.9
	Phase III	10.94	13.7	23.2
	Phase IV	11.68	9.1	21.8
	Natural ground	15.90	9.6	30
MSW with 30% Soil	Phase I	10.80	24.5	33.1
	Phase II	11.31	34	29.4
	Phase III	11.62	13.1	26.4
	Phase IV	11.88	12.9	23.7
	Natural ground	15.90	9.6	30

5.2.3 Effect of Decomposition on MSW Stability

The decomposition of MSW with time affected the stability of bioreactor landfills considerably. Results from slope stability analysis for a slope of 3:1 are presented in Figure 5.4. Figure 5.4 shows the safety factors calculated by the modified Bishop method using GSTABL, and 5.5 shows the total incremental displacements output from PLAXIS. It can be observed from Figure 5.4 and 5.5 that the critical failure surface predicted by PLAXIS and GSTABL are almost the same. Further, the shear strains and maximum slope movements results from PLAXIS in Stage 3, presented in Figure 5.6 (a) and (b), confirms the failure pattern predicted by GSTABL, where the number of points yielded are more (Figure 5.6 (c)). However, it should be noted that

GSTABL predicted higher factor of safety than PLAXIS at different phases of decomposition for all the conditions evaluated.

The factors of safety predicted by both FEM and limit equilibrium program GSTABL are presented in Figure 5.7. The factor of safety decreased as the decomposition of MSW in bioreactor landfills increased with time. The factor of safety from FEM analysis decreased from 2.31 in Stage 1 (immediately after closure), to 1.34 in Stage 4 (after complete stabilization/decomposition). With time each solid waste layer in the landfill goes to the next stage of decomposition, and the strength properties of solid waste decreases. Therefore, the decrease in shear strength with each stage of decomposition decreased the factor of safety. The results also suggest that the stability of bioreactors should be evaluated using the strength characteristics determined as a function of time and decomposition, rather than using average values.

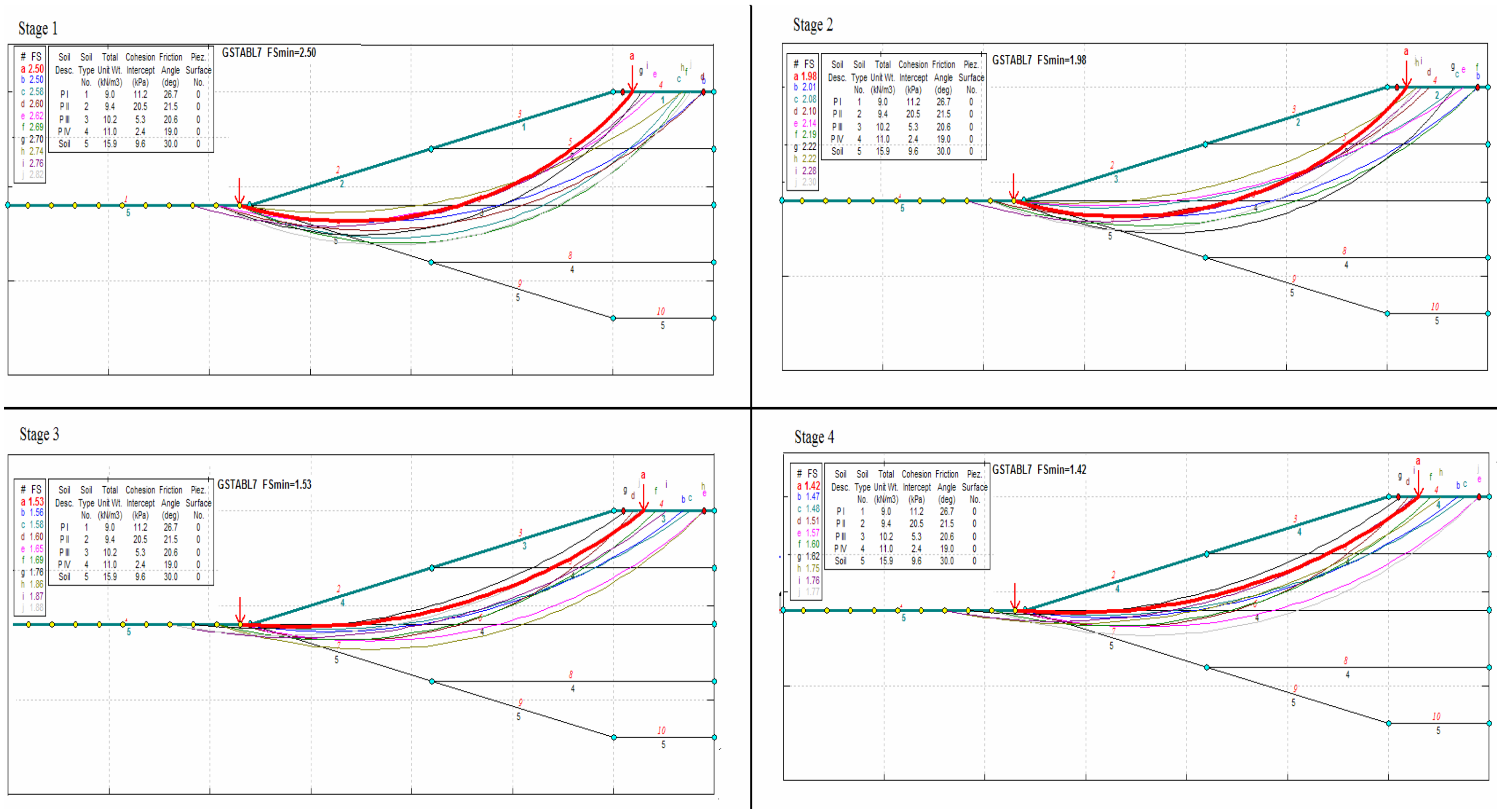


Figure 5.4 Safety factors calculated by the modified Bishop method using GSTABL in stage 1 for a slope of 3:1.

