PERMEABILITY OF MUNICIPAL SOLID WASTE IN BIOREACTOR LANDFILL WITH DEGRADATION

by

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ABSTRACT

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Bioreactor landfills are operated and controlled to accelerate refuse decomposition, gas production and biological stabilization of the municipal solid waste. In favorable environmental conditions biological stabilization of the waste in a bioreactor landfill is expected to be much faster when compared to the conventional landfill. The fundamental process used for waste stabilization in bioreactor landfill is leachate recirculation, which creates a favorable environment for rapid microbial decomposition of the biodegradable components of solid waste. Therefore, clear understanding of the mechanism of moisture movement within the solid waste would be necessary for successful design and operation of the bioreactor landfill.

Permeability is an important parameter during the design of leachate collection and recirculation system. In the current study an experimental program was designed to determine the variation of coefficient of permeability of MSW with degradation and to determine the influence of density and cover soil on permeability of MSW.

MSW samples representing various stages of decomposition were generated in eight laboratory scale reactors operated under conditions designed to simulate decomposition in bioreactor landfills. The reactors were destructively sampled at the end of each phase of degradation based on the reactors methane production rate curve, P^H and volatile organic content. A series of constant head tests were performed on the representative MSW samples at different stages of decomposition to determine the variation in permeability with degradation. Tests were repeated at three densities and two percentages of soil.

Test results indicated a decrease in particle size with degradation which was mainly due to the breakdown of matrix structure of individual components within MSW. The coefficient of permeability of MSW decreased from 0.0088 cm/s (Phase I) to 0.0013 cm/s (Phase IV). There is an overall decrease in the permeability with increase in density and percentage soil. The trend is the same for the samples at each phase of degradation. The percentage decrease in permeability is much higher when there is combined effect of both increase in density and increase in percentage of cover soil.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

Municipal solid waste (MSW) is either a solid or semisolid waste that includes household and commercial wastes collected within a given area. According to the US Environmental Protection Agency (EPA), total generated municipal solid waste (MSW) production in 2005 was 247.3 million tons in United States. About 55% of the generated MSW was landfilled.

Landfilling is an engineered method of waste disposal on land with minimal impact on the surrounding environment. Physical, chemical and biological process occur within the landfill that convert the waste to leachate and gas (Reinhart, 2002). Compared to conventional sanitary landfills, bioreactors provide the potential for more rapid, complete and predictable attenuation of solid waste constituents, enhance gas recovery and reduce adverse environmental impacts (Pohland, 1997). Figure 1.1 gives the schematic of a bioreactor landfill system.

The fundamental process used for waste treatment in bioreactor landfill is leachate recirculation. Recirculation of leachate generated back into the landfills creates a favorable environment for rapid microbial decomposition of the biodegradable solid waste. The successful implementation of bioreactor landfills depends on the understanding of the impact of additional moisture on physical and engineering properties of MSW. Accordingly, the hydraulic properties of wastes and their impact on the flow of fluids within the waste mass will also be affected.

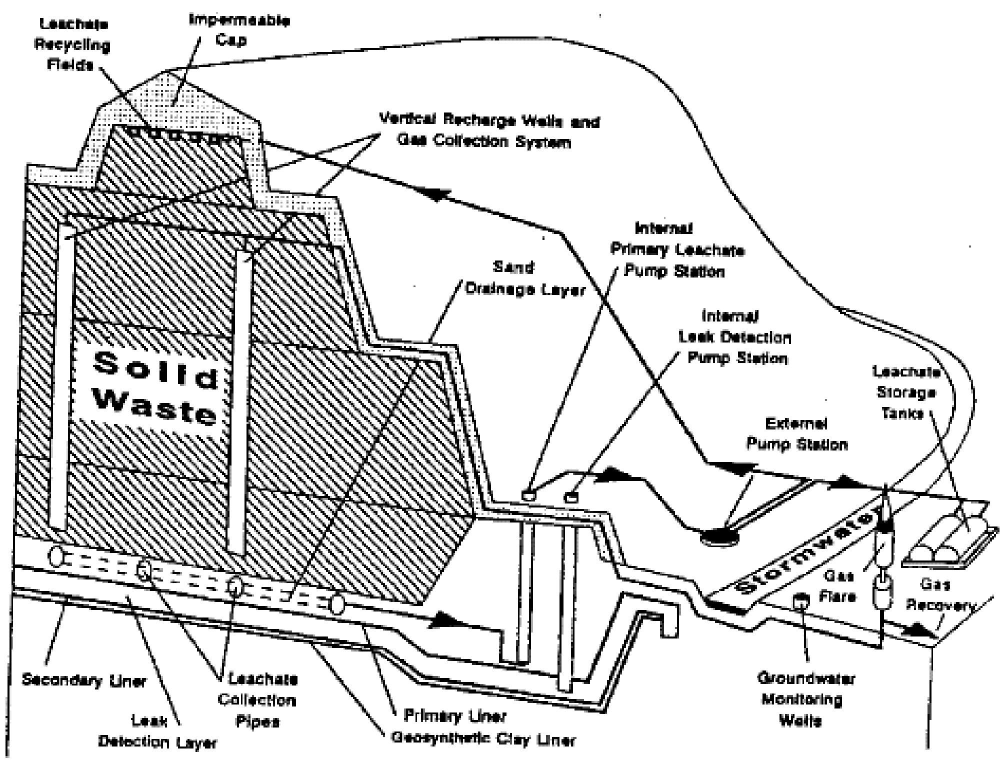


Figure 1.1 Schematic diagram of a bioreactor landfill system (Pohland, 1996)

In an attempt to understand the hydraulic properties of the municipal solid waste as a function of degradation, an experimental program was developed to understand the variation in permeability with degradation and the factors that influence the change in permeability of municipal solid waste.

1.2 Problem Statement

Leachate recirculation plays an important role in successful operation of the bioreactor landfill. Permeability of MSW in a bioreactor landfill is an important parameter to determine the recirculation rate and overall performance of landfill It is also necessary during the design of the containment system. Designing with improper estimate of permeability might lead to leachate accumulation in some pockets of landfill resulting in non uniform degradation of the waste thus, causing differential settlement and structural failure of the landfill components. In order to better estimate the leachate generated and design of leachate recirculation system, clear understanding of the permeability of the MSW and the factors influencing the permeability is necessary.

1.3 Objective

Degradation of solid waste effects the physical and engineering properties of MSW. With degradation, the matrix structure of MSW components break down into finer particles. The degradation process is expected to increase the percentage of fine content and density of MSW. Therefore the objective of the current study is to

a. Prepare MSW Samples at different stages of degradation.

b. Determine the permeability of MSW as a function of degree of degradation.

c. Determine the effects of percentage fine content and density on permeability of MSW, and

d. Determine the effects of Cover Soil on permeability of MSW

1.4 Methodology

Methodology of the current research consisted of a comprehensive literature review on the permeability of municipal solid waste and factors influencing the permeability and degradation of the waste, laboratory testing and data analysis. Municipal solid waste (MSW) at different stages of degradation is generated in a laboratory scale bioreactors with leachate recirculation under controlled conditions (Hossain et al, 2007). Initially, moisture content, specific gravity and particle size distribution were completed.

Constant head permeability tests were performed on the remolded samples from the reactors to determine the variation of permeability with degradation. The tests were repeated at three densities to determine the influence of packing density on permeability. Additionally two percentages of soil, 20% and 30%, were added to the samples and the tests were carried out at three densities to determine the influence of percentage cover soil on the permeability.

1.5 Thesis Organization

A brief summary of the chapters included in the thesis is presented here:

Chapter 2 presents a brief overview of municipal solid waste, classification, properties, permeability of MSW, factors influencing permeability and its determination and the degradation of municipal solid waste.

Chapter 3 describes all the experimental variables and procedures including sample preparation, particle size analysis, specific gravity and permeability testing.

Chapter 4 presents all the experimental results and comprehensive analysis of test results from the current research. Comparison of the results with existing literature is also presented.

Chapter 5 summarizes the main conclusions from the current research and some key recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Solid Waste Degradation

The rate of biodegradation of MSW is a function of waste composition, waste nutrient level, presence of buffering agent, Moisture content and operational practices (Hossain, 2002). The rate and characteristics of leachate produced and biogas generated from a landfill vary from one phase of degradation to another and reflect the processes taking place inside the landfill. Figure 2.1 presents the observed trend of leachate characteristics with MSW degradation.

Phase I: Aerobic Phase: Transformation from aerobic to anaerobic environment occurs in this phase. This phenomenon can be observed by the decrease in oxygen trapped within the pores of the waste. The gas generated constitutes of mainly CO_2 and N_2 leachate strength is relatively very low in this phase.

Phase II: Anaerobic Acid Phase: In this phase, the P^H value decreases which is accompanied by biomass growth associated with the acidogenic bacteria and rapid consumption of substrate and nutrients. The gas produced is still mainly CO_2 and little amount of methane. With the transition to phase III, the P^H value and methane production increases. The decomposition is estimated to be in between 15 to 20%

Phase III: Accelerated Methane Production Phase: In this phase, intermediate acids are consumed by methane forming bacteria and converted into methane and carbon dioxide. There is an increase in methane production and increase in P^H value. Most of the methane production is due to the depletion of accumulated carboxylic acids in earlier phase.

Phase IV: Decelerated Methane Production Phase: This is the final state of landfill stabilization, nutrients and available substrate reduces and the biological activity shifts to relative dormancy. Gas production drops significantly and the leachate strength remains constant and at much lower concentrations than earlier phases. Decomposition is about 50 to 70% in this phase depending on the methane production and operating environment.

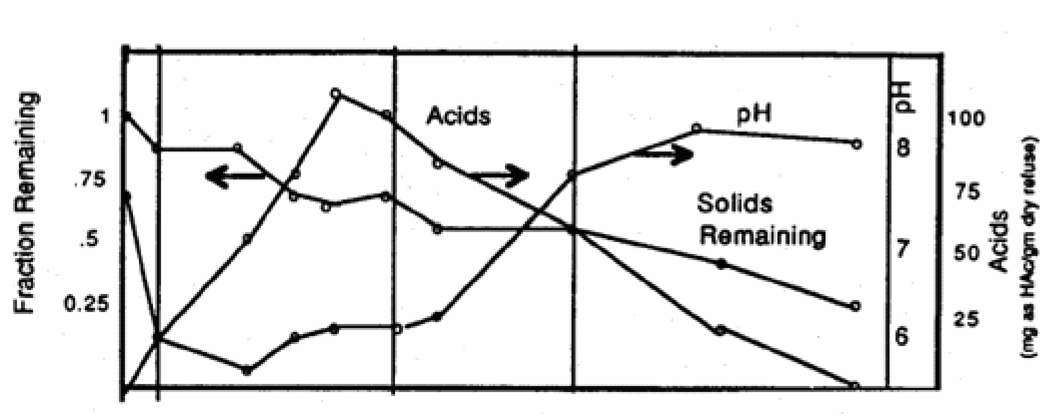


Figure 2.1 Observed trend in leachate characteristics (Hossain, 2002)

2.2 Properties of Municipal Solid Waste

The major challenge for the geotechnical engineers is to determine the engineering properties of MSW due to the heterogeneity of the MSW components. Reliable engineering properties are important to evaluate and predict landfill behavior. However, determining engineering properties is extremely difficult as mentioned by Manasslero et al. (1997) due to the following reasons,

1) Difficulties in sampling of MSW which simulate the insitu condition,
2) Lack of generally accepted sampling procedure for geotechnical characterization of waste material,
3) Change in properties of municipal solid waste with time,
4) Level of training and education of the personnel on site for basic interpretation and understanding of the measurements, and,
5) Heterogeneity of the MSW within the landfill and its variation with geographical location.

2.2.1 Engineering Classification of Municipal Solid Waste

Landva and Clark (1990) classified the waste based on biodegradability of the individual constituents as the rate of decomposition may not be the same for all materials. The group OP is highly degradable under favorable conditions when compared to the other group of materials. The other three groups possibly contain void forming constituents which have a significant influence on hydraulic characteristics of MSW. Figure 2.2 presents the classification system proposed by Landva and Clark (1990)

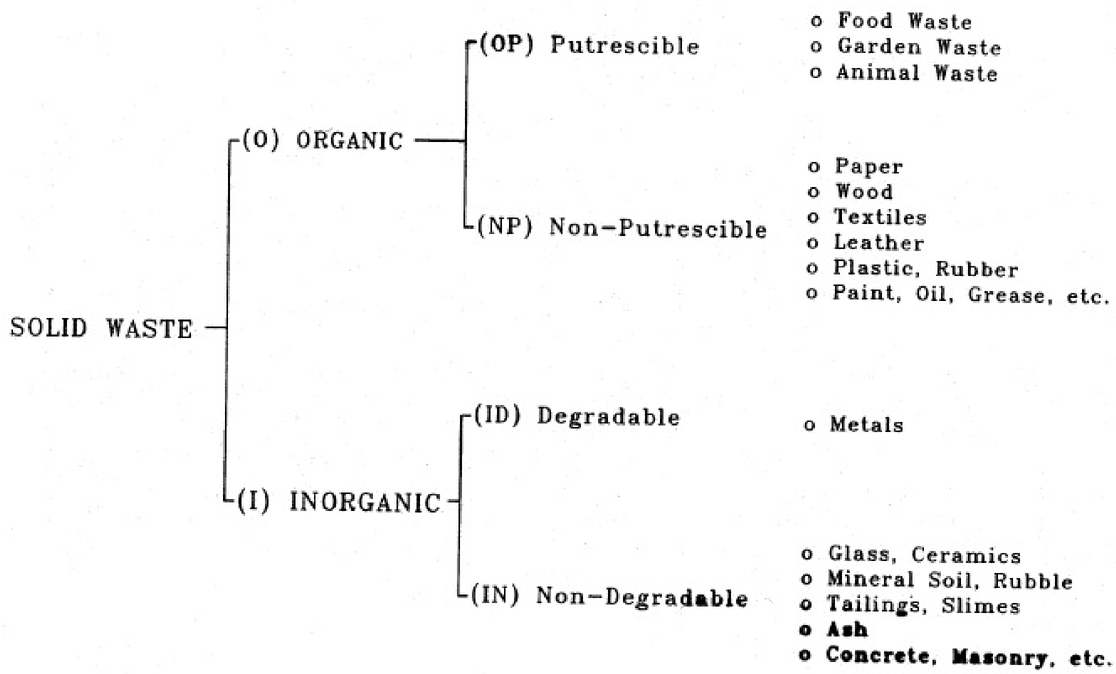


Figure 2.2 Classification system suggested by Landva and Clark (1990)

2.2.2 Unit Weight of MSW

MSW is highly heterogeneous material. The factors which influence unit weight are composition of MSW, placement procedure, type and amount of compaction, depth of sampling, moisture content and the thickness of daily cover. Table 2.1 illustrates the range of densities of components of MSW, which play a major role in unit weight of MSW. The layer thickness and the degree of compaction also influence the unit weight of the MSW.

Table 2.1 Typical refuse composition (Landva and Clark, 1992)

Category	Percent of total weight	Unit weight kN/m^3	
		Dry	Saturated
Food Waste	5-42	1.0	1.0
Garden refuse	4-20	0.3	0.6
Paper products	20-55	0.4	1.2
Plastic, rubber	2-15	1.1	1.1
Textiles	0-4	0.3	0.6
Wood	0.4-15	0.45	1.0
Metal Products	6-15	6.0	6.0
Glass and ceramics	2-15	2.9	2.9
Ash, rock and dirt	0-15	1.8	2.0

Landva and Clark (1990) proposed a general equation for average unit weight of the MSW based on unit weight of individual constituent of the waste as

$$\gamma_c = \frac{1}{\sum_{1}^{n} \frac{w_i}{w_c} \times \frac{1}{\gamma_i}} \qquad (2.1)$$

where, $\frac{w_i}{w_c}$ is the weight of constituent i as a fraction of the total weight w_c of the constituent, γ_i is the unit weight of constituent and n is the number of constituent. The average unit weight when exposed to moisture is given as

$$\gamma_c' = \gamma_c \left[1 + \sum_{1}^{n} \frac{w_i}{w_c} \times \frac{\Delta\gamma_i}{\gamma_i} \right] \qquad (2.2)$$

where, $\Delta\gamma_i$ is the increase in unit weight of constituent i.

Table 2.2 gives the average unit weights of refuse fill. It can be observed that the average unit weight of MSW is in the range of 20 to 85 pcf depending on the compaction effort and composition.

Table 2.2 Refuse fill average unit weights

Source	Refuse placement conditions	Unit weight	
		kg/m^3	lb/ft^3
U.S Department of Navy (1983)	Sanitary landfill Un shredded Poor Compaction Good Compaction Best Compaction Shredded	 320 641 961 881	 20 40 60 55
Sowers (1968)	Sanitary Landfill depending on the compaction effort	481-961	30-60
NSWMA (1985)	Municipal Refuse in a landfill after degradation and settlement	705-769	44-49
Landva and Clark (1986)	Refuse Landfill (refuse to soil cover ratio varied from 2:1 to 10:1)	913-1346	57-84
EMCON Associates (1989)	For 6:1 refuse to daily cover soil	737	46

Source**:** Sharma (2004)

2.2.3 Particle Size

The particle size ranges from soil to large objects such as demolition waste. Life cycles changes, legislation, seasonal factors, pretreatment and recycling activities result in a changing waste stream over time (Dixon, 2005). Within the landfill, specimens from shallower depths indicated coarser particle distribution compared to the samples at greater depth. The difference in the grain size distribution may be attributed to the higher degree of decomposition of the deeper samples. The above statement can be supported by experimental results from Gabr (1995). Figure 2.3 shows the particle size analysis on two specimens at depth 19.2m and 14.4m given by Gabr (1995).