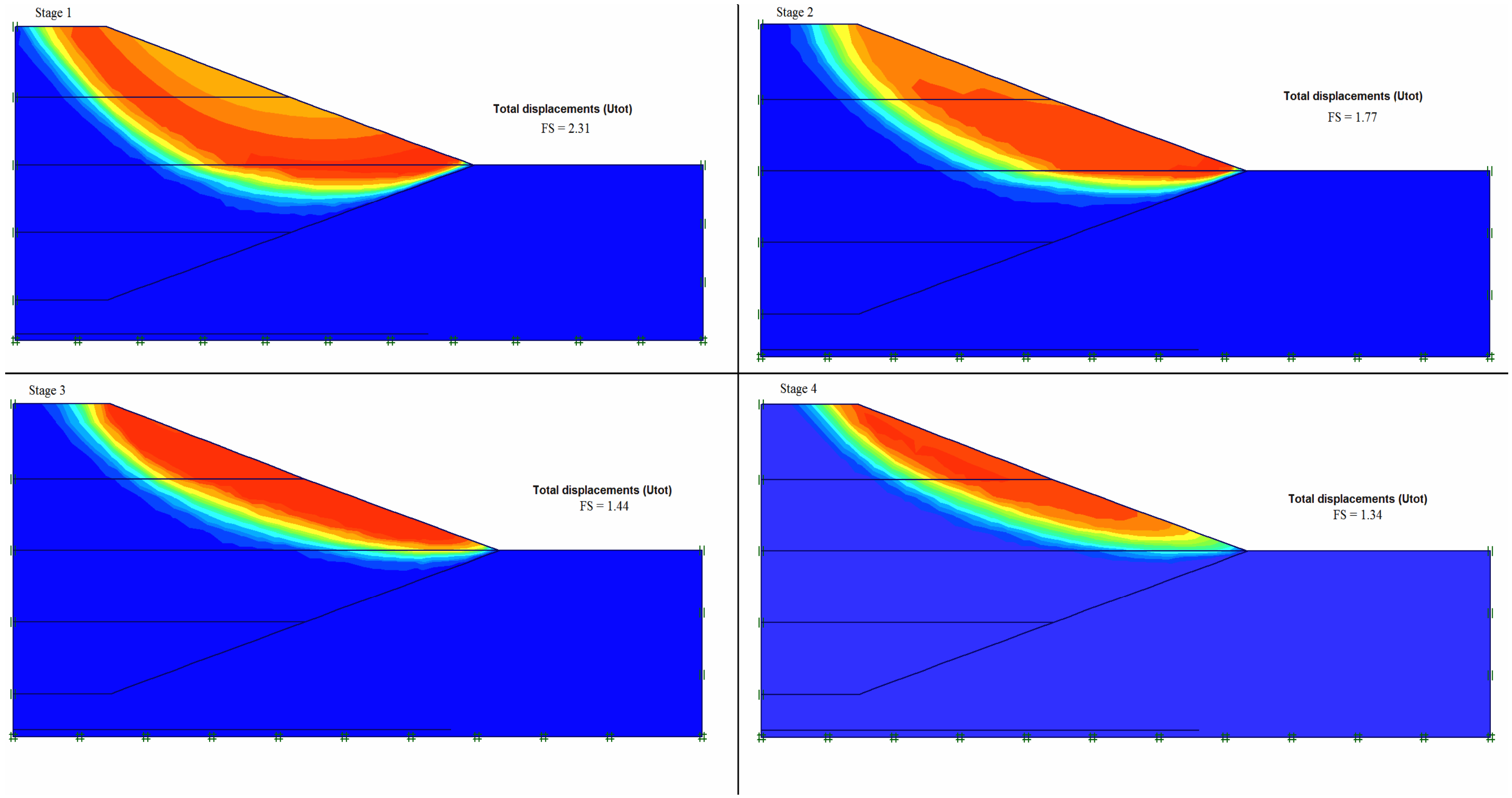
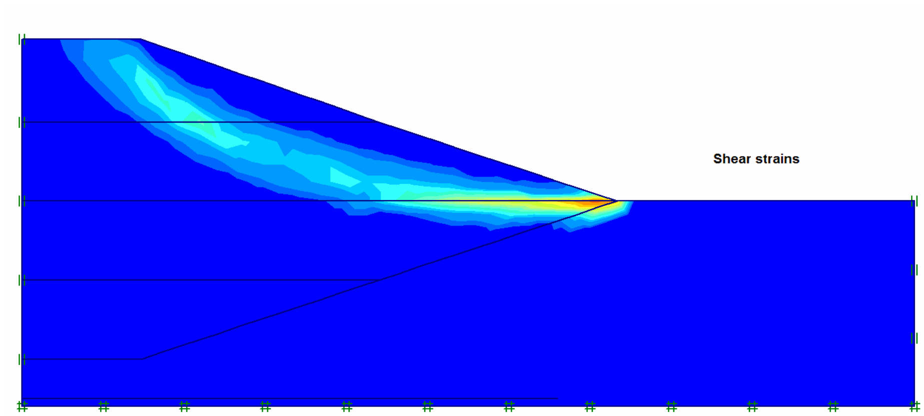
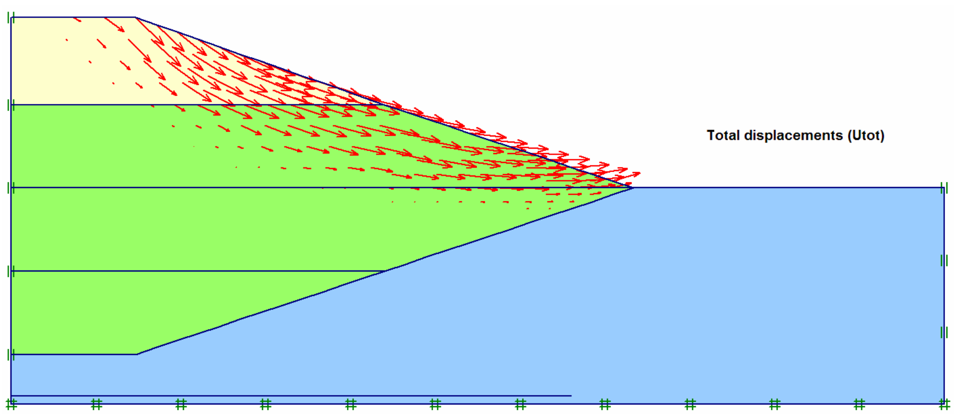


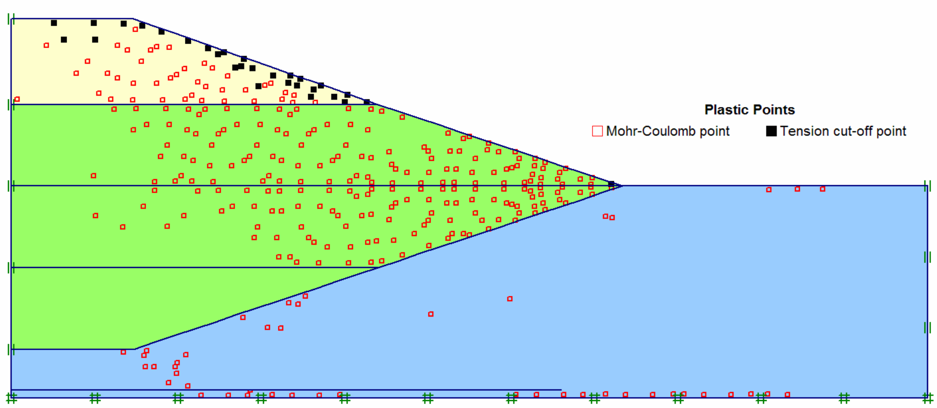
Figure 5.5 total incremental displacements from PLAXIS in stage 1 for a slope of 3:1



(a)



(b)



(c)

Figure 5.6 Outputs from PLAXIS analysis in stage 3 for a slope of 3:1: (a) shear strains; (b) total displacements; (c) plastic points

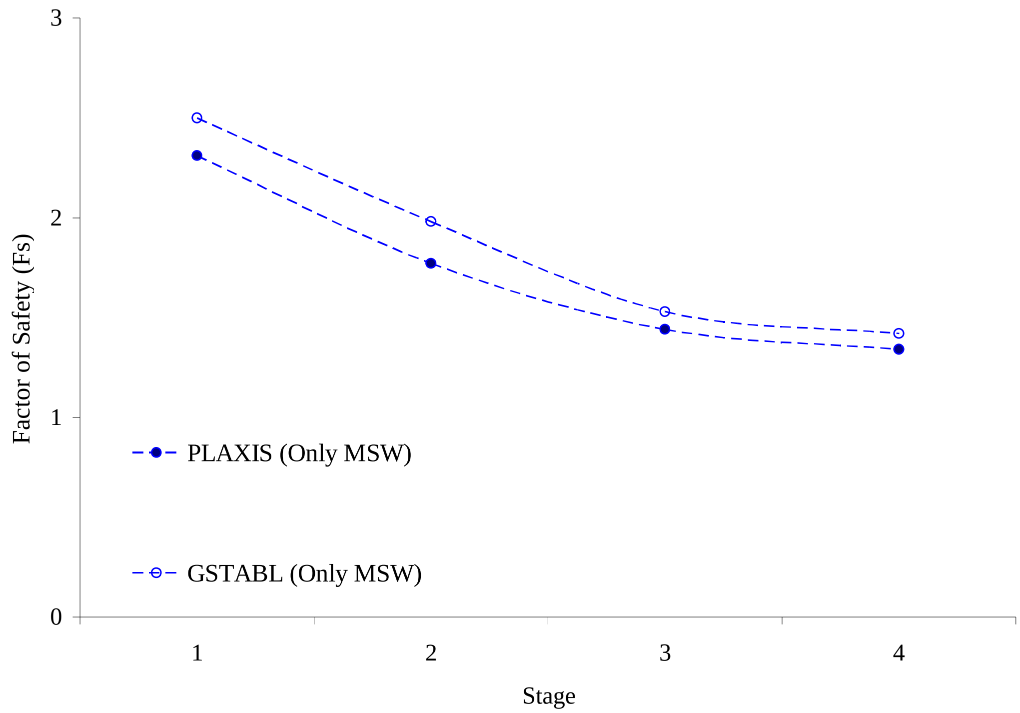


Figure 5.7 Factor of safeties from PLAXIS and GSTABL analysis at different stages of decomposition