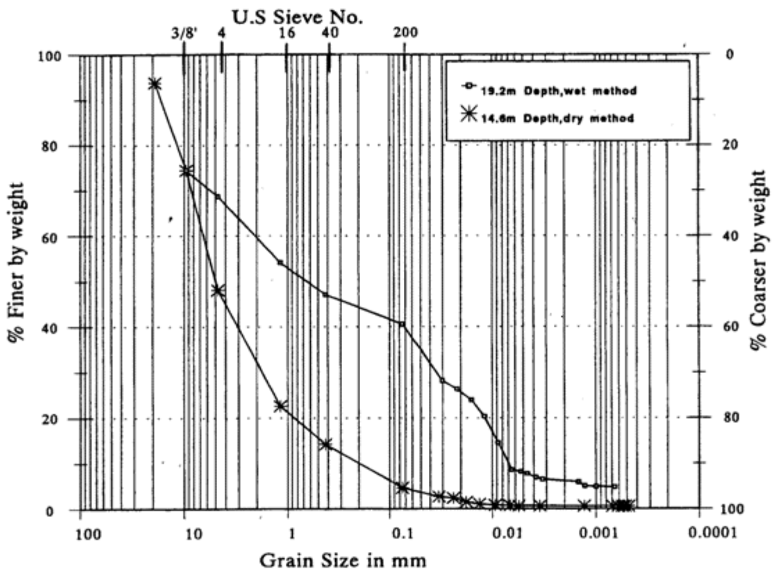


Figure 2.3 Grain size distribution using dry and wet testing (Gabr, 1995)

Dry Mechanical sieving was carried out on one sample from shallow depth, the sample from 19.2m is washed through series of sieves, and hydrometer analysis was conducted on fraction passing No. 200 sieve. Test results indicated an increase in percentage of fines with increase in depth.

2.2.4 Specific Gravity

Landva and Clark (1990) indicated that the determination of the index process of samples of refuse fill is a long and somewhat complex procedure. Gabr (1995) reported the specific gravity of the MSW from the tests done on the entire particle size distribution as 2.0 and for the finer fraction (<No. 200 sieve) as 2.4. The lower values of specific gravity were attributed to the presence of decomposed organic matter. Pelkey (1997) from the test results on fraction finer than 4.75mm sieve of the sample which consisted mainly of cover soil with minor amounts of glass and organic material reported a value of 2.3 to 2.5.

2.2.5 Moisture Content

Beaven and Powrie (1996) defined the moisture content of the waste of the refuse as the ratio of the mass of water to the mass of dry solids present (WC_{dry}). 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 (1999) defined the mechanism of moisture retention within the waste mass for the purpose of characterizing the distribution of liquids as

1) Moisture within the waste mass (within the intraparticle voids)

2) Moisture between particles (within inter particle voids), held by capillary stresses

3) Moisture between particles, retained by layers with lower permeability.

The gravimetric moisture content (w) is defined as ratio of the weight of water (w_w) to the weight of solids (w_s) ie.,

$$w = \frac{w_w}{w_s} \qquad (2.3)$$

The insitu volumetric moisture content (θ) is the ratio of between volume of water (v_w) to total volume (v) ie.,

$$\theta = \frac{v_v}{v} \qquad (2.4)$$

The relationship between gravimetric and volumetric moisture content as given by Zornberg (1999) is

$$\theta = \frac{\gamma_d}{\gamma_w} \times w \text{ or, } \theta = (1-n) \cdot G_s \cdot w \qquad (2.5)$$

where n is the porosity defined as the ratio of volume of voids to total volume.

Kelly (2002) determined the moisture content using the modified standard method 2540-B (APHA 2540-B). The sample was dried at 105°C and moisture content was determined after cooling the oven dried sample in dessicator as the percentage of weight loss from the original sample. Gabr (1995) determined the moisture content by oven drying at 60°C so as to prevent the combustion of volatile matter.

Gabr (1995) estimated the attainable weight density and optimum moisture content through compaction tests. Figure 2.4 gives the representative average of the moisture density relationship. The variation is similar to that observed for soils.

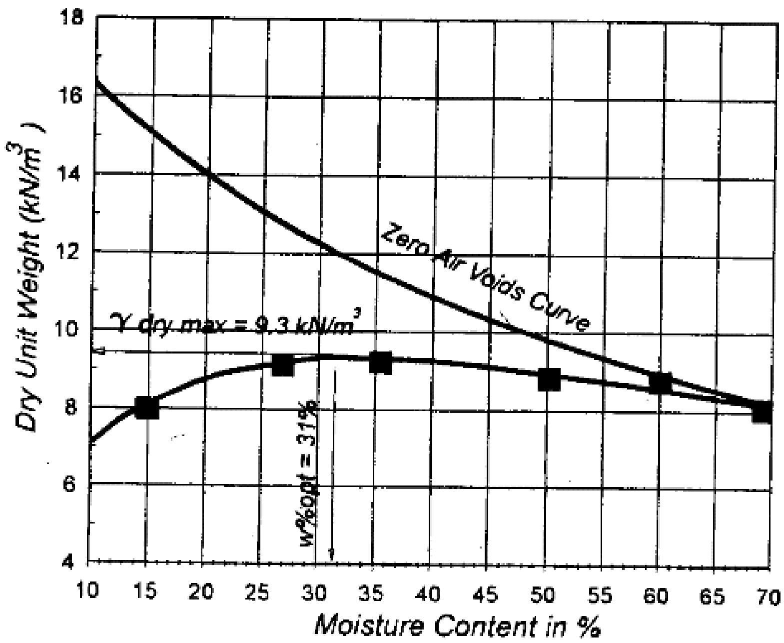


Figure 2.4 Compaction curve: maximum dry density and optimum moisture content (Gabr, 1995)

2.3 Permeability of Municipal Solid Waste in Landfill

Permeability is a property of material which permits the passage of any fluid through its interconnecting pore spaces. The coefficient of permeability in compacted wastes is

$$K = Cd^2 \frac{\gamma}{\mu} = k \frac{\gamma}{\mu} \qquad (2.6)$$

Where, C is dimensionless constant or shape factor, d is average size of pores, γ is specific weight of water, and μ dynamic viscosity of water. Intrinsic permeability (Cd^2 = k) is dependent on the property of the solid material, including pore size distribution, tortuosity, specific surface and porosity (Tchobanoglous, 1993). Typical values of intrinsic permeability in compacted landfill are 10^{-11} m^2 to 10^{-12} m^2 in vertical direction and 10^{-10} m^2 in horizontal direction. Permeability is normally determined using field pumping tests or field percolation tests (Pelkey, 1997).

2.3.1 Factors Influencing Moisture Transport

The physical properties that influence the permeability in MSW are density, particle size, porosity, material type, degree of saturation, stage of decomposition, and depth within the landfill. Density of the refuse, in turn is dependent on the refuse composition, the amount and degree of compaction, surface cover, over burden pressure and moisture content of the refuse during compaction. In addition to the refuse density the strain in a porous media has a significant influence on the permeability (Blieker, 1995). Figure 2.5 presents the variation of permeability with the dry density of MSW.

During the regular land filling the refuse is compacted in thin lifts leading to horizontal stratification within the landfill, which might result in greater horizontal permeability of the waste than the vertical permeability (Powrie and Beaven 1999). In addition to the particle size, the application of daily and intermediate soil covers leads to anisotropy and heterogeneity within a landfill (Hyder and Khire 2004). Hence, along with the physical properties of the solid waste, various other factors like refuse placement and amount of compaction, properties of cover soil, depth of landfill contribute to the behavior of MSW in a landfill.

Moisture usually tend to flow through the large pores, leading to flow channeling. Oweis et al., (1990) found that channeling results in the downward movement of leachate through interconnected pores at rates faster than the uniform flow under gravity. This variation in flow result in non uniform leachate recirculation resulting in non uniform biodegradation leading to differential settlements (Hyder and Khire 2004).

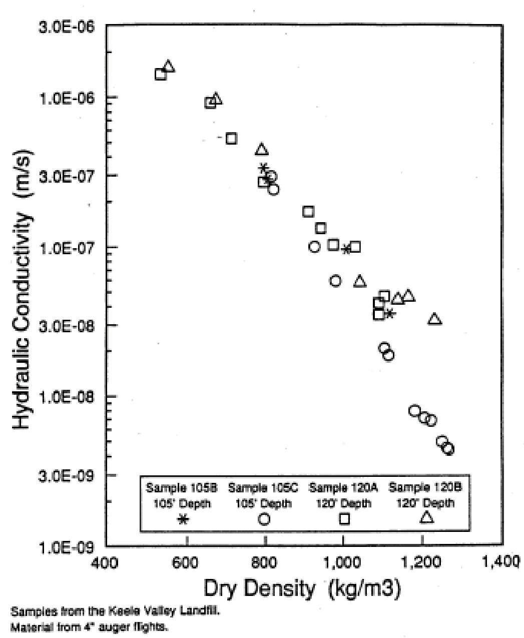


Figure 2.5 Permeability with dry density (Blieker, 1993)

2.3.2 Permeability with Depth of Landfill

In a landfill as depth increases, effective stress on the waste increases. Increase in the effective stress increases the waste density (Powrie and Beaven, 1999). Blieker (1993) from his study on Brock west landfill indicated difficulties in drilling with the increase in depth due to the probable increase in density which supports the assumption of increase in density with depth. Figure 2.6 presents the decrease in permeability with the increase in depth due to the possible increase in density.

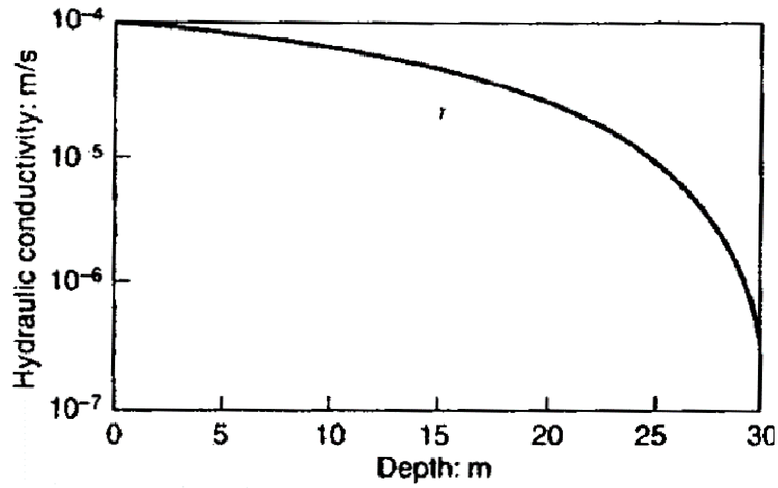


Figure 2.6 Variation of permeability with depth (Powrie and Beaven, 1999)

2.4 Previous Studies on Permeability of MSW

Permeability of the MSW can be determined by laboratory tests and field tests. A brief overview of previous studies on permeability of MSW on undisturbed samples and reconstituted samples is presented in this section. Table 2.3 gives a brief summary of test results of permeability from previous researchers. Values of permeability obtained so far from the literature did not consider the stage of decomposition.

2.4.1 Laboratory Studies on Determination of Permeability

2.4.1.1 Constant and falling head tests

Fungaroli and Steiner (1979) were one of the pioneers to study the internal behavior of sanitary landfills under laboratory and field conditions (Shank, 1993). As a part of their study on shredded MSW, the saturated coefficient of permeability (k_s) was measured as a function of average particle size and density. The study concluded that the k_s was inversely proportional to density. For shredded MSW, the k_s ranged from 2.0 x 10^{-4} cm/s at to 1.1 x 10^{-2} cm/s at densities 737 lb/ft^3 to 504 lb/ft^3 respectively. The variation was attributed to the sample size, affect of permeameter sidewalls, and refuse characteristics.

Gabr (1995) performed constant and falling head tests on triaxial compression specimens by measuring the flow rates through the saturated specimens before the consolidation phase. The observed values of the permeability from his testing were in the order of 10^{-7} to 10^{-5} m/s. No particular trend was observed in the values of permeability either with the hydraulic gradient or the unit weight which might be due to the heterogeneity of the sample. Chen et al., (1995) studied the variation in permeability with density of the samples and hydraulic gradient. Constant head tests were conducted on test columns at densities 160 kg/m^3, 320 kg/m^3 and 480 kg/m^3 with hydraulic gradient from 2 m/m - 4 m/m. The permeability varied from 9.6 x 10^{-2} cm/s to 4.7x 10^{-5} cm/s when compacted to densities 160 to 480 kg/m^3 respectively and no significant influence was observed due to the variation in hydraulic gradient.

Bleiker (1993) used fixed ring apparatus to study the relation between the permeability and density of the refuse samples from Keele Valley Landfill on Toronto, Ontario. Canada A small portion of sample was placed in a fixed brass ring having a diameter 63mm and a thickness of 19mm and the effective stress was increased causing compression. The permeability at each effective stress level was determined at the end of 90 minutes by applying the head at one side of the sample and recording the volume of water that passed through the sample on the other end at a given period of time. Tests results indicated a decrease in permeability with decrease in porosity, increase in density and effective stress. The change in permeability were over several orders (10^{-6} to 10^{-8} m/s) of magnitude and suggest significant changes in permeability with change in depth.

Table 2.3 Previous studies reporting permeability of MSW

Source	Permeability	Unit weight t/m^3	Comments	Test
Fungaroli and Steiner (1979)*	10^{-4} to 10^{-2} cm/s			Constant Head
Krofiatis et al., (1984)	8 x 10^{-3} to 1.3 x10^{-2} cm/s		Refuse was six months old collected from local landfill	Constant Head
Noble and Arnold (1991)*	8.4 x 10^{-5} to 6.6 x10^{-4} cm/s			Constant Head
Bleiker et al., (1993)	1.0 x 10^{-6} cm/s 1.58 x 10^{-5} cm/s 6.3 x 10^{-6} cm/s 3.98 x 10^{-5} cm/s 6.3 x 10^{-6} cm/s 6.3 x 10^{-6} cm/s		22.9 m <10 years 19.8 m <10 years 24.4 m <10 years 22.9 m <10 years 27.4 m <10 years 30.5 m <5 years	Falling Head test on core samples
Chen and Chynoweth (1995)	4.7 x 10^{-5} to 9.6 x10^{-2} cm/s		Refuse derived fuel from National Ecology of Baltimore, MD containing mostly paper and plastic.	Constant Head
Landva and Clark (1998)	2 x 10^{-6} to 2 x10^{-3} cm/s (vertical) 4 x 10^{-5} to 1 x10^{-3} cm/s (Horizontal)			Constant Head
Powrie and Beaven (1999)	1.5 x 10^{-4} to 3.4 x10^{-5} cm/s 2.7 x 10^{-6} to 3.7 x10^{-8} cm/s	390 kg/m^3 720 kg/m^3	Crude house hold waste obtained directly from the tipping face of the landfill.(approximately six months of testing)	Constant Head
Townsend et al., (1995)*	3 x 10^{-6} to 4 x 10^{-6} cm/s		1-3 years	Zaslasky Wetting front
*Shank(1993)				

Table 2.3 - continued

Source	Permeability	Unit weight t/m^3	Comments	Test
Koerner and Eith (2005)	1.2×10^{-2} cm/s to 6.9×10^{-2} cm/s (Initial test results)		12 columns of 100 mm PVC flow columns. (0-3years) experiments under progress.	Flow columns
Gabr (1995)	10^{-3} to 10^{-5} cm/s	7.4 to 8.2 kN/m^3	15 to 30 years old sample recovered from auger cuttings.	Constant head and Falling head tests in triaxial compression cells
Durmusoglu (2006)	4.7×10^{-4} to 1.24×10^{-2} cm/s		Samples 2.5 to 3.0 m deep from Rock Prairie Road Landfill in Brazos County, Texas Approximately 10 years old sample	Falling head test, In small and large scale consolidometer
Ettala (1987)	5.9×10^{-7} to 2.5×10^{-6} cm/s 2.1 -2.5×10^{-5}cm/s	Strong compaction Slight compaction	13 infiltration measurements	Modified double cylinder infiltrometer and pumping tests.
Shank (1993)	6.7×10^{-5} to 9.8×10^{-4} cm/s		Approximately 20 years	Slug test
Jang et al., (2002)	2.91×10^{-4} cm/s 1.07×10^{-3} cm/s 2.95×10^{-3} cm/s	1.2 1.0 0.8	Tests were conducted in a Modified Tempe cell at three compacted densities	Constant Head
Jain (2006)	6.11×10^{-5} to 5.4×10^{-6} cm/s 2.34×10^{-5} to 5.6×10^{-6} cm/s 1.9×10^{-5} to 7.4×10^{-6} cm/s		8 locations @ 3-6m 10 locations @ 6-12m 5 location @ 12-18m	Borehole Permeameter test
Moore (1997)	3.9×10^{-4} cm/s		Permeability in test cell with leachate recirculation	Empirical method

Table 2.3 - continued

Source	Permeability	Unit weight t/m^3	Comments	Test
Korman et. al. (1987)	2 x 10^{-5} to 1 x 10^{-6} (FW) 5 x 10^{-6} to 3 x 10^{-7}(FW) 2 x 10^{-6} to 5 x 10^{-7}(LW) 1 x 10^{-7} to 4 x 10^{-7}(LW)	Depth 26.5-26.9 ft 41.5 ft	Tests were conducted on both fresh waste (FW) and landfilled waste(LW). Two regid wall permeability tests were performed on fresh waste and two flexible wall permeability tests were conducted on landfilled waste	Flexible wall and regid wall permeability tests
Beaven and Powrie (1995)	1.7 x 10^{-4} cm/s 2 x 10^{-2} to 3.5 x10^{-7} cm/s 1 x10^{-7} cm/s 3.5 x 10^{-3} to 1 x10^{-5} cm/s	0.75 – 1.36 0.62 – 0.97 0.32 – 0.95 0.5 – 1.18	DM2 PV1 PV2 DM3 Where, DM is crude domestic refuse obtained from tipping face of landfill and PV is Processed (pulverized) refuse passing 150mm filter.	Large scale compression cell
Landva and Clark (1986)	2.6 x 10^{-2} cm/s 1.6 x10^{-2} cm/s 3.9 x 10^{-2} cm/s 3.0 x 10^{-3} cm/s 1.1 x 10^{-2} cm/s 1.3 x 10^{-2} cm/s 1 x 10^{-3} cm/s 8 x 10^{-2} cm/s 5 x 10^{-3} cm/s 1 x 10^{-2} cm/s 1.1 x 10^{-2} cm/s 1.3 x 10^{-2} cm/s	12.5 kN/m^3 14.5 kN/m^3 13.0 kN/m^3 11.1 kN/m^3 12.9 kN/m^3 10.0 kN/m^3 13.6 kN/m^3 11.4 kN/m^3 10.7 kN/m^3 12.3 kN/m^3 13.1 kN/m^3 10.5 kN/m^3	Calgary Edmonton, Alberta Mississauga Waterloo	Insitu test pits

2.4.1.2 Flexible wall Cell

A flexible wall permeability cell is similar to a triaxial cell as shown in Figure 2.7. The specimen diameter ranges from 38 mm to 152 mm. The height of the specimen is kept small, so as to reduce the time of testing. Specimen is enclosed in a flexible latex membrane with porous discs at both the ends. The membranes are sealed to the bottom pedestal and top cap. The soil specimen is saturated using back pressure, until the value of B (Skempton pore pressure parameter) is close to 0.95 and is maintained during the permeability testing (Oweis, 1990).