5.2.4 Effect of Cover Soil Addition on MSW Stability

The factor of safety increased as the cover soil content increased in bioreactor landfills. The factors of safety predicted by both FEM and limit equilibrium program GSTABL at different cover soil content are presented in Figure 5.8. The factor of safety in Stage 1 from FEM analysis increased from 2.31 in MSW without soil, to 3.03 in MSW with 30% soil. The cover soil had a reinforcing effect on the shear strength properties of MSW in bioreactor landfill. The cover soil added to the samples entered the inter-particle voids, acted as a reinforcing agent, and increased its strength in all phases of decomposition. Hence, the increase in shear strength with the addition of cover soil increased the factor of safety.

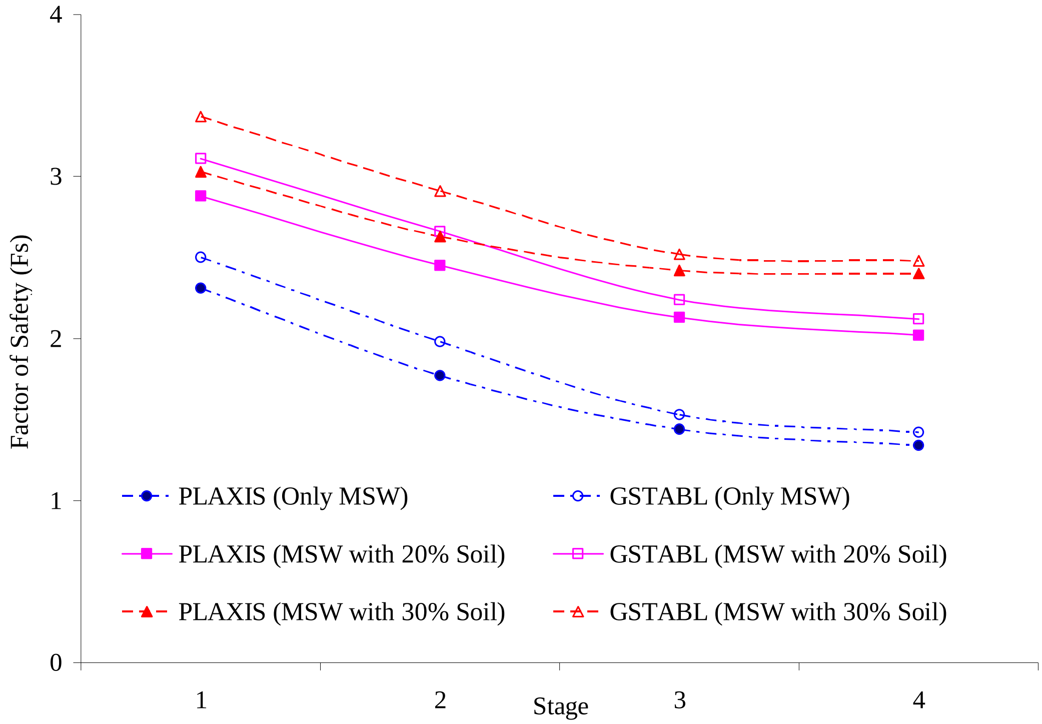


Figure 5.8 Factor of safeties from PLAXIS and GSTABL analysis at different cover soil content

5.2.5 Comparison between PLAXIS and GSTABL Results

The solid waste properties and landfill geometries used in the FEM model are similar to those entered in the limit equilibrium GSTABL analysis. However, significantly different factors of safety were computed by both the programs (Table 5.4). The factor of safety predicted by GSTABL is higher than the factor of safety predicted by PLAXIS analysis. The principal limitation of limit equilibrium methods is that the ground deformations are not taken into account (FHWA, 2003). It is assumed that a state of limit equilibrium is achieved instantaneously along the entire failure surface (Figure 5.4). This assumption eliminates the ability to predict localized failure, progressive failure, and slope movements that may occur even though the global factor of safety may be greater than 1.0. Analysis methods that are capable of capturing these features are limited to numerical methods because of the complex boundary conditions, the need to introduce soil stress-strain behavior, and other factors (FHWA, 2003). These results suggest that the limit equilibrium method overestimates the factor of safety, and emphasis the need to use the finite element method when there is a need to go beyond limit equilibrium analysis.

Table 5.4 Factor of safeties from PLAXIS and GSTABL analysis at different cover soil content

Stage	Only MSW		MSW with 20% Soil		MSW with 30% Soil	
	PLAXIS	GSTABL	PLAXIS	GSTABL	PLAXIS	GSTABL
1	2.31	2.5	2.88	3.11	3.03	3.37
2	1.77	1.98	2.45	2.66	2.63	2.91
3	1.44	1.53	2.13	2.24	2.42	2.52
4	1.34	1.42	2.02	2.12	2.4	2.48

5.3 Seismic Stability Analysis

About 50% of the continental United States comes under the designated seismic impact zone. A seismic impact zone is defined in the regulations as the area with a ten percent or greater probability that the maximum horizontal acceleration in lithified material will exceed 0.1 g in 250 years (Repetto and Bray, 1992). Therefore the newly proposed federal regulations have focused increase attention on seismic design of solid waste fills. They have mandated that the solid waste landfills located in the seismic impact zones should be designed to resist the earthquake. In this section the dynamic stability of MSW in bioreactor landfill was analyzed considering the degree of decomposition. A seismic slope stability analysis was performed using finite element model (FEM) PLAXIS. Also, the results from the finite element program PLAXIS were compared with the results from limit equilibrium program STABL.

5.3.1 Finite Element Modeling

The finite element program PLAXIS has been adopted for evaluating the seismic stability of bioreactor landfill. The cross-section utilized for the numerical model, material model, analysis cases, and material parameter are same as those used in static stability analysis. Except that the dynamic analysis uses additional damping parameter, which is discussed in the following sections. The bioreactor landfill is modeled as a two dimensional plane strain model.

The damping ratio was affected by the degradation. However the effect of damping ratio was more pronounced only at strains greater than 10^{-2} %. For smaller strains the material damping ratio is not significantly reduced with strain, but remained roughly constant at values of about 6 -8 % (Hossain et al. 2007). The Rayleigh damping coefficients were determined from the following relationship, and at two frequencies of vibration (PLAXIS, 2002).

$$\alpha + \beta\omega_i^2 = 2\omega_i\xi_i$$

Where α and β are Rayleigh damping coefficients, ξ_i is the damping ratio, and ω_i is the corresponding frequency.

5.3.1.1 Analysis Type

The calculation in PLAXIS involved two phases. In the first phase dynamic analysis was performed followed by the slope stability analysis using *Phi-c reduction* calculation type at each case of decomposition. Phi-c reduction is an option available in

PLAXIS to compute factor of safety. This option can be selected as a separate calculation type in the general tab sheet (PLAXIS, 2002). Dynamic loads are introduced into the model by means of prescribed displacements. In earthquake problems the dynamic loading source is usually applied along the bottom of the model resulting to shear waves that propagates upwards (PLAXIS, 2002). In this analysis the earthquake records from Sakarya earthquake are used. This earthquake had a magnitude of 7.4 occurred in Kocaeli Province of Turkey. The earthquake was a result of lateral movement of North Anatolian Fault. The traced fault rupture length on the ground surface is about 110 km. the right lateral displacement ranges up to 4.9 meters, and average about 2.5 – 3 meters. The acceleration time history of this earthquake is shown in Figure 5.9, and the dynamic parameters used in the analysis are presented in Table 5.5.

For slope stability analysis in *Phi-c reduction* type of calculation the load advancement number of steps procedure is followed. The incremental multiplier is used to specify the increment of the strength reduction of the first calculation step. The strength parameters are reduced successively in each step until all the steps have been performed. The final step should result in a fully developed failure mechanism, if not the calculation must be repeated with a larger number of additional steps. Once the failure mechanism is reached, the factor of safety is given by (PLAXIS, 2002):

$$SF = \frac{available}{strength}\,\frac{strength}{atfailure} = \text{value of } \Sigma Msf \text{ at failure}$$

Table 5.5 Dynamic parameters used in the modeling

Component	Sakarya Earthquake
Magnitude	7.4
Peak acceleration value (g)	0.376
Duration (sec)	19.4
Frequency (Hz)	0.86
Displacement amplitude (m)	0.762