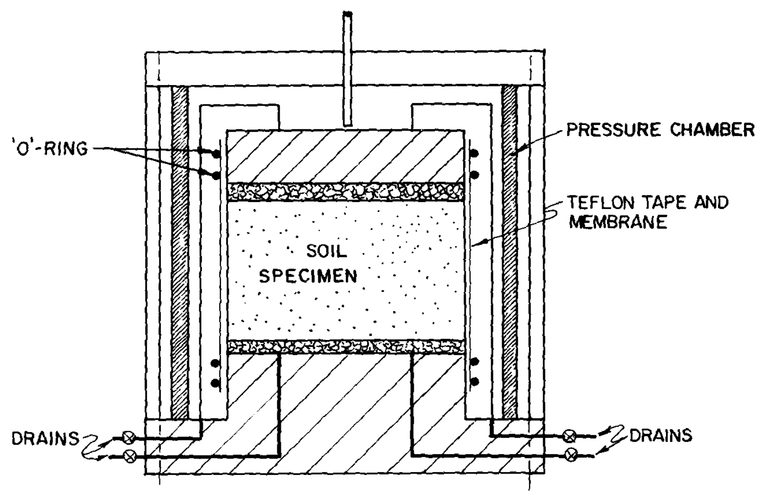


Figure 2.7 Flexible wall permeameter (Oweis, 1990)

Korman et al., (1987) determined the saturated coefficient of permeability of fresh waste using flexible wall permeability test and of land filled waste on rigid wall permeability test. Fresh wastes are reconstituted to the field density while the land filled samples were tested at the sampled diameter and density. The values of permeability obtained are in the order of 2 x 10^{-5} cm/s to 3 x 10^{-7} cm/s for fresh wastes and in the order of 2 x 10^{-6} cm/s to 5 x 10^{-7} cm/s for land filled wastes.

2.4.1.3 Oedometer Cell Permeameter

A fixed ring consolidation permeameter cell is shown in Figure 2.8. The soil specimen is placed in a ring with a diameter of 40 – 100mm and a eight of up to 100mm. The consolidometer is placed in a loading frame and the desired axial load is applied. The air is flushed out from the bottom. One of the two outlets at the two outlets at the bottom is closed and a head is applied through the other outlet. The head is applied using a stand pipe of a small diameter '*a*'. A constant head is maintained at the exit. The permeability is determined using the equation 2.4, where t is the total time of flow, h_1 is the head at the beginning of the flow and h_2 at the end of flow.

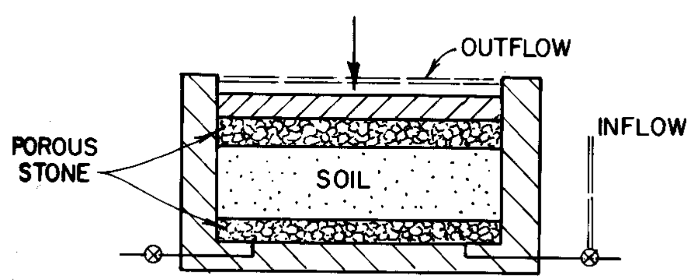


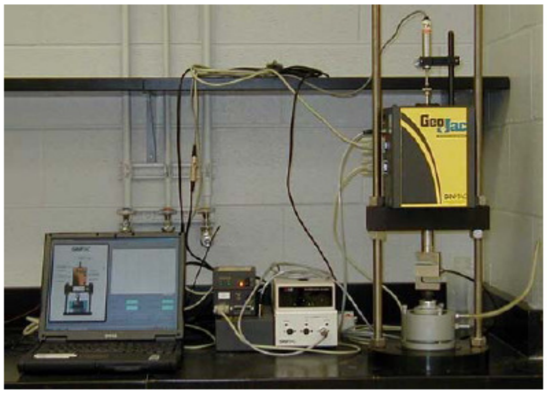
Figure 2.8 Consolidation ring permeameter (Oweis, 1990)

$$k = \frac{aL}{At} \ln \frac{h_1}{h_2} \qquad (2.6)$$

for soils with low permeability, additional pressure '*dp*' may be applied to reduce the test duration. The permeability is then given by the following equation.

$$k = \frac{aL}{At} \ln \frac{h_1 + dp / \gamma_w}{h_2 + dp / \gamma_w} \qquad (2.7)$$

Durmusoglu (2006) conducted a series of laboratory test to evaluate permeability and compression characters of MSW samples on small and large scale consolidation apparatus as shown in Figure 2.9. The small scale conslolidometer used in this study was a conventional apparatus described in ASTM-D2435-90, formed by a stainless steel ring of 6.35cm inner diameter and 2.54 cm deep. The cell was subjected to vertical loads by means of 8.9 kN capacity load frame. The large scale consolidometer consisted of a 71.12 cm diameter and 55.88 cm high stain less steel cylinder of 5.10 cm thickness with a circular load plate on the top. Several 0.3 cm diameter holes were drilled to necessitate for drainage. The set up was mounted on plate of larger diameter where a seal was attached for avoiding the liquid leakage. The lift had a capacity of applying loads upto 2,500 kN for long periods of time and permitted application of load increments as required.



a) b)

Figure 2.9 Consolidometer cell a) Conventional consolidometer b) Large scale consolidometer cell (Durmusoglu et al., 2006)

The MSW samples were sieved to exclude particles larger than 0.5cm and compacted at standard proctor compactive effort before it was placed into the cell. The large scale consolidometer was filled with the refuse having particles smaller than 2.0 cm. The height of the specimen within the ring ranges from 19.7 cm to 24.1 cm. Durmusoglu (2006) maintained the diameter to height ratios in between 2.95 to 3.61 which were greater than 2.5. Falling head permeability tests were conducted at the field capacity at the end of each load increment. Results were in agreement with the previous works and observed permeability's are in the order of 4.7×10^{-6} to 1.24×10^{-4} m/s. The results from the small scale tests were comparable to large scale setup. Durmusoglu (2006) from the compression test results postulated that a conventional small scale consolidometer can be used for testing even though the samples are more disturbed.

Pelkey (1997) determined the vertical and horizontal permeability of the sample approximately five years old obtained from the test pits 6.4m deep at Spruce Lake landfill, Saint John, NB. Canada. Tests were conducted to determine the variation in permeability with vertical stress. Pelkey used a 44.7cm diameter and 54 cm deep consolidometer cell to determine the vertical permeability. Stand pipes were positioned around the consolidometer to measure the pressure heads within the samples. The sample was placed in 6-8 lifts compacted using 5.6 kg hammer that was dropped from a height of 20 to 30 cm. Horizontal coefficient of permeability(k_h) test apparatus consists of a 769 mm diameter by 450 mm deep consolidometer, a constant pressure system, a constant head container and two stand pipes placed on the top to monitor the heads in the system. The permeability was determined using a flownet developed for radial flow. Test results concluded that the anisotropy of the waste has strong effect on the permeability and the ratio of horizontal to vertical coefficients of permeability for the refuse ranged from 0.5 to 1.0 for varying vertical stress. The obtained vertical coefficient of permeability is in the order of 10^{-3} at 55 kPa and 10^{-4} cm/s at 289 kPa.

2.4.1.4 Pitsea Compression Cell

Powrie and Beavan (1999) conducted a constant head flow test in a Pitsea compression cell to determine the permeability of crude unprocessed household waste. Pitsea cell is a purpose built steel cell as shown in Figure 2.10, accommodating a sample of waste 2m in diameter and upto a 3 m height (six times that of conventional oedometer) which is necessary to get a representative results from highly heterogeneous samples.

Figure 2.10 Pitsea compression cell (Powrie, 2005)

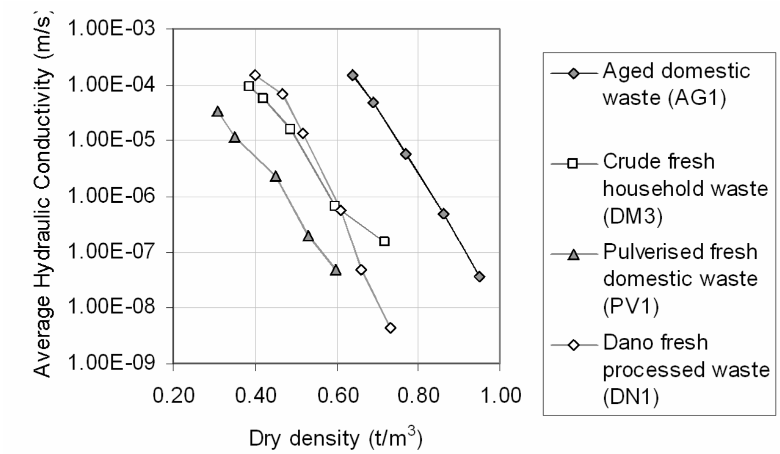
The cylinder was suspended vertically within a steel support frame. The feet of the support frame were mounted on load cells, enabling to monitor the weight of the contents of the cell continuously. Test setup had a capability of applying overburden pressures up to 600 kpa in five to six steps representing different depths of the landfill of up to 60 m. Powrie and Beaven (1999) gives a detailed description of the test setup. The refuse was placed in five layers compressed to the desired density of 0.5 Mg/m^3 to a depth of 2.5 m. The Upper platen was lowered onto the sample and an initial load was applied using the hydraulic system and the compression of refuse was monitored with time. The applied load was maintained until the compression ceases (1% in 24hrs) which normally took 2-7 days.

The total vertical stresses indicated by the pressure cells installed at various depths within the refuse were also recorded. The waste was saturated by allowing water flow into the sample through the lower platen. The drainable porosity of the saturated waste was measured at constant vertical load from the volume of leachate drained per unit volume.

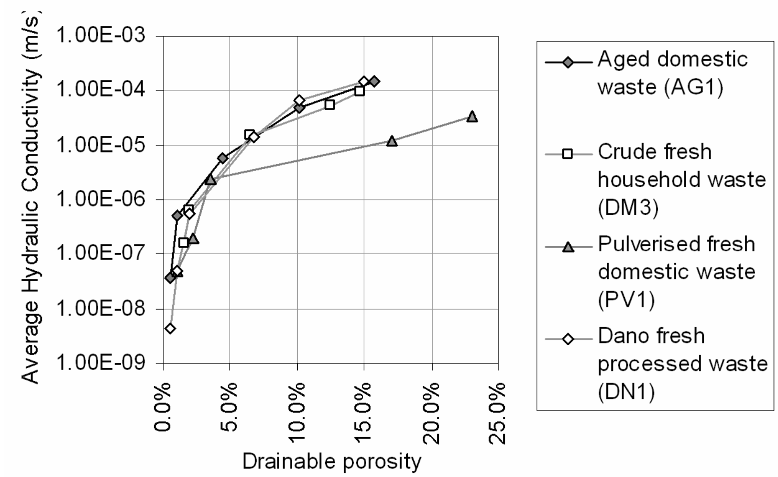
Powrie and Beaven (1999) from their test results of constant head flow test on crude unprocessed household in a large scale compression cell concluded that the coefficient of permeability decreases with the increase in the effective stress from 10^{-3} m/s to 10^{-7} m/s, when the stress increases from 50kPa to 850 kPa respectively. Powrie and Beaven (1999) gave an expression for variation of k with effective stress as given below. Figure 2.11 gives the variation in vertical permeability against the drainable porosity and density for wastes reported by Powrie (2005).

$$k\ (\text{m/s}) = 2.1(\sigma_v')^{-2.71} \qquad (2.8)$$

where, σ_v' is the effective stress in kPa and k is the coefficient of permeability in m/s.



(a)



(b)

Figure. 2.11 Vertical permeability against (a) the density; and (b) drainable porosity, for wastes (reproduced from Powrie et. al., 2005)

2.4.2 Field tests

2.4.2.1 Test pits

Landva and Clark (1986) reported in-situ permeability results obtained from the large scale percolation tests in the pits excavated for unit weight measurements during a field investigation program on waste fills across Canada.

The permeability estimated on the basis of the rate of water level recession and flow nets applicable to any particular level. The permeability reported is in the order of 1×10^{-5} to 39×10^{-5} cm/s. Permeability measured in test pits in Calgary, Edmonton, Mississauga and Waterloo in Canada with their respective unit weights are given in Figure 2.12

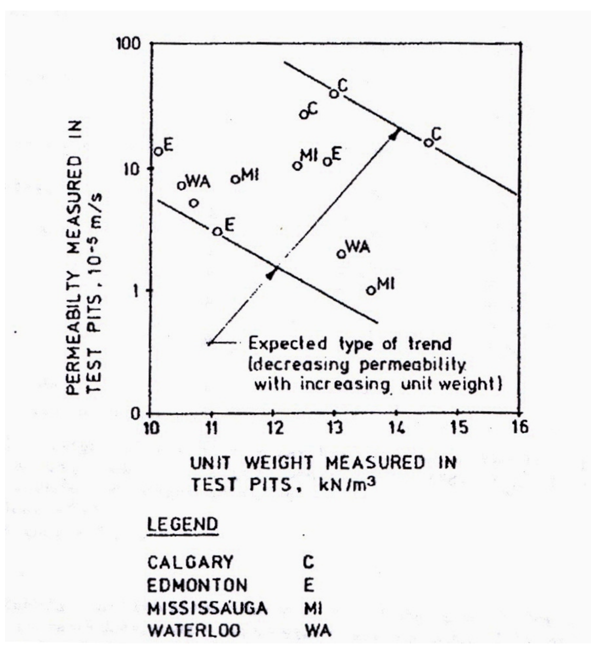


Figure 2.12 Permeability and unit weight as measured in insitu test pits. (Landva and Clark, 1986)

2.4.2.2 Borehole tests

The borehole permeameter test is one of the several methods for estimating saturated coefficient of permeability in situ in the vadose zone. Jain et al., (2006) estimated the in situ saturated permeability of MSW using the bore hole permeameter test at 23 locations in a 4-hectare full scale landfill site Florida, USA. Test area consisted of relatively new and un-degraded waste. The site was equipped with large number of vertical wells and consisted of relatively new and un-degraded wastes. The liquids added consisted of leachate from the landfill cell where the experiment was conducted and from adjacent landfill units. Liquid was added to wells until the water level or pressure stabilized; the flow rate added and the pressure at the bottom of wells are continuously monitored. A constant head of water is maintained in a bore hole excavated into unsaturated media until a steady infiltration rate is reached. The model proposed by Zangar (1953) was selected to determine permeability. Zangar's formula for determination of saturated permeability assuming a case with deep water Table is given as.

$$k_s = \frac{Q}{C_u r_w H} \quad C_u = \frac{2\pi(2AH - A^2)}{r_w H\left[\sinh^{-1}\left(\frac{A}{r_w}\right) - \left(\frac{A}{H}\right)\right]} \qquad (2.9)$$

Where, r_w is radius of the borehole, A is length of casing (screened section), H is the pressure head acting at the bottom of the bore hole; Q is the flow rate at steady state and k_s is field saturated permeability.

From the investigation, Jain (2006) estimated the permeability at 23 locations were in the range of 5.4×10^{-6} cm/s to 6.9×10^{-5} cm/s. The range of permeability was relatively lower than the previous studies. The average permeability of the waste was observed to decrease with the depth of the landfill. The ratio of the permeability of the waste estimated with air as the fluid and water as fluid was found to be in the range of 220 to 3500, the reason for this might be due to the presence of entrapped gas phase.