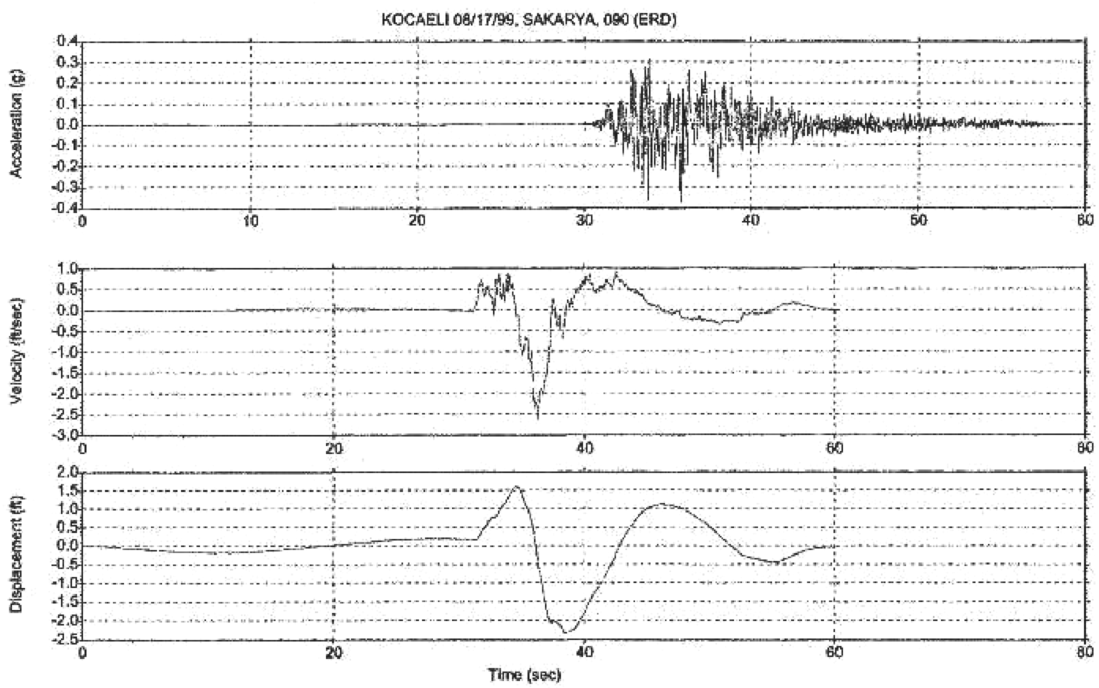


Figure 5.9 Acceleration-time history of Sakarya Earthquake (Karadeniz, 2003)

5.3.2 Limit Equilibrium GSTABL Slope Stability Analysis

The seismic stability of the slope was analyzed using GSTABL slope stability software. GSTABL with STEDwin is a powerful, comprehensive a 2-dimensional, limit equilibrium slope stability program. GSTABL performs all the slope stability analyses calculations, while the STEDwin provides an extremely user-friendly graphical user interface. The solid waste parameters used in the analysis are same as those used in static analysis. The basis behind the assumption of these values was discussed in the previous sections. The solid waste parameters, dimensions, and the procedure followed to compute the stability at each case of decomposition in the bioreactor landfill are same as that used in FEM analysis. A pseudostatic seismic coefficient of 0.376 g was used in the analysis for each of the different stages analyzed.

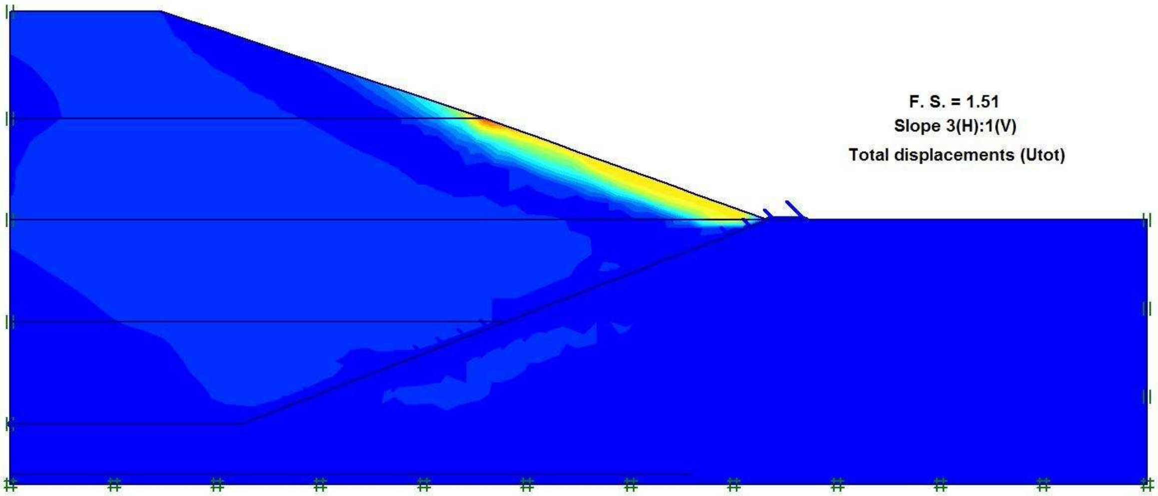
5.3.3 Effect of Decomposition on MSW Stability

The seismic stability of bioreactors was analyzed by using both finite element program PLAXIS and slope stability software GSTABL. Results from dynamic slope stability analysis in Stage 1 for a slope of 3:1 are presented in Figure 5.10. Figure 5.10 (a) shows the safety factors calculated by the modified Bishop method using GSTABL, and 5.9 (b) shows the total incremental displacements output from PLAXIS, after the Sakarya station earthquake. It can be observed from Figure 5.10 that the critical failure surface predicted by PLAXIS and GSTABL are almost the same.

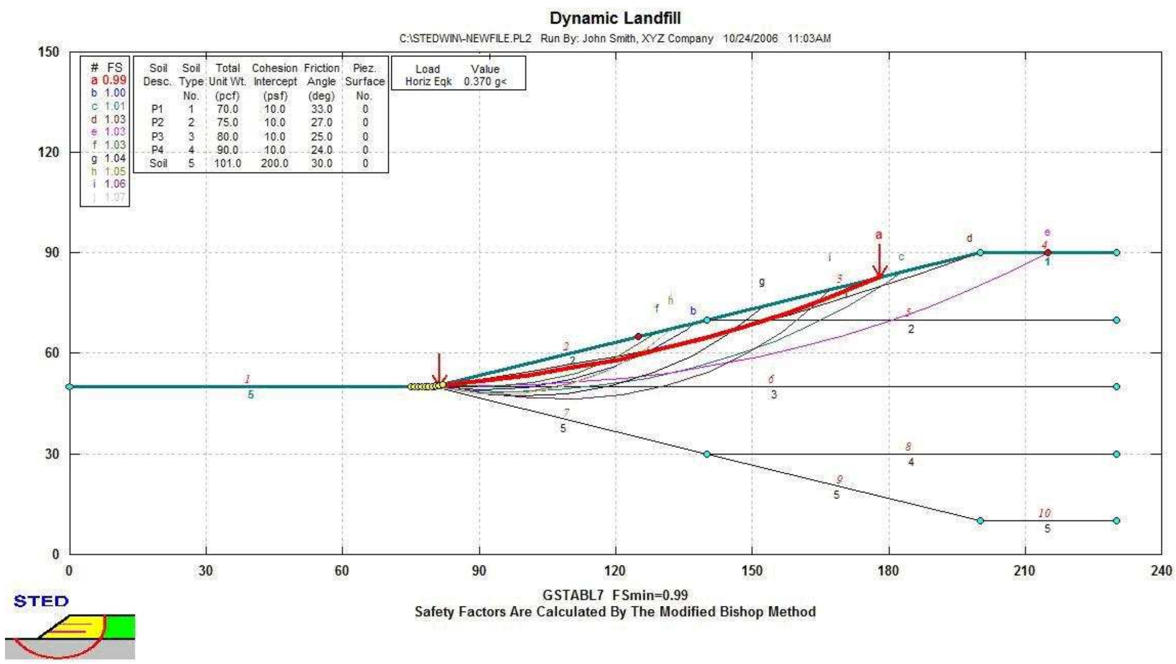
The factors of safety predicted by both FEM and limit equilibrium program GSTABL are presented in Table 5.6. The factor of safety decreased as the MSW degrades with time. The reduction in factor of safety for dynamic analysis was more pronounced in limit equilibrium program GSTABL than in FEM PLAXIS. In all the stages studied GSTABL underestimated the factor of safety in seismic stability analysis.

In the dynamic analysis, GSTABL does not include the damping properties of solid waste. Whereas, the laboratory results indicated that the solid waste material induces significant damping. As we can observe from Figure 5.11 the material damping values significantly reduced the acceleration of the earthquake, and there by increased the factor of safety.

The principal limitation of limit equilibrium methods is that ground deformations are not taken into account (FHWA, 2003). It is assumed that a state of limit equilibrium is achieved instantaneously along the entire failure surface. This assumption eliminates the ability to predict localized failure, progressive failure, and slope movements that may occur even though the global factor of safety may be greater than 1.0. These results suggest that the limit equilibrium method underestimates the factor of safety for dynamic analysis. And it also emphasis the utilization of finite element method when there is a need to go beyond limit equilibrium analysis.



(a)



(b)

Figure 5.10 Results from seismic slope stability analysis in case 1 for a slope of 3:1: (a) total incremental displacements from PLAXIS; (b) safety factors calculated by the modified Bishop method using GSTABL

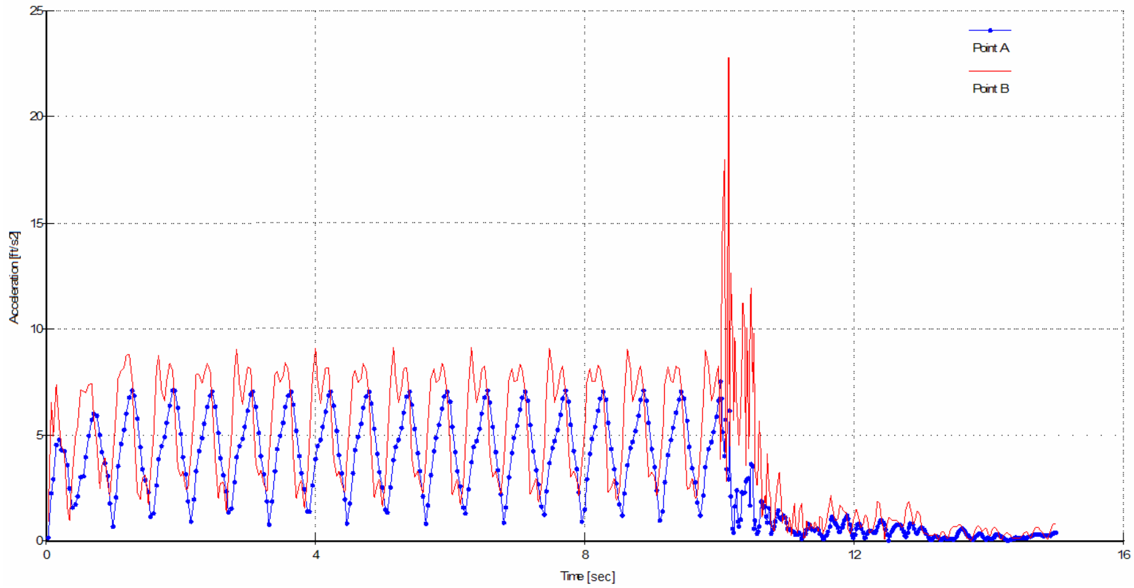


Figure 5.11 Maximum horizontal acceleration with time

Table 5.6 Factor of safety from PLAXIS and GSTABL analysis

Stage	Dynamic	
	PLAXIS	**GSTABL**
Stage 1	1.51	0.89
Stage 2	1.47	0.67
Stage 3	1.34	0.51
Stage 4	1.33	0.48