2.4.2.3 Pumping tests

Oweis (1990) reported the values of permeability from pumping test at a municipal landfill in northern New Jersey. The landfill contains a leachate mound with a maximum saturated thickness of about 35 feet. The test well consisted a 6 inch. diameter stainless steel casing and screen assembly installed in a 20 inch. diameter bore hole using cable tool method of well construction. Three additional observation wells were installed of 2-in. diameter stainless steel casing and 90 ft of 10 - slot well screen. Piezometers were installed to measure the fluid levels immediately outside well screen. Results showed a non linear relation between the discharge and the drawdown suggesting turbulent conditions. The average transmissivity of the refuse was observed to be 600 gpd/ft. The average storage coefficient value was about 0.05. Considering an average saturated thickness of 30 ft the calculated hydraulic conductivity was 10^{-3} cm/s

Ettla (1987) measured the hydraulic infiltration and hydraulic conductivity at two different landfills which entirely differ in their disposal technology. Neither of the landfills have leachate discharge. During maximum runoff the leachate was pumped from basin to the receiving waters. The calculation of hydraulic conductivity was based on the volume of the basin, leachate discharge and levels of the water Table in refuse. The saturated hydraulic conductivity of landfill was determined by pumping the leachate at the rate of 150 – 200 m^3/d from a bore hole and checking the water Table in observation tubes around the borehole.

The measured hydraulic conductivity in Holla landfill was in the order of 10^{-5} cm/s and in Lahti landfill in the order of 10^{-7} to 10^{-6} cm/s. The hydraulic conductivity differed significantly between the two landfills. The variation of hydraulic conductivity was attributed to the presence of parched water in Lahti Landfill and the variation in degree of compaction.

2.4.2.4 Flow columns

Koerner and Eith (2005) conducted a field investigation to obtain the residual permeability of 12 flow columns over time. The experimental set up confirms to ASTM D 1987 consisting of PVC flow column that houses the waste, soil/geotextile, and gravel supported by stain less steel screen as shown in Figure 2.13. The upper and lower tubes are joined to the coupler by containment rings. Normal pressure to the degraded waste on the top of the column with a spring and a reaction bar and the test is conducted in accordance to ASTM D 2434 "Standard Test Method for Permeability of Granular Soil (Constant Head)". The flow columns were connected to the leachate circulation system on a monthly interval and replaced back in drums of heated leachate for incubation until the next permeability reading. Figure 2.14 shows the Details of ASTM 1987 Columns being used for the investigation. The investigation is still in progress and the initial test results after one month gave a permeability in the order of 1.2×10^{-2} cm/s to 6.9×10^{-2} cm/s.

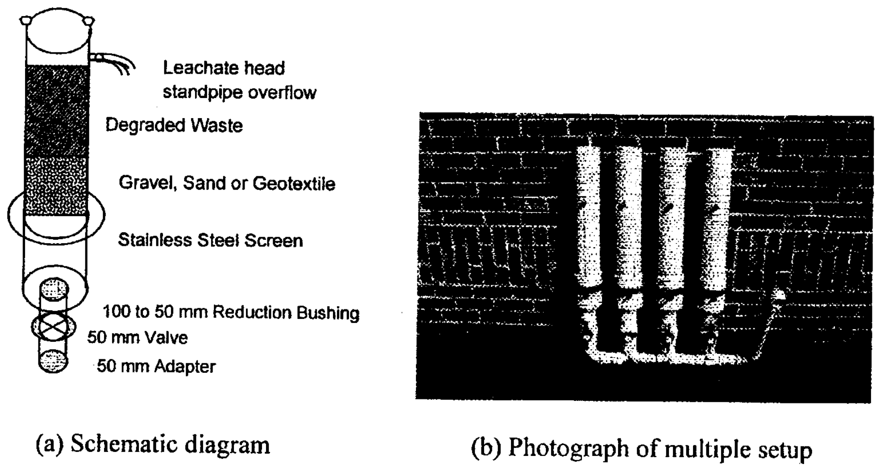


Figure 2.13 Details of ASTM D 1987 columns being used for this field investigation (Koerner and Eith, 2005)

2.4.2.5 Horizontal Injection Lines

Townsend (1995) studied the leachate recycle at solid waste landfill using horizontal injection at the Alachua county southwest landfill in north central Florida. The 27-acre landfill was lined and equipped with leachate collection and removal system.

Tests conducted in the same landfill using infiltration pond estimated the values of vertical permeability, k_y as 3×10^{-6} to 4×10^{-6} cm/s. The waste compaction was observed to be greater than the density in leachate injection area. The values of permeability estimated were found to be more than one order of magnitude than the previous estimates of k_y indicating a definite anisotropic conditions. The ratio of estimated vertical to horizontal permeability is in the order of 1 to 0.01.

2.4.2.6 Slug tests

The Slug Test Method was used to evaluate the permeability of an aquifer. Shank (1993) conducted slug tests in the existing gas vents of the municipal landfill of Alachua County, Florida. The Alachua county southwest landfill is located on a 232 – acre site, southwest of Gainesville; FL. Landfill operations at the site began in late 1973. The landfill site comprised of a number of separate landfill units. Two closed unlined units and one lined unit. 35 gas vents were installed in 24-inch diameter borehole with depths ranging from 28 to 35 feet, with well casings of 4 inch and 6 inch. sections. A total of 7 PVC slug tests , 3 pump slug tests were conducted. Two types of tests were conducted, the conventional method with a volumetric slug and a new method with removal of slug by means of submersible pump. The results from PVC slug test ranged from 8.6 x $10^{-4 \text{ to}}$ 1.5 x 10^{-2} cm/s with a geometric mean of 1.2 x 10^{-3} cm/s and a standard deviation of 3.0 x 10^{-3} cm/s. The pump slug tests yielded k_s values ranged from 6.7 x 10^{-5} to 9.8x 10^{-4} cm/s. Bouwer and Rice slug test analysis method was used in determination of permeability.

Literature available so far does not indicate the variation in permeability as a function of decomposition of the municipal solid waste. In the current study an attempt is made to determine the variation of permeability of MSW with degradation. Test methodology adopted and results are discussed in the following sections.

CHAPTER 3

EXPERIMENTAL PROGRAM AND PROCEDURE

3.1 Introduction

This chapter briefs the sample preparation, laboratory tests and procedures and experimental program used in the current work. The MSW samples used in the current research was collected in October 2005 from a transfer station in Burlington, Texas. The sample was mixed thoroughly and standard collection procedure was followed for obtaining a representative sample. The sample was transferred to the lab in 14 bags and later on physical characterization of the waste, including visual inspection of refuse composition, weight percentage of each constituent were determined. Figure 3.1 gives the weight percentage of each bag.

3.2 Sample Preparation

Municipal solid waste (MSW) at different stages of degradation was generated in eight laboratory scale bioreactors with leachate recirculation and under controlled conditions for ongoing research by Haque (2007). Two sets of bioreactor cells were built in the laboratory. Each set of reactor consists of four 16-gallon reactors to generate samples at different stages of decomposition. Composition of each reactor and their weight percentage is presented in Table 3.1 and Table 3.2. The first set of reactors were set up without soil, and the second set of reactors with soil to simulate the intermediate covers.

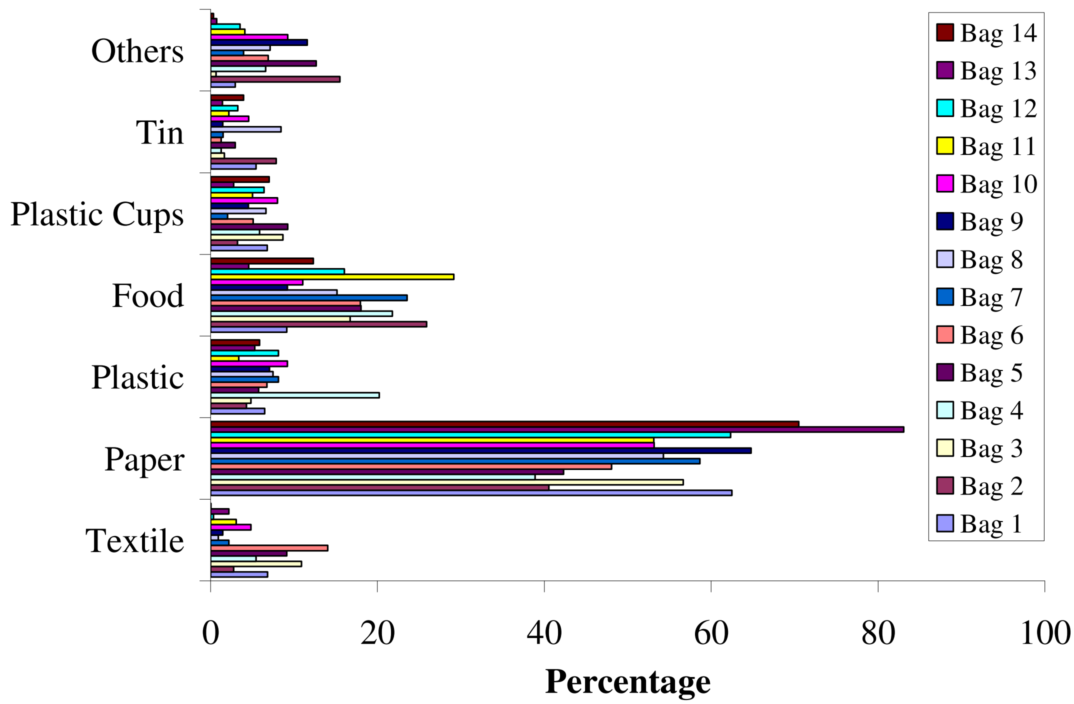


Figure 3.1 Composition of each bag of MSW sample obtained from the transfer station (Haque, 2007)

Prior filling the reactors, glass, tin and hard plastic bottles were removed. Each sample is thoroughly mixed and the reactors were filled in equally distributed layers and hand compacting it to get a uniform compaction. At the end of each phase, the reactors were dismantled and destructively sampled. The stage of decomposition was determined from the gas composition, and by the volatile solids composition (Haque, 2007). Gas was collected in five-layer gas bags and the volume was measured by pumping it out through a standard pump which pumps at a rate of 0.5 L/min. Methane gas concentration was measured using a gas chromatograph equipped with a thermal conductivity detector.

Table 3.1 Typical waste composition in each reactor set 1 and their percentage by weight

Reactor / Material	1-1	1-2	1-3	1-4
Textile	12	0	6.4	4.2
Plastic	17.0	15.2	12.2	13.9
Paper	51	63.7	66.8	57.4
Food	19.6	21.1	14.6	24.5

Source: Haque (2007)

Table 3.2 Typical waste composition in each reactor set 2 and their percentage by weight

Reactor / Material	2-1	2-2	2-3	2-4
Textile	1.9	14.6	3.7	0.0
Plastic	7.0	7.0	4.0	9.7
Paper	50.3	50.0	50.1	61.7
Food	31.7	18.7	4.0	19.1
Soil	9.1	9.8	9.2	9.5

Source: Haque (2007)

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 1.5L. Reactors were operated under conditions designed 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. The leachate was neutralized with potassium hydroxide and sulfuric acid for acidic and alkaline conditions as necessary and recycled 4 days a week to accelerate the decomposition in laboratory. All reactors were maintained at a room temperature of 22 – 29 ˚C.

The volatile solids were determined in accordance with Standard Methods APHA Method 2440-E (Hossain et al, 2007). Samples were dried at 105˚C to a constant weight and held in a desiccator. Approximately 100 grams of the 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 desiccators to a constant weight. The percent weight loss from ignition yielded the total amount of volatile matter.

Figure 3.2 Two sets of bioreactor cells with and without soil representing the four phases of decomposition (Hossain et al, 2007).

3.3 Experimental program

An experimental program was designed to determine the permeability with degradation of the MSW. Tests were also conducted to determine the influence of density and the percentage of cover soil on permeability of the municipal solid waste. Tests were conducted on samples obtained from the reactors at each stage of decomposition to determine the variation in

- Particle size distribution with degradation
- Permeability with degradation
- Permeability with the change in finer fraction
- Permeability with change in density.
- Permeability with percentage of cover soil

Table 3.3 gives the notations followed and Table 3.4 gives the testing program and number of tests carried out in the current research.

Based on the literature review the unit weight of MSW ranges between 20pcf to 80pcf depending on the compaction effort and percentage of soil. Therefore for the current study, tests were proposed to be performed at 40pcf (640.73 kg/m^3), 50 pcf (800.92 kg/m^3) and 60 pcf (961.10 kg/m^3). During landfilling, soils are used as daily cover. The percentage of soil in MSW varies between 15 to 30%. To consider the effects of daily cover soil on the permeability of MSW, a second set of tests were planned to be performed at 20% and 30% of soil. The grain size distribution of the cover soil is presented in Figure 3.4., and the properties of the soil used are given in Table 3.5

Table 3.3 Experimental program and variables

Test	Material	Variables	Number of tests
Particle Size Analysis	Cover Soil		1
	MSW		8
Specific Gravity	MSW	Entire sample Fraction passing US sieve No.200	12 4
Moisture Content	MSW		12
Permeability	MSW	4 phases and 3 densities	12
	MSWRS1+20% soil	4 phases and 3 densities	12
	MSWRS2 + 20% soil	4 phases and 3 densities	12
	MSWRS1 + 30% soil	4 phases and 3 densities	12
	MSWRS2 + 30% soil	4 phases and 3 densities	12

Table 3.4 Notations

Notation	Explanation
RS1	Reactor Set 1 without soil
RS2	Reactor Set 2 with soil
RSx-n	Reactor set ‘x’ with n% of soil. Where x=1 or 2, and n= 0, 20 and 30

Table 3.5 Properties of Cover Soil

Soil Classification	SW-SM Well graded sand with silt and gravel
Percentage of particles passing US sieve 200	9.52
Specific Gravity	2.54
Coefficient of permeability (cm/s)	0.00081
Density (kg/m^3)	1742

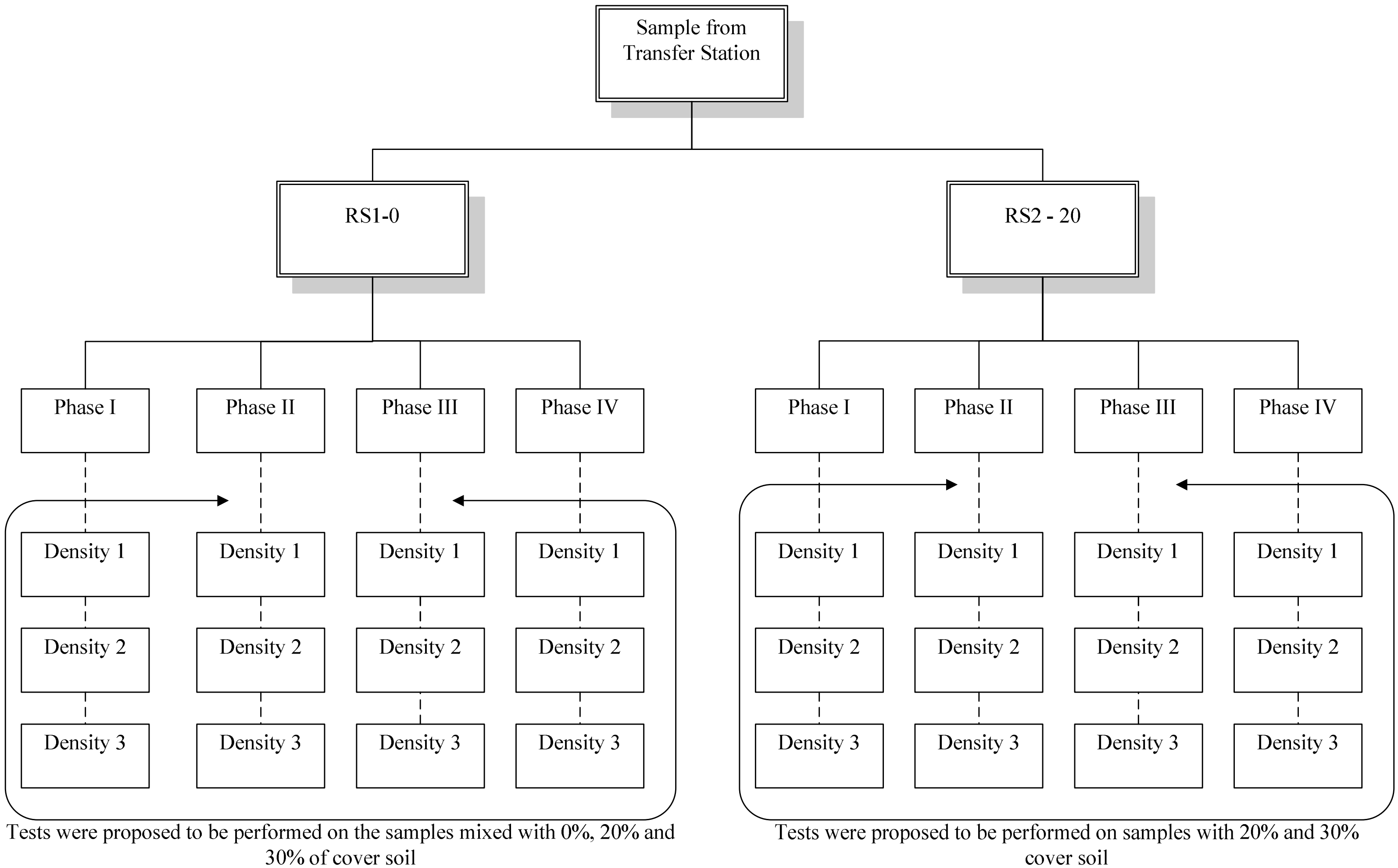


Figure 3.3 Flow diagram representing the samples considered for permeability testing

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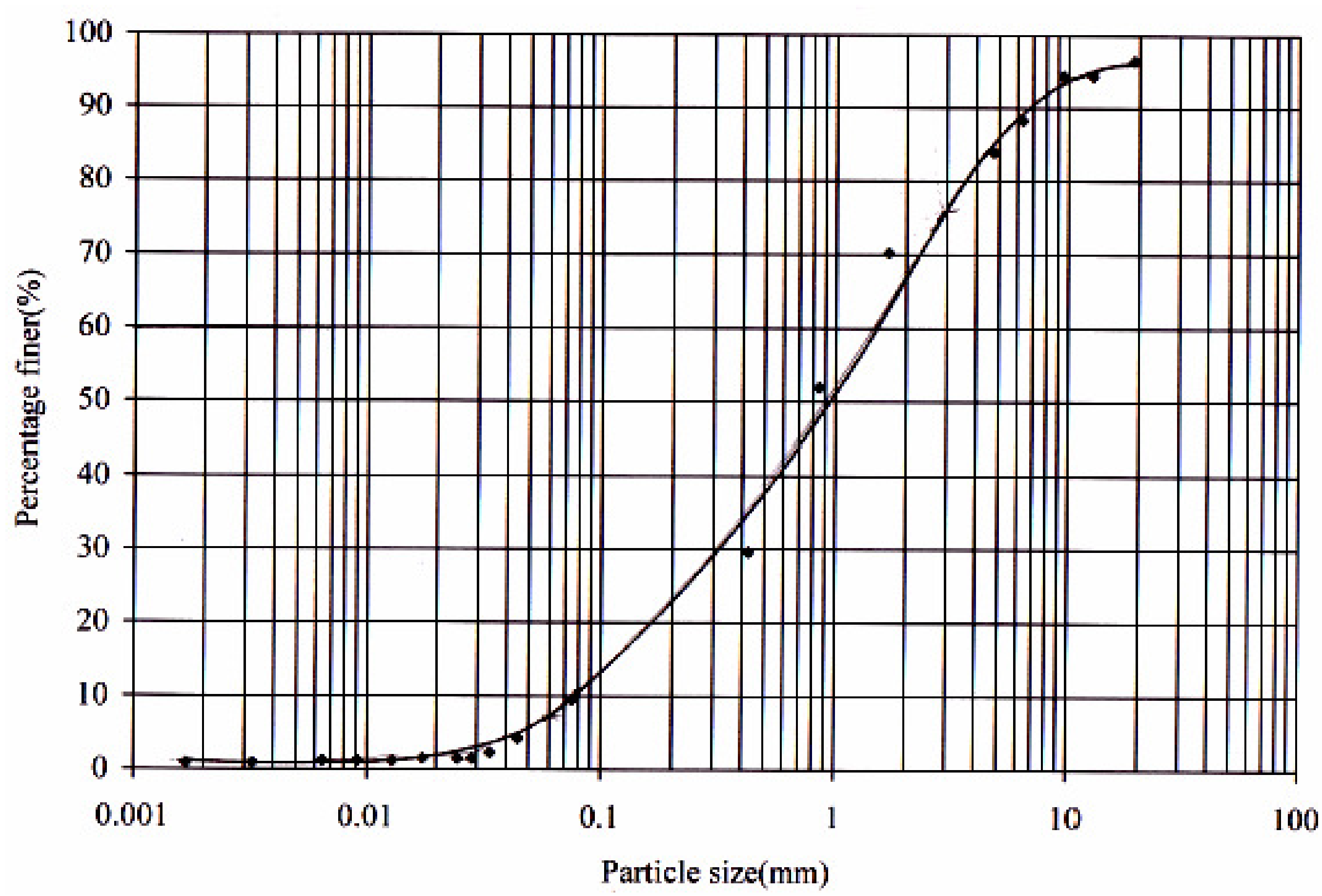


Figure 3.4 Grain size distribution of cover soil

3.4 Laboratory Tests

Determination of engineering properties of MSW is difficult due to the heterogeneity and vide variety of particles in MSW. Landva and Clark (1990) concluded that geotechnical testing of these complex material is feasible as long as it is recognized that application of conventional testing methods and analysis may not be applicable. The following sections present a brief description of different test procedures adopted in the current study.

3.4.1 Moisture Content

Moisture content of the samples were determined according to standard method ASTM D 2974 – 00 and APHA 2540 - B (Kelly, 2002). Samples were oven dried at a temperature of 105^{o}C and moisture contents were determined by by both dry weight basis and wet weight basis.

3.4.2 Specific Gravity

The specific gravity tests were conducted in accordance with ASTM test method ASTM D 854-02 and ASTM D 5057-90. Three tests were done on representative samples for each phase of degradation and an average value was reported. Additionally, tests were also conducted on fraction passing through US Sieve No. 200. The specific gravity of the specimen was determined by the following equation and temperature correction is applied (ASTM D 854-00).

$$G_s = \frac{(w_s)}{(w_1) - (w_2 - w_s)} \qquad (3.1)$$

Where w_s = weight of oven dried sample, w_1= weight of pycnometer + water and w_2 = weight of pycnometer + sample + water

Figure 3.5 shows the typical sample and test apparatus used for determination of specific gravity. The samples for determination of specific gravity for the fraction passing US sieve No. 200 is obtained as given section 3.3.4.1.

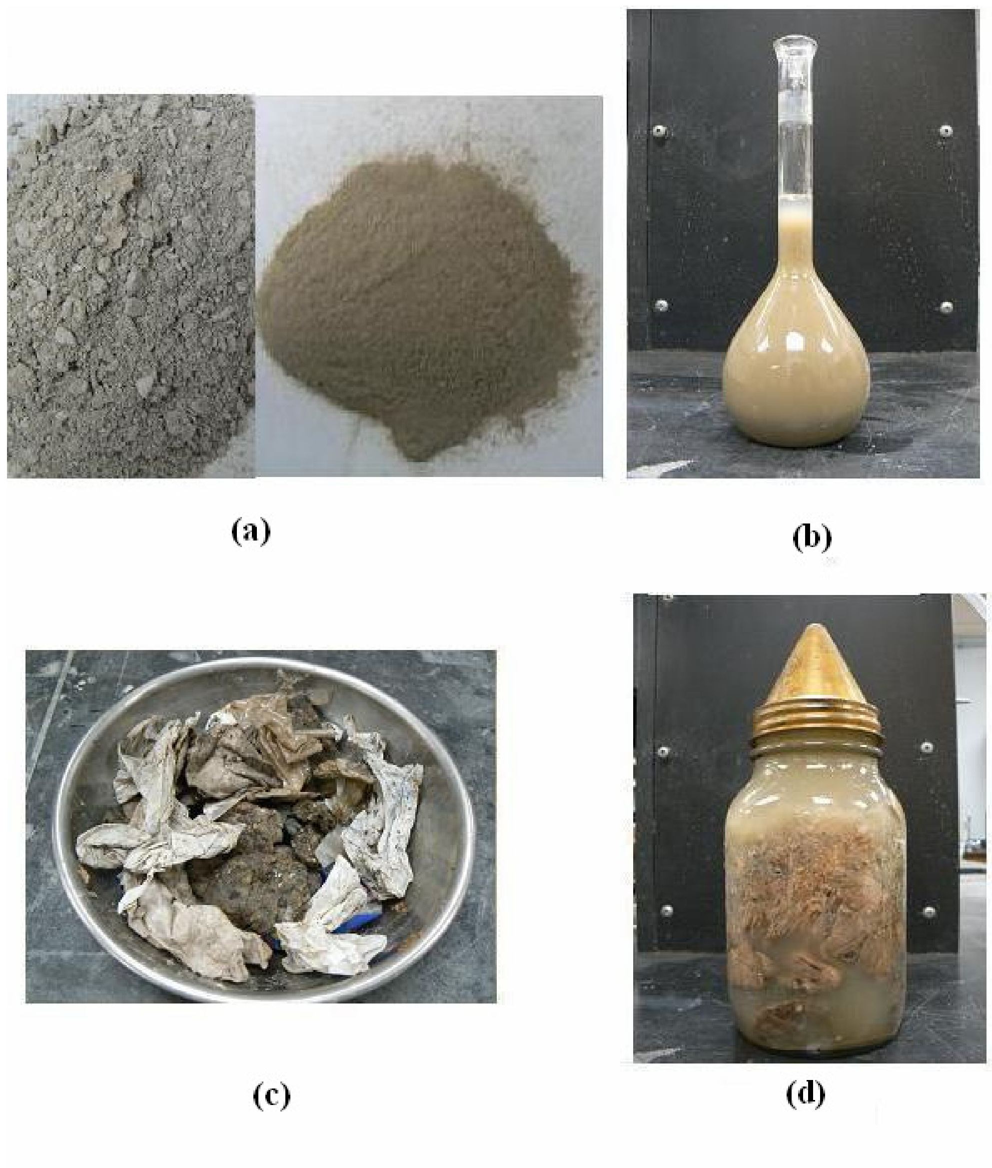


Figure 3.5 Typical sample and apparatus used; a) Fraction passing US sieve No. 200; b) Volumetric flask; c) Representative sample; d) Pycnometer

3.4.3 Particle Size Analysis

Considering the vide range of particle size and the nature of the waste, wet sieve analysis was conducted. Wet sieving is preferred as the particles adhere when dried and conventional dry analysis may not give accurate results. For fraction passing US sieve No. 200 hydrometer analysis is adopted. The samples were prepared following the test procedure given in ASTM D2217 and the wet sieve analysis was conducted in accordance with ASTM D422-63. The test procedure is carried out in three stages.

1. Determination of finer fraction passing US sieve No. 200
2. Mechanical wet sieve analysis on fraction retained on US sieve No. 200
3. Sedimentation analysis of the fraction passing US sieve No. 200

3.4.3.1 Determination of finer fraction passing US sieve No 200.

Oven dried samples weighing approximately 0.25 kg were quartered and washed through US sieve no. 200 and the sample retained is further analyzed by wet sieving. From the percentage of mass retained, the percentage of finer fraction is calculated as given below (ASTM D 1140-00).

$$f = \frac{w_p}{w_t} \times 100 \qquad (3.2)$$

where w_p= weight of sample passing through US sieve No. 200, ie., w_t-w_r and w_t and w_r are the total weight of sample taken and weight of sample retained on US sieve No. 200. the wash water thus obtained is carefully preserved for determination of specific gravity and hydrometer analysis.

3.4.3.2 Mechanical Analysis

The sample retained on #200 sieve is further 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 were collected, dried and weighed. The percentage passing through each sieve is calculated by dividing the weight of sample retained on each sieve to the total weight of the sample. The gradation of the portion passing through US sieve 200 is obtained by hydrometer analysis of the wash water from the wet sieve analysis. Tests were carried out on two representative samples of each phase and the average grain size distribution was plotted.

3.4.3.3 Hydrometer analysis

The water collected during wet sieving is oven dried to obtain approximately 750ml of solution containing the fraction passing through US sieve No 200. The solution is further mixed with dispersing agent solution prepared to be at concentration of 40g/l. The obtained mixture was stirred thoroughly and the solution was transferred to the sedimentation cylinder. The cylinder is made up to 1000ml and then placed at a location where minimal disturbance is expected. The test is carried out in accordance with ASTM test method for particle size analysis of soils (ASTM D 422-63)

(a) (b)

Figure 3.6 Hydrometer test (a) Typical fraction passing US sieve No. 200; (b) Graduated cylinders with hydrometer and test solution

3.4.4 Permeability

The effects of MSW decomposition on permeability were determined using the constant head permeability method in the laboratory. The coefficient of permeability of the MSW samples were measured at different phases of decomposition and densities. Tests were also conducted to determine the influence of percentage of finer fraction and density on the permeability of MSW. The MSW particles are much thinner and flatter than the soil particles and the flow in waste might be through inter particle and intra particle voids, hence, the general principles applicable for soils may not be applicable to MSW. However, due to the lack of standard test procedure for determination of permeability of municipal solid waste, the standard test procedure for determination of permeability of the granular soils (ASTM D 2434-68) is adopted for the current work. The test setup consist of an acrylic cylinder with inside diameter of 15.24 cm (6 inches) and a height of 24 cm, porous stones, stand, clamps, silicon grease and a tank maintaining a constant hydraulic head. Table 3.6 presents a brief overview of sample size, mode of compaction for permeability testing used in previous studies.

3.4.4.1 Sample Preparation:

The remolded sample of known weight from the reactors at its natural moisture content was taken and the particles greater than half the diameter of the cylinder were shredded so as to reduce the boundary effects. The sample was then transferred to acrylic cylinder in five uniformly distributed layers to achieve the required uniform density. The required densities were obtained by changing the packing of sample by maintaining the constant height of the sample. The weight of the sample is predetermined by multiplying the volume of the sample with the required density.

Table 3.6 Glossary of sample size, mode of compaction for permeability testing from previous studies.

Source	Sample Description	Maximum particle size	Sample placement	Test
Pelkey (1997)	five years old obtained from the test pits 6.4m deep at Spruce Lake landfill, NB, Canada	Equal to diameter of sample	Compacted in 6-8 roughly equal lifts with a 5.6 kg hammer that was dropped from a height of 20 to 30	Constant head test in consolidometer
Gabr (1995)	The samples were retrieved from field auger cuttings. Majority of waste assumed to be 15 and 30 years old	$1/6^{th}$ of the diameter of the specimen	Compacted into a 70.6mm diameter and 152mm long split mould. Three lifts with 12 blows from a standard proctor test hammer	Falling head and constant head test on triaxial compression specimens
Korman (1987)	Waste from paper mills approximately 1 to 15 years old at 2 to 16 feet deep and fresh wastes. Tests were conducted on undisturbed samples from Shelby tubes and hollow stem auger and reconstituted samples.	Not reported		Regid wall permeability tests on fresh wastes and flexible wall permeability tests on landfilled waste

Table 3.5 - continued

Source	Sample Description	Maximum particle size	Sample placement	Test
Durmusoglu et. al. (2006)	Approximately 10 year old sample from Rock Prairie Road Landfill in Brazos County, Tx.	Large scale consolidometer 2 cm Small scale cell 0.5 cm.	compacted at standard proctor capacitive effort	Falling head test in large and small scale consolidometer. Large scale compression cell is of 71.2 cm diameter and 55.8cm high.
Chen (1995)	Typical mixture of paper, plastic and refuse derived fuel (RDF) from National Ecology of Baltimore, MD	Not reported	Packed with increments of less than 2 kg of MSW to allow uniform compression.	Constant head tests in a test column of 122 cm long and 38.1cm diameter.
Bleiker (1993)	Disturbed refuse samples from Keele Valley Landfill, Toronto, Ontario	Not reported	A small portion of sample is placed in the ring and each effective stress level is applied for 90 minutes.	Falling head test in a Fixed brass ring having a diameter of 63mm and a thickness of 19mm
Beaven and Powrie (1995)	Crude Domestic Refuse directly from tipping face of landfill and pulverized refuse passed through 150mm filter.	Not reported	Placed and compressed approximately to field density.	Constant head flow test in Pitsea compression cell of 2m diameter and 3m high.

3.4.4.2 Test Procedure:

The acrylic cylinder along with the accessories are weighed. The sample is then transferred to the cylinder as given in the pervious section and the acrylic cylinder along with sample are mounted on the stand and the clamps were tightened. The entire setup is weighed again so as to determine the weight of the sample. The height of the sample is measured and recorded. The setup is connected to the water line making sure that there are no air bubbles along the water line. The head is measured and the flow in sample is allowed to stabilize until no air bubbles appear in the outlet pipe. When the flow rate is constant the permeability, k, is determined from the total amount of flow, Q, in a given time, t, as

$$k = \frac{QL}{hAt} \qquad (3.3)$$

where h is the hydraulic head, A area of cross section of specimen, and L is the height of the sample. Figure 3.7 shows the step by step procedure for determination of permeability.