CHAPTER 6

SUMMARY AND CONCLUSION

Bioreactor landfills are operated to enhance refuse decomposition, gas production, and waste stabilization. The major aspect of bioreactor landfill operation is the recirculation of collected leachate back through the refuse mass. The addition of leachate to accelerate the decomposition changes the physical and engineering properties of waste. Therefore the geotechnical characteristics of waste mass are considerably affected. Eight bioreactor landfills were setup in the laboratory to generate MSW samples at different stages of decomposition. Consolidated drained triaxial tests and resonant column tests were performed using statically compacted specimens at their natural moisture content to determine the shear strength and dynamic characteristics of MSW in bioreactor landfills. In addition, in order to study the effect of cover soils present in solid waste, samples were remolded at three different conditions: samples without soil, and those with 20 and 30% of soil. The results from the experimental program are summarized as follows:

- Paper is a major degradable component of MSW, and it has a strong reinforcing effect on shear strength. However, as the MSW degrades with time, the representation of paper in MSW decreases. At the same time, percentage of plastic content in MSW increases significantly, which creates more potential sliding surfaces. Due to these combined effect, shear strength of MSW are expected to decrease with time and decomposition.

- Based on the results from CD Triaxial test, at 20% strain level the friction angle of MSW decreased from 26.7° in Phase I, to 19° in Phase IV, and cohesion decreased from 11.2 KPa in Phase I to 2.4 KPa at Phase IV.
- The cover soil had a reinforcing effect on the shear strength properties of MSW in bioreactor landfill. Shear strength envelope shifted up with an increase in soil percentage in all the four phases of decomposition. Based on the experimental results, the friction angle of MSW were 26.7°, 29°, 33.1° for samples without soil, samples with 20% soil, and samples with 30% soil, respectively. Therefore, cover soils are expected to increase the shear strength of MSW.
- The shear strength parameters increased with an increase in strain for all the phases of decomposition. The friction angle increased from 17.7° at 10% strain, to 24.7° at 15% strain, and finally to 28.4° at 20% stain for Phase I samples. These results clearly indicate that shear strength of MSW is also a function of axial strain.
- As the material degraded, the shear modulus reduction curves shifted to the left and the threshold strain decreased. This shift is due to the breakdown of fibrous nature of solid waste particles as it degrades. The stronger Phase I samples required higher shear strains to induce plastic deformation, whereas the highly degraded Phase IV samples required lesser shear strain to induce the plastic deformation.

- The shear modulus increased from 2.41 MPa in Phase I to 17.88 MPa in Phase IV at a constant confinement of 69 kPa. Higher percentage of fines in the final stages of decomposition increased the shear modulus of MSW.
- Effect of confinement on small-strain shear modulus was less pronounced in initial stages of decomposition than in the later stages of decomposition. The fibrous materials in Phase I samples did not allow the sample to get denser with an increase in confinement, resulting in smaller increase in shear modulus.
- The addition of cover soil to MSW increases its shear modulus in the initial stages of decomposition, and it decreased its shear modulus in advanced stages of decomposition.
- Damping ratio increased from 12% in Phase I to 21% in Phase IV specimens. At larger strain the fibrous nature of Phase I samples would have decreased the material damping, whereas, the degraded Phase IV samples with a minimal reinforcement would have increased its material damping. Also, damping ratio was not quiet affected with an increase in confinement
- The increase in soil content in the initial stages of decomposition decreased the representation of reinforcing fibers and thereby increased its damping.
- The factor of safety estimated from both PLAXIS and GSTABL decreased as the solid waste degraded with time in both static and dynamic analysis.
- The limit equilibrium method overestimates the factor of safety for static analysis and underestimates the factor of safety for dynamic analysis. Therefore,

- The factor of safety values for dynamic analysis in Stage 1 decreased from 1.51 in FEM PLAXIS analysis to 0.99 in limit equilibrium GSTABL analysis.
- Critical failure surface predicted by PLAXIS and GSTABL were very similar. PLAXIS predicts the progressive failure pattern, including the plastic points on the slope, and considers damping coefficient in dynamic analysis. However, in GSTABL user defines the range of failure slope locations. GSTABL did not consider the material damping values and underestimated the seismic stability of solid waste slopes.

Based on the results from this extensive study, it is concluded that the stability of bioreactor landfills should be evaluated using the strength characteristics determined as a function of time and decomposition rather than using average values. Further, it also emphasis the use of finite element method when there is a need to go beyond limit equilibrium analysis.

CHAPTER 7

RECOMMENDATION FOR FUTURE STUDY

Based on the results from this study the following recommendations are made:

1. Inclusion of control materials along with the MSW samples in the reactor might be useful to identify the extent of degradation.
2. Further study on influence of cover soils with different generally used cover soils.
3. Based on the information generated in this research, evaluation of failed waste slopes may provide useful insight.
4. MSW typically consists of food, paper, and plastics as a major constituent. Variation in the composition of these materials can significantly affect the waste response in different ways. Therefore the strength properties of MSW evaluated with different waste composition may provide additional insight for landfills where the composition of waste may be known and can help the engineer make better design decisions.

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BIOGRAPHICAL INFORMATION

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