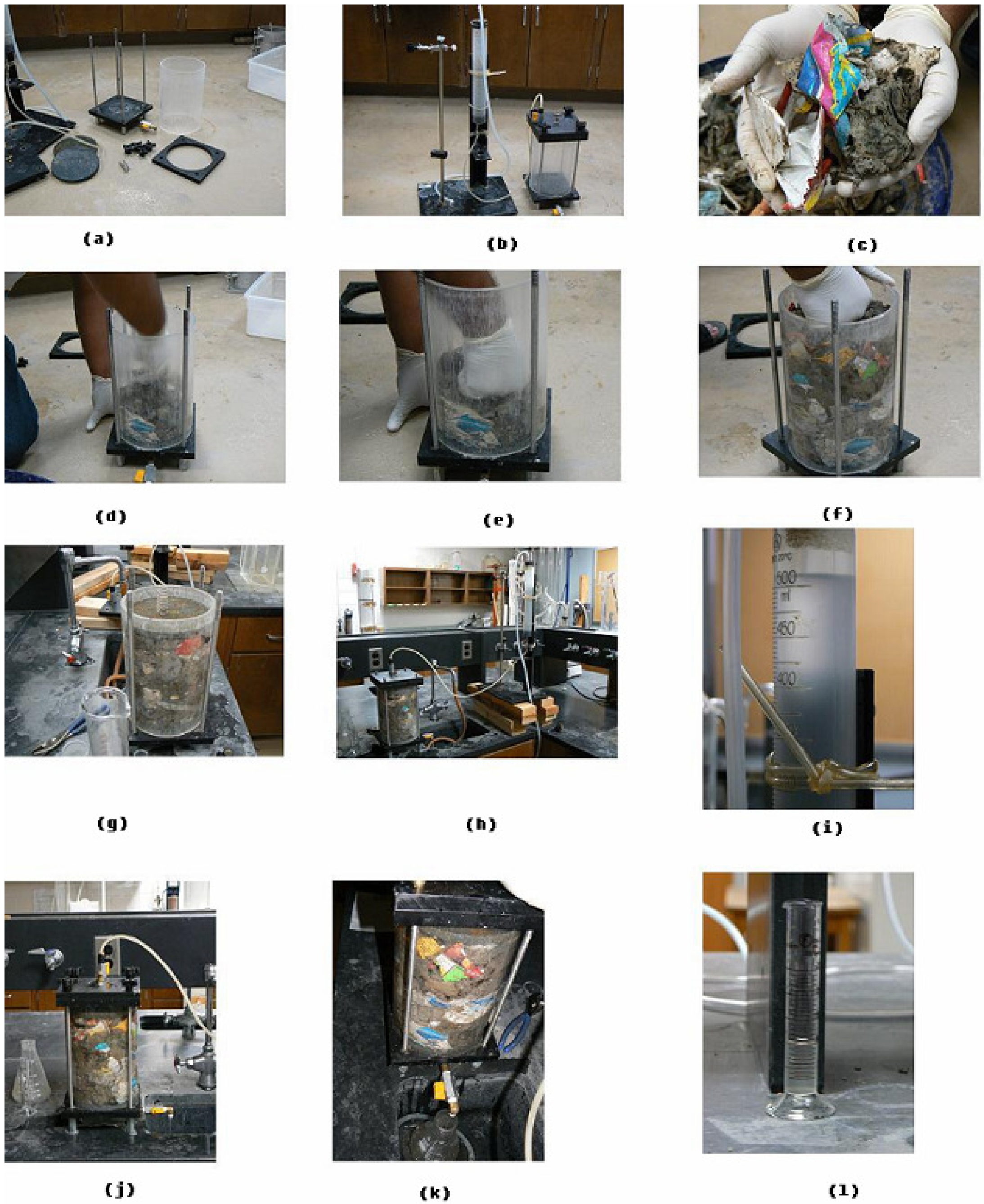


Fig 3.7 step by step procedure for determination of coefficient of permeability. (a) and (b) apparatus and experimental setup; (c) representative sample; (d), (e) and (f) sample placement and compaction; (g) sample mounted on the stand with porous stone on the top; (h) set up connected to water line (i) maintaining constant head; (j) allowing the flow in sample to stabilize (k) collecting the water drained at a given time; (l) measuring the water collected.

CHAPTER 4

ANALYSIS OF TEST RESULTS

4.1 Introduction

Particle size analysis, along with moisture content and specific gravity of the sample were determined for preliminary characterization of the sample at each phase of degradation. The following sections provide the test results.

4.2 Refuse Decomposition Results

Based on the experimental results methane production rates and the pH of leachate are presented in Figures 4.1 and Figure 4.2 respectively. Recirculation of neutralized leachate along with anaerobic digester sludge enhanced the refuse decomposition. The results show that at 25^{th} day the samples were in anaerobic acid phase. The rate of methane production was maximum after 106 days and the samples were in accelerated methane production phase. After 225 days the samples were in decelerated methane production phase. The reactors were destructively sampled after 25 days, 106 days, 225 days and 253 days to obtain the representative at the end of each phase of decomposition (Hossain et al, 2007).

The change in percentage of volatile solids from each of the reactor is presented in Table 4.1. Leachate recirculation had a significant effect on the degradation of the waste. The percent change (utilized) in volatile solids increases from 0.91 in Phase I to 39.24 in final phase. The cumulative methane production increased significantly with waste degradation and time. The cumulative gas production was only 23.49 L in phase I compared to 515.4 L in Phase IV. With degradation and conversion of Volatile organic content to gases, gas production increased significantly. Therefore, the percentage of Volatile organic content is expected to change with time and degradation.

Table 4.1 Methane Production and Sample Composition in Sampled Reactors (Hossain et al, 2007)

Phase	Time of Reactor Operation	Cumulative Methane Production (L)	% Change in Volatile Solids
1	25	23.49	0.91
2	106	195.03	1.40
3	225	487.73	12.88
4	253	515.41	39.24

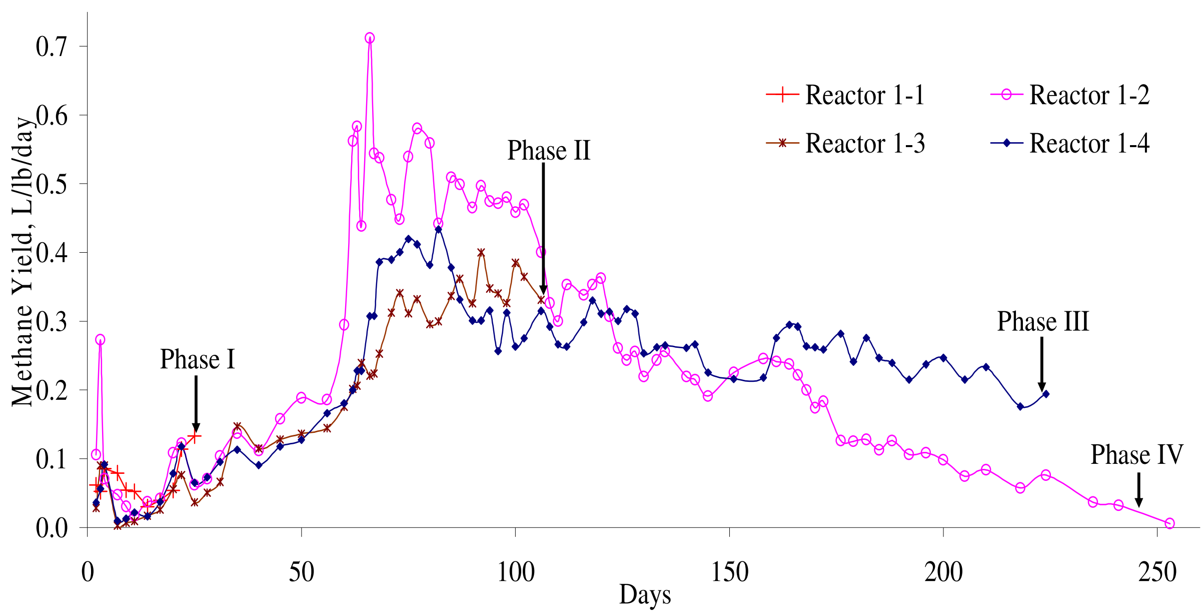


Figure 4.1 Rate of gas production from reactors at each phase of Decomposition of reactors without soil (Hossain et al, 2007)

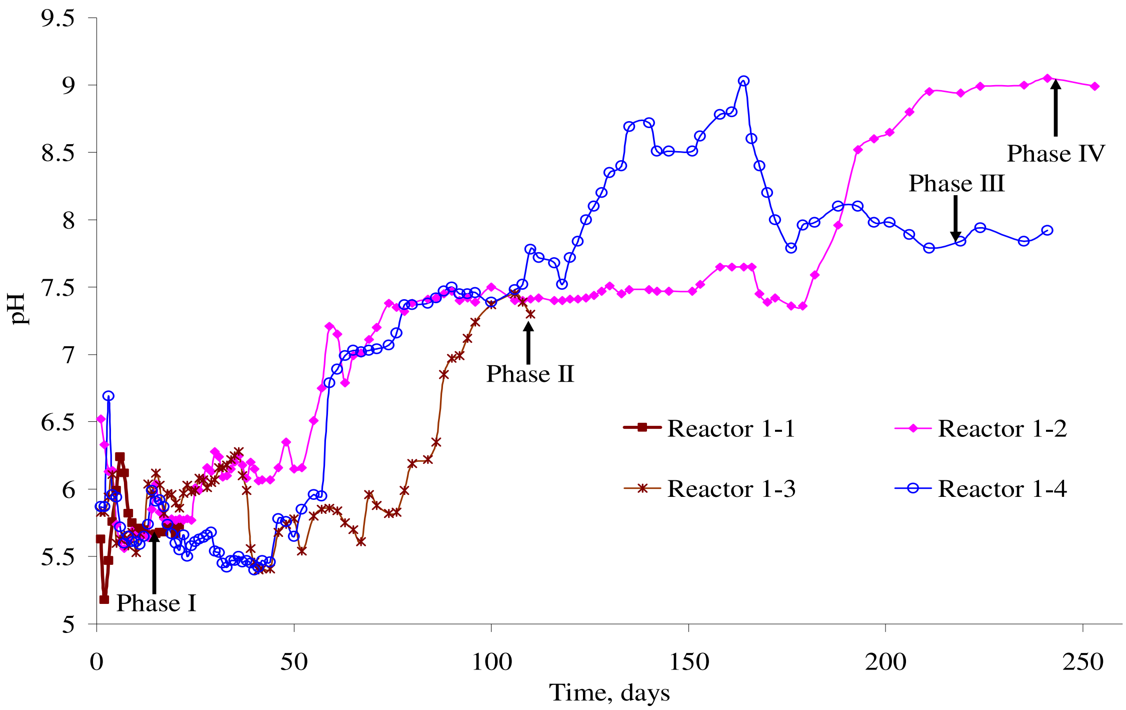


Figure 4.2 pH of generated leachate from the bioreactor cells (Hossain et al, 2007)

<u>4.3 Change in composition with degradation</u>

The change in weight percentage of degradable constituents for the sample in the first set of reactor is given in Figure 4.3 and that of reactor set 2 are given in Figure 4.4. From the plots it can be observed that there is a decrease in weight percentage of degradable constituents with the stage of degradation. The percentage decrease increased for each phase of disintegration. Food wastes are completely consumed by the end of second phase and paper approximately 50% at the end of phase IV in the first set of reactors. The rate of decomposition also depends on the type of individual constituent. Although each reactor doesn't have the same constituents the results are observed to be comparable.

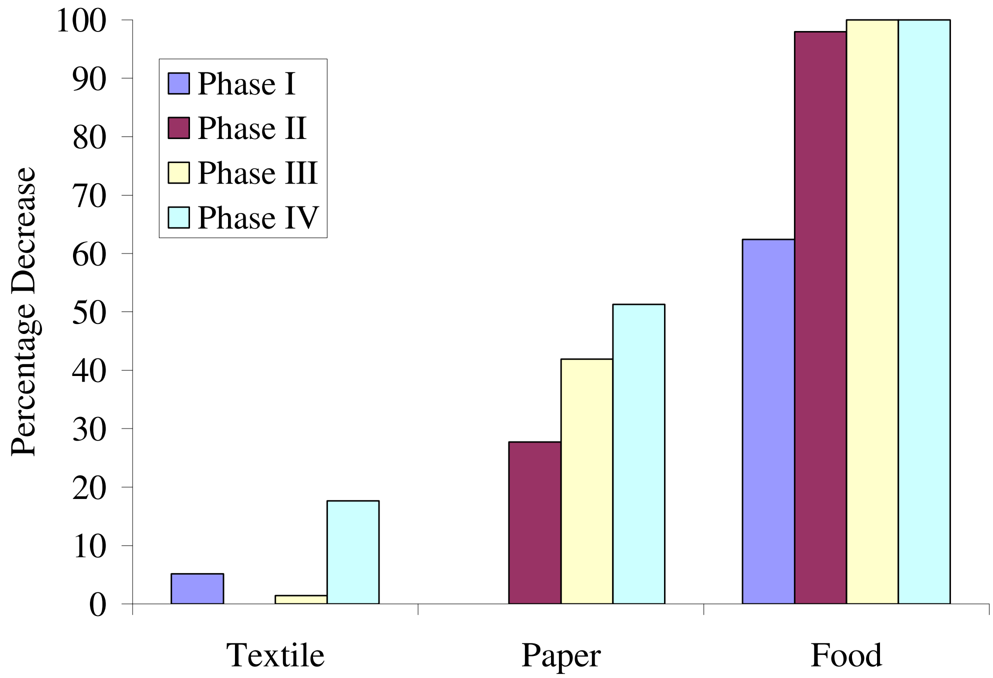


Figure 4.3 Change in weight percentage of degradable constituents in reactor set 1 (Haque, 2007)

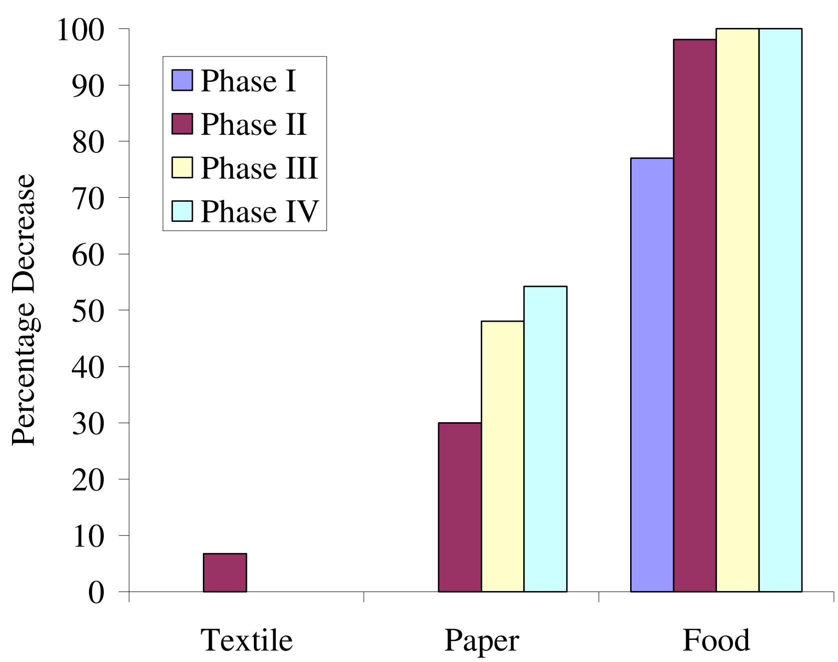


Figure 4.4 Change in weight percentage of degradable constituents in reactor Set 2 (Haque, 2007)

4.4 Geotechnical Testing

4.4.1 Particle Size Analysis

From visual inspection there is no observable disintegration of paper and plastic, in Phase I and Phase II of degradation but it appeared like all the food wastes were consumed during these phases. Letters on the paper were clearly visible even after the second phase of disintegration. Chunks of paper and textile were observed in phase III implying a partial disintegration of paper and textile However, paper was completely disintegrated and is in the form of paste at the end of phase IV. Figure 4.5 shows the disintegrated paper in each phase. Figure 4.8 shows the typical fractions retained on 2-inch US sieve, 1-inch US sieve, US sieve # 60 and US sieve # 200 during particle size distribution. Wet sieve analysis on the fraction retained on US sieve No. 200 indicated particle disintegration as the stage of decomposition progresses. Figure 4.6 and Figure 4.7 presents the particle size distribution curves for municipal solid waste at different stages of decomposition from reactor set 1 and 2 respectively

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 degradation and with degradation, the matrix structure of paper, textile and other degradable constituents were broken down into smaller particles. This 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. Figure 4.9 presents the variation in percentage of fraction passing US sieve No 200 with degradation of municipal solid waste. The increase in finer fraction with degradation is about 2-3 times, which is expected to change the hydraulic behavior of MSW in a landfill.

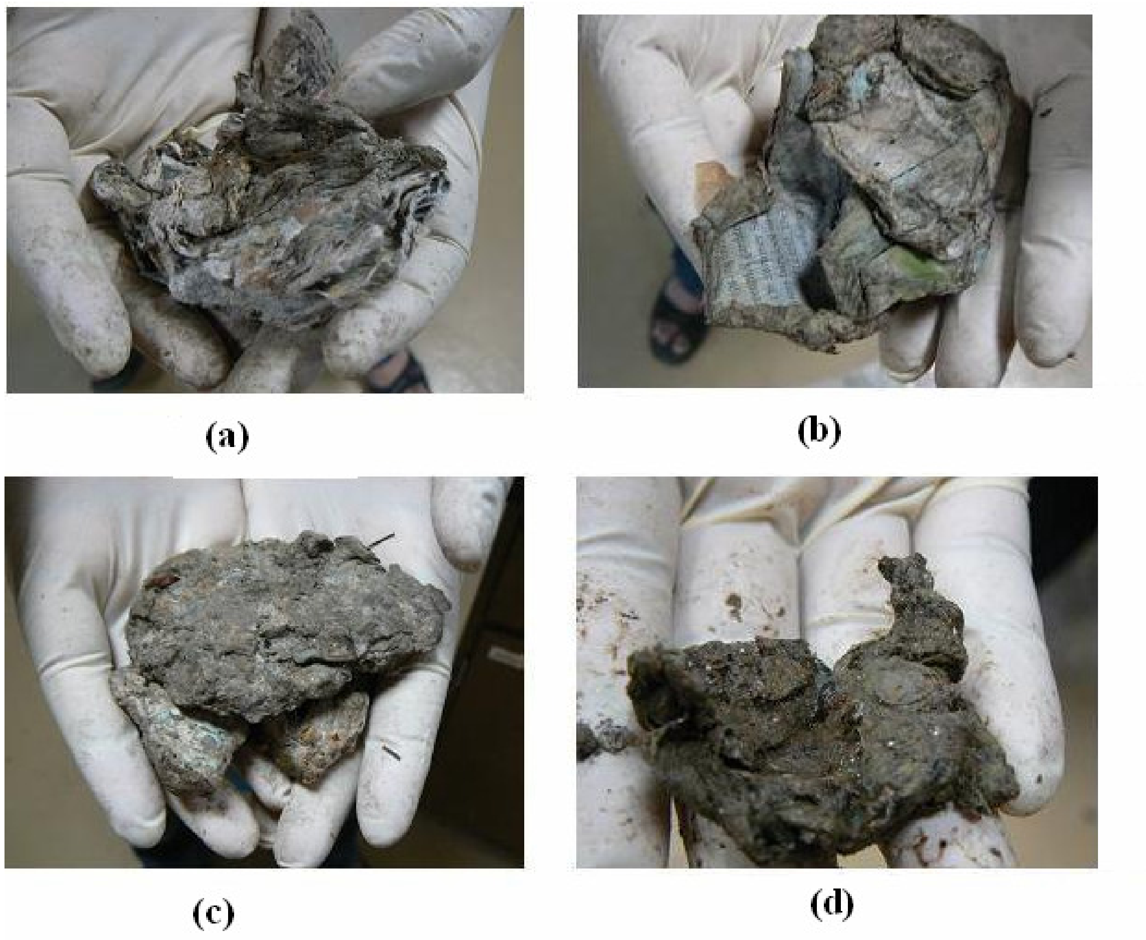


Figure 4.5 Disintegration of paper with degradation; (a) Phase I; (b) Phase II; (c) Phase III; (d) Phase IV

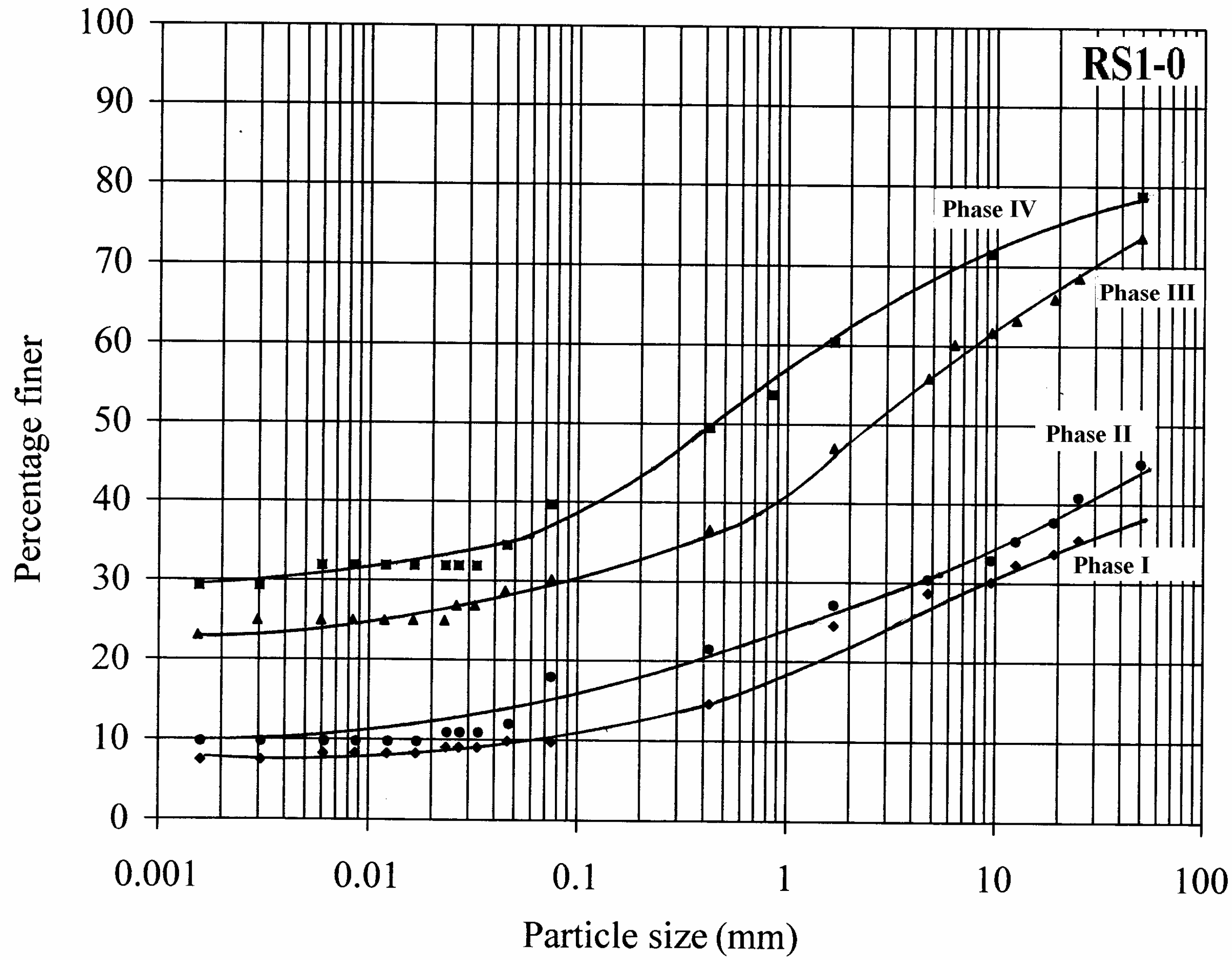


Figure 4.6 Particle size distribution of MSW with degradation from reactor set 1

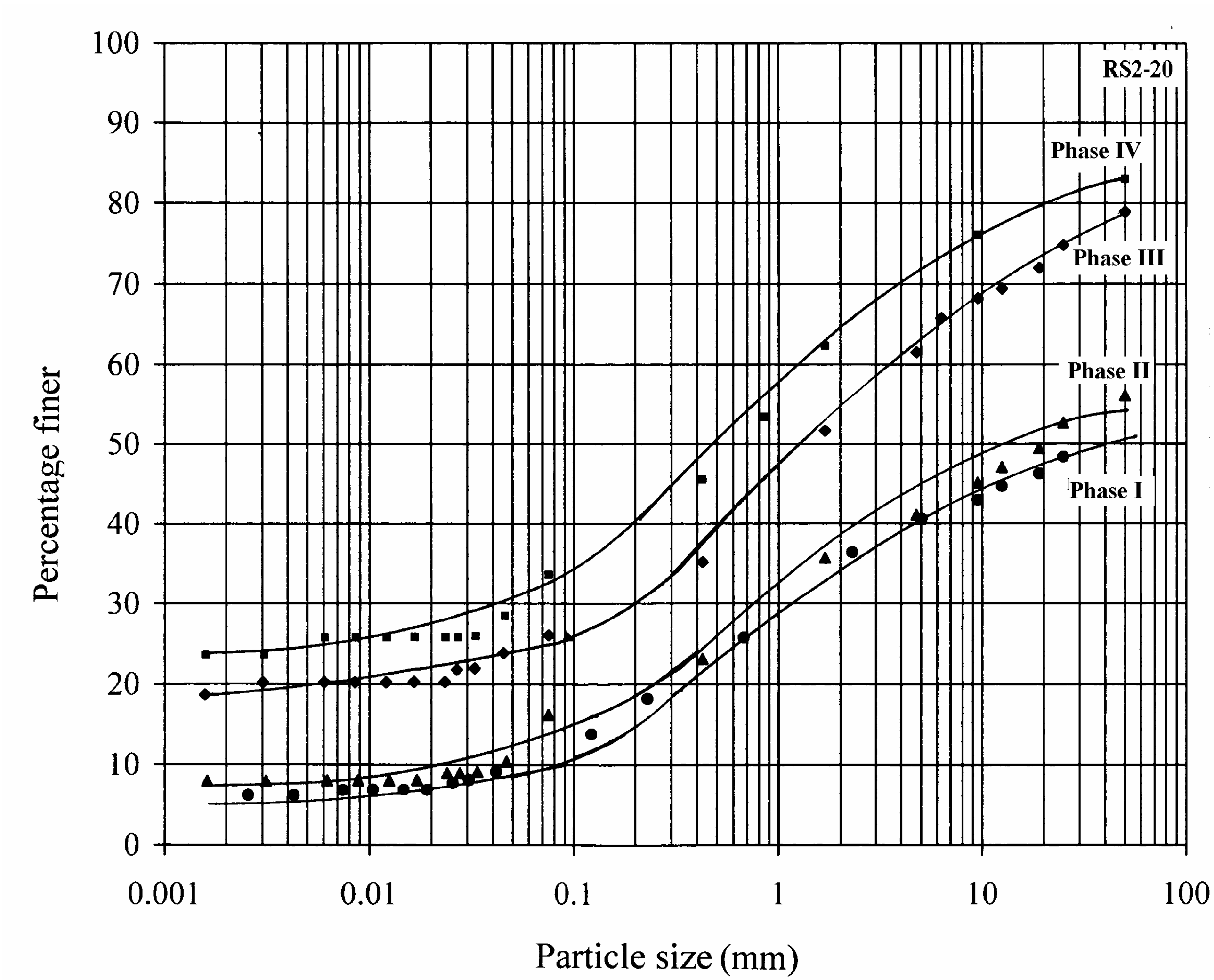


Figure 4.7 Particle size distribution of MSW with degradation from reactor set 2

(a)

(b)

(c)

(d)

Figure 4.8 Typical sample retained on the corresponding sieve; (a) Fraction Retained on 2 – inch US sieve; (b) Sample Passing 1 Inch US sieve and retained on 1/4th –inch US sieve; (c) Sample Passing US – sieve # 40 and retained on US sieve # 60; (d) Sample Passing Us sieve # 60 and retained on US sieve # 200

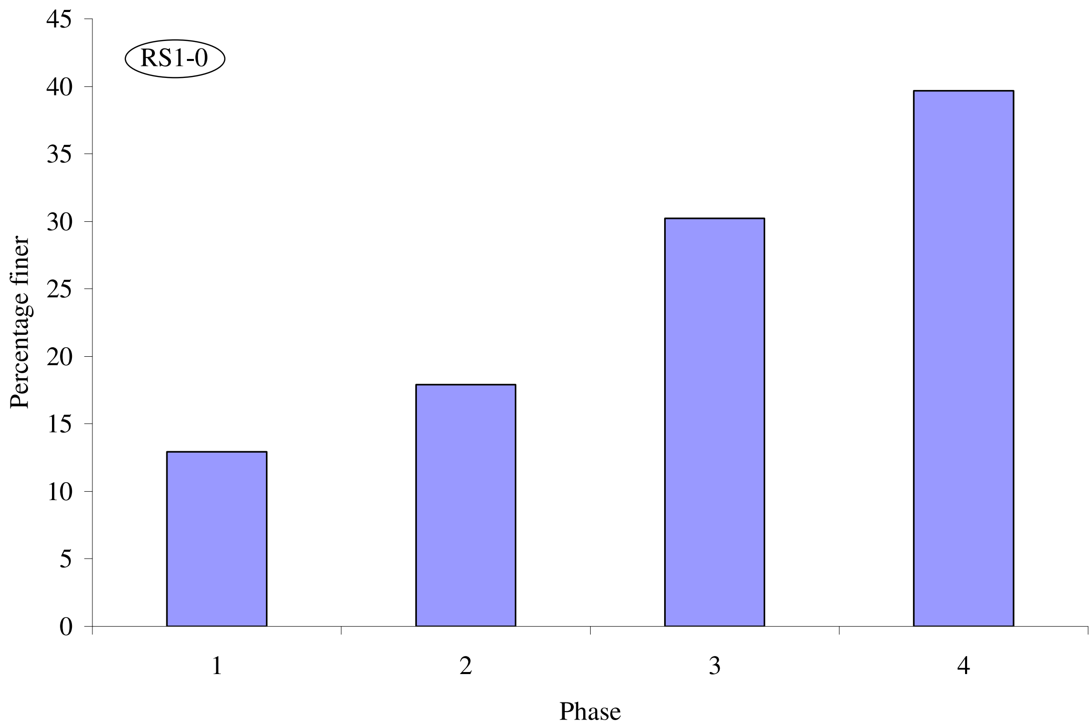


Figure 4.9 Percentage of particles finer than 75µm (US Sieve No. 200)
with degradation

4.4.2 Specific Gravity

A total of 12 specific gravity tests were conducted on the waste samples at each phase of degradation. Additionally, tests were also carried out on the fraction finer than US sieve 200. Table 4.2 presents the test results of the specific gravity of MSW. The average value of specific gravity is decreasing with the degradation of MSW. The possible reason might be due to the increase in percentage of plastic which has a relatively low specific gravity and decrease in percentage of paper with decomposition.

Table 4.2 Test results of specific gravity of MSW

Material	Test 1	Test 2	Test 3	Average	STDEV	Particles Passing US Sieve No. 200
MSW-Phase I	1.11	0.94	1.15	1.07	0.114	1.65
MSW-Phase II	0.83	1.11	0.92	0.95	0.137	1.54
MSW-Phase III	0.91	0.97	0.86	0.91	0.055	1.52
MSW-Phase IV	0.89	0.90	0.92	0.91	0.012	1.46

STDEV – Standard Deviation

An attempt was made to compare the results with the values calculated based on the specific gravity of the individual constituent. Table 4.3 presents the typical values of specific gravity of individual constituents from the literature. The values of specific gravity were obtained by the following equation

$$\frac{\sum_{x=1}^{n}\left(p_x.G_{sx}\right)}{100} \qquad (4.1)$$

where p_x is the percentage of the individual constituent with specific gravity, G_{sx}.

Table 4.3 Typical values of specific gravity from literature.

Material	Specific Gravity
Paper*	1.20
Plastic#	0.91(LDPE) to 0.97 (HDPE)
Food*	0.43 (Oats)-0.77 (Potato, Wheat)
Textile*	1.31(wool)

* http://www.reade.com/Particle_Briefings/spec-gra2html
# www.plasticusa.com/specgrav.html

Table 4.4 presents the experimental and calculated values of specific gravity. The variation in specific gravity can be clearly observed with the change in composition. Hence, the decrease in values of specific gravity with each phase can be attributed to the change in percentage composition of individual constituent of the sample.

Table 4.4 Experimental and calculated values of specific gravity of MSW

Material	MSW	
	experimental	calculated
MSW-Phase I	1.07	1.2
MSW-Phase II	0.96	1.16
MSW-Phase III	0.91	1.14
MSW-Phase IV	0.91	1.12

4.4.3 Moisture Content

The results of average moisture content of the MSW from the reactors with and without soil with degradation were presented in Table 4.5. The observed increase in moisture content with degradation can be attributed to the particle disintegration resulting in decrease in pore spaces, enabling the MSW to hold the moisture.

Table 4.5 Moisture content of MSW

Material	Moisture Content (%)			
	Sample from Reactor without Soil		Sample from Reactor with soil	
	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis	Wet Weight Basis
MSW-Phase I	149.1	59.5	126.8	55.3
MSW-Phase II	158.6	59.7	197.1	65.9
MSW-Phase III	180.4	63.3	230.3	68.9
MSW-Phase IV	198.4	64.7	245.1	69.6

4.4.4 Permeability

4.4.4.1 Permeability with degradation

Permeability tests were conducted on MSW samples at each phase of degradation at three given densities. Permeability of MSW was in the order of 10^{-2} cm/s after the first phase of degradation and decreased to the order of 10^{-4} cm/s at the final phase of degradation. Figure 4.10 presents the change in permeability of MSW at each phase of degradation at 700 kg/m^3 and Figure 4.11 presents the variation in permeability with percentage of particles passing US sieve # 200. The change in permeability might be due to the particle disintegration with decomposition and the resulting increase in percentage of finer fraction. With the increase in percentage of finer fraction, there might be a significant change in pore size, geometry and continuity resulting in the decrease of fluid flow. Blieker (1993) from laboratory fixed ring test results on samples from Keele Valley Landfills reported a higher coefficient of permeability for a 5 year old sample when compared to a 10 year old sample which implies a reduction in permeability with the age of MSW.

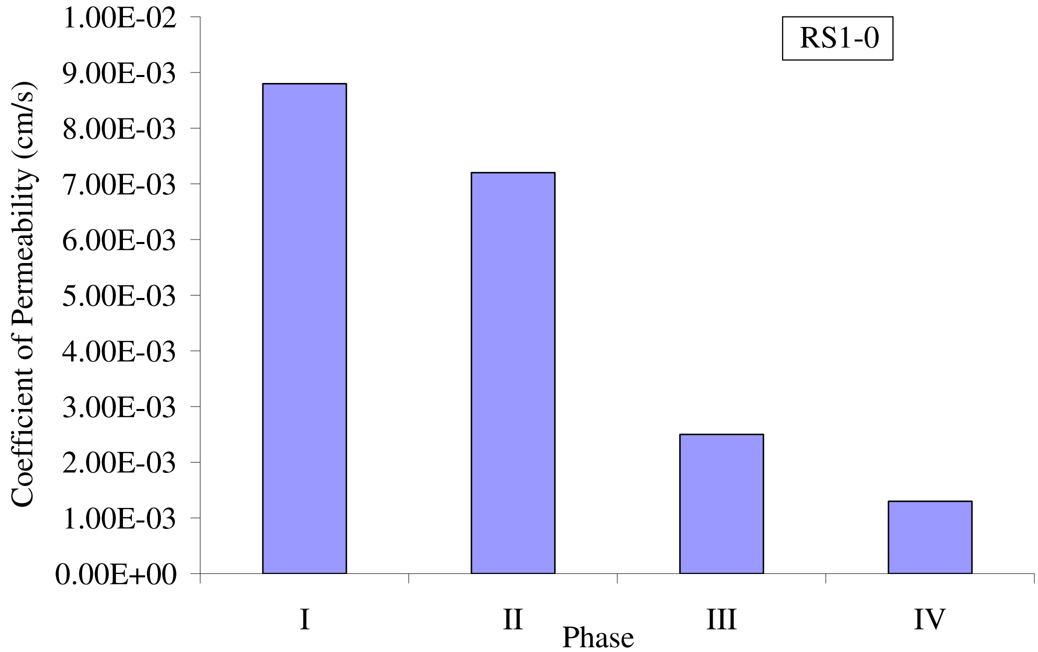


Figure 4.10 Permeability with degradation of the samples from reactor set 1

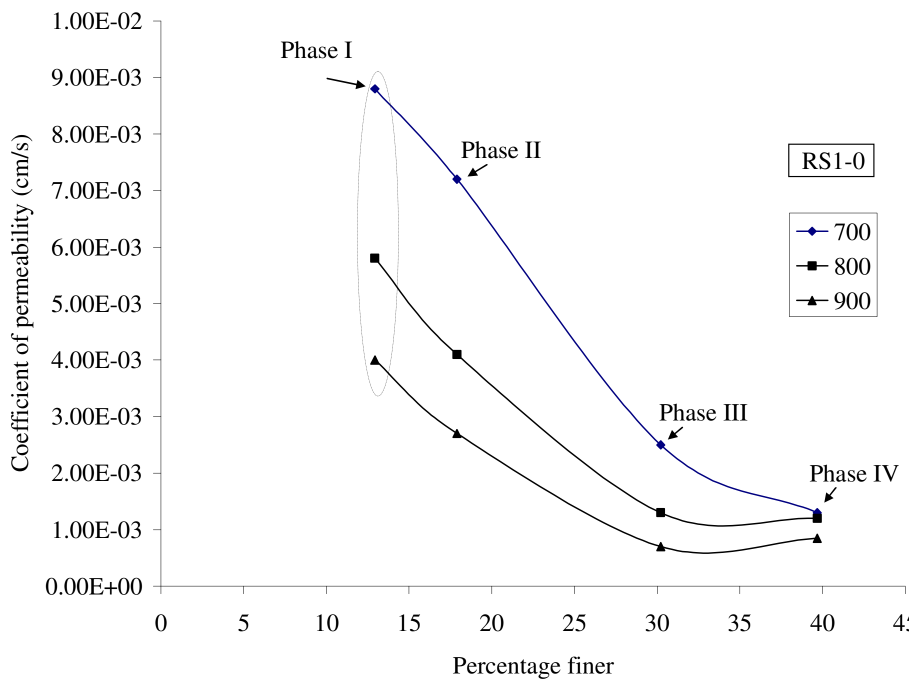


Figure 4.11 Permeability with the percentage of particles passing US Sieve No. 200

4.4.4.2 Permeability with voids ratio.

Moisture transport in MSW might be through the inter particle and intra particle voids depending on their size and continuity. The void ratio of the specimen is determined using the equation

$$e = \frac{G_s \rho_w}{\rho_d} - 1$$

where G_s = Specific gravity of the solid components; ρ_w = density of water and ρ_d = dry density of specimen $= \frac{\rho}{1+w}$; where, ρ = density of sample and, w = moisture content (dry)

Average value of specific gravity (G_s) obtained is considered for the calculation. The Variation in permeability of the MSW at Phase I, II, III and IV of degradation with the calculated void ratio is presented in Figures 4.12, 4.13, 4.14 and 4.15 respectively. With the increase in the density of sample the voids ratio decreases, thus, decreasing the permeability

Figure 4.16 presents the observed trend of permeability plotted on a logarithmic scale against voids ratio. From Figure 4.16 it can be understood that permeability decreases with decrease in voids ratio of MSW. The possible reason might be the decrease in size of the flow channels with the decrease in voids ratio, resulting in an overall reduction of permeability.

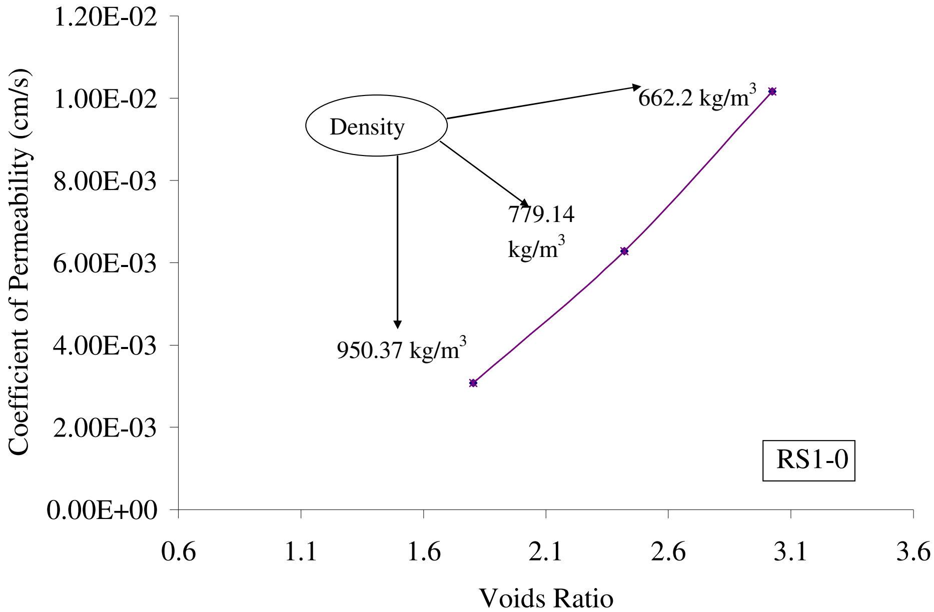


Figure 4.12 Permeability with voids ratio of MSW at phase I

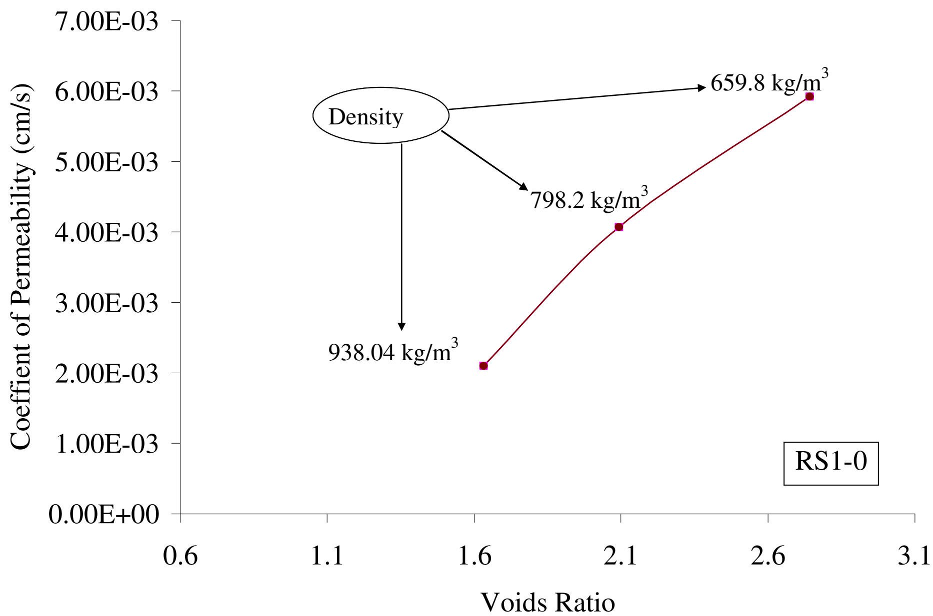


Figure 4.13 Permeability with voids ratio of MSW at phase II

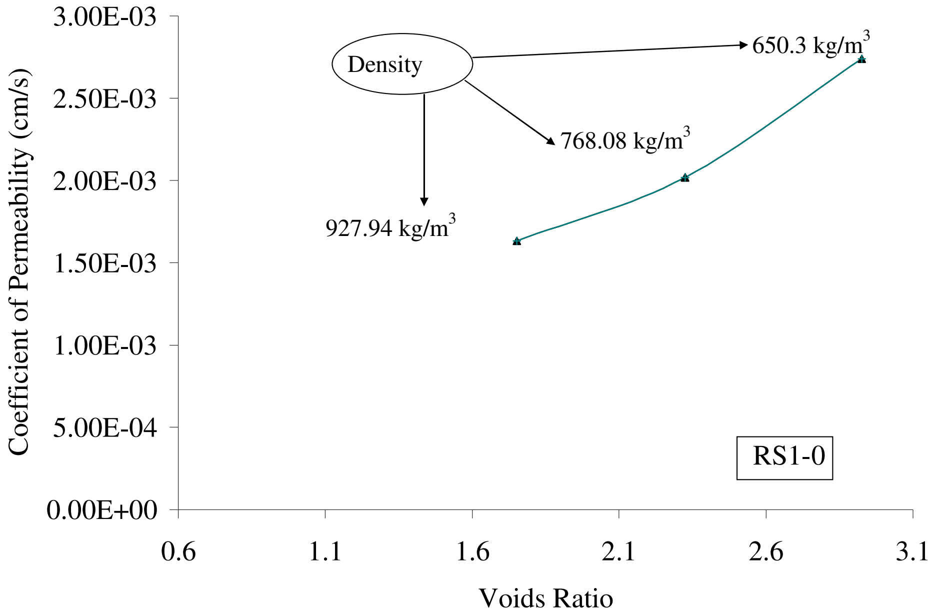
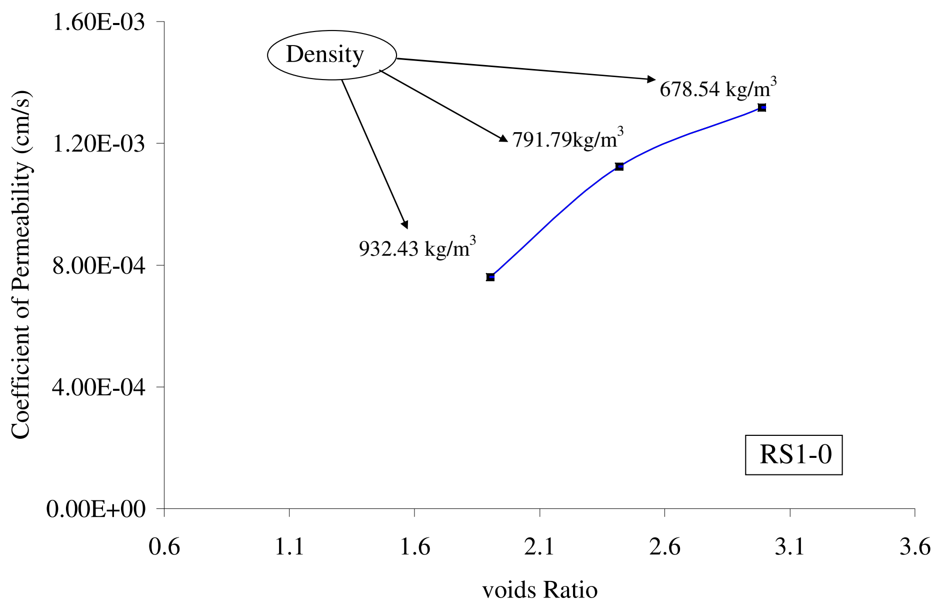


Figure 4.14 Permeability with voids ratio of MSW at phase III



4) Phase IV

Figure 4.15 Permeability with voids ratio of MSW at phase IV

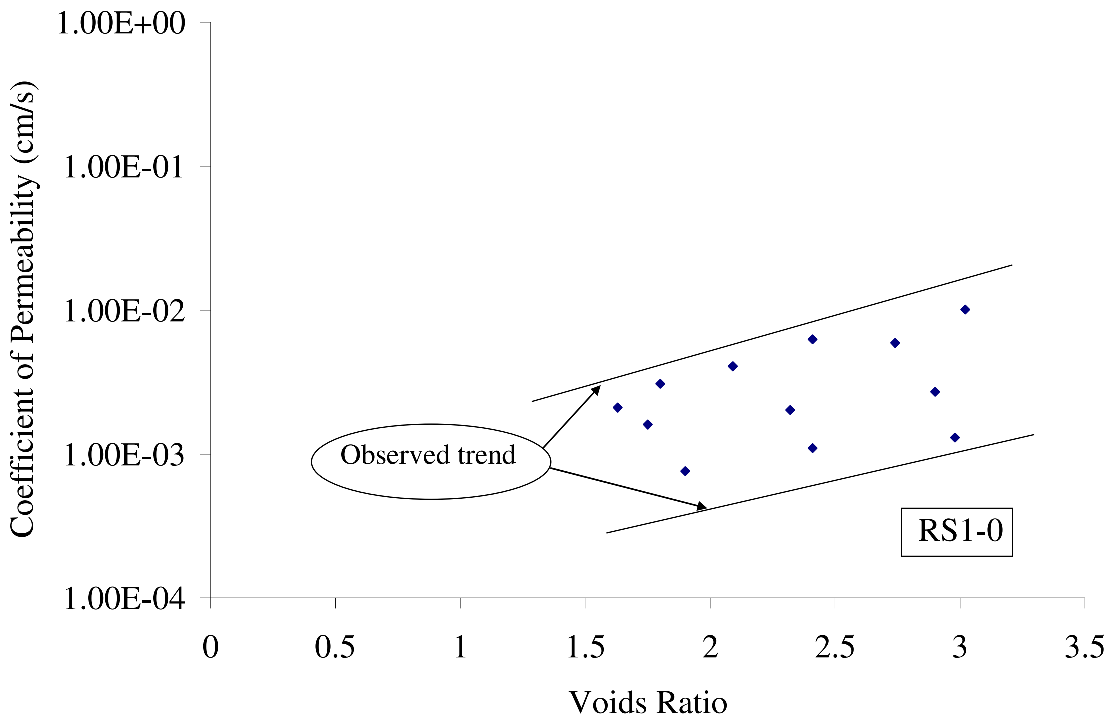


Figure 4.16 Observed trend of permeability with void ratio

4.4.4.4 Permeability with Density

The permeability of MSW decreased with the increase in density. Results of change in permeability with increase in density are presented in Figure 4.17. With the change in the density, the particle size and orientation changes, also, there will be a significant change in pore size and geometry. In order to study the variation in permeability of MSW at each phase of degradation at a given density, test results were interpolated at 700 kg/m^3, 800 kg/m^3 and 900 kg/m^3. Table 4.6 gives the percentage decrease in coefficient of permeability with increase in density from 700 kg/m^3 to 800 kg/m^3 and 700 kg/m^3 to 900 kg/m^3 at each phase of degradation. The Percentage decrease in coefficient of permeability with increase in density from 700 to 900 kg/m^3 for phase I material is 55.5 % which is greater than the percentage decrease of coefficient of permeability for the sample at phase IV. The reason for this behavior might be the composition and size of the individual constituent of the sample. Paper and plastic being more compressible, at lower density, the pore size will be significantly wider when compared to the size and continuity of the pore spaces at a higher density, resulting a decrease in amount of fluid flow through the pores at higher density. In contrast the paper in the phase IV is in the form of a paste, which with compaction might not have a significant reduction in void space. Figure 4.18 gives the observed trend in interpolated values of coefficient of permeability at a given density. It can be concluded from Figure 4.18 that the coefficient of permeability decreases with the increase in density at all stages of degradation.

Table 4.6 Percentage decrease in coefficient of permeability with increase in density from 700 kg/m^3 to 800 kg/m^3 and 700 kg/m^3 to 900 kg/m^3 at each phase of degradation.

	Percentage Decrease in Permeability	
Phase of Degradation	700 kg/m^3 to 800 kg/m^3	700 kg/m^3 to 900 kg/m^3
Phase I	34.09	54.54
Phase II	43.05	62.5
Phase III	48	72
Phase IV	7.69	34.61

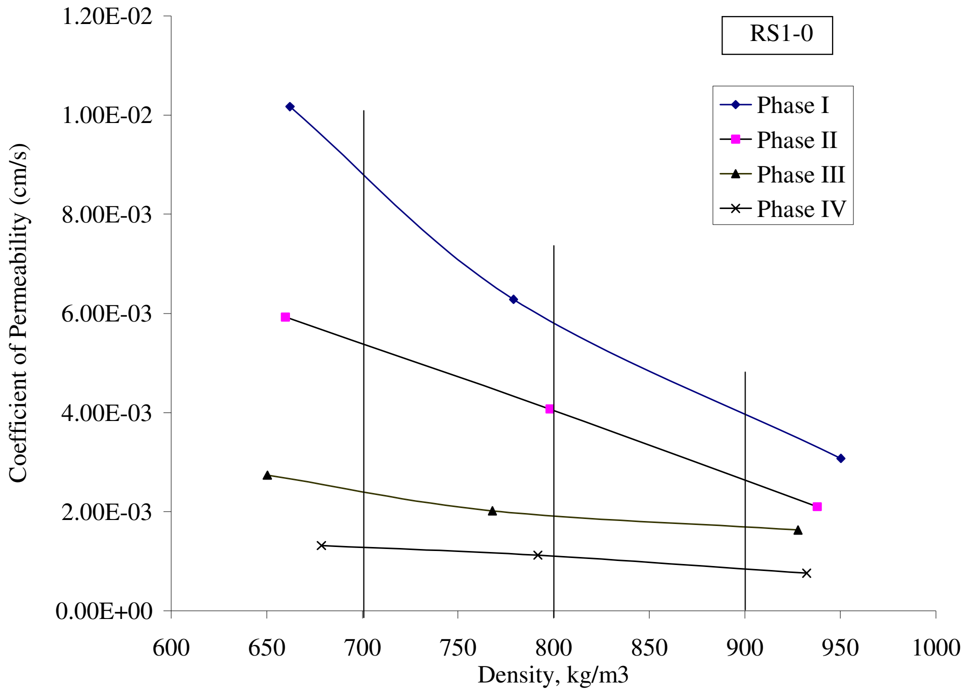


Figure 4.17 Permeability with density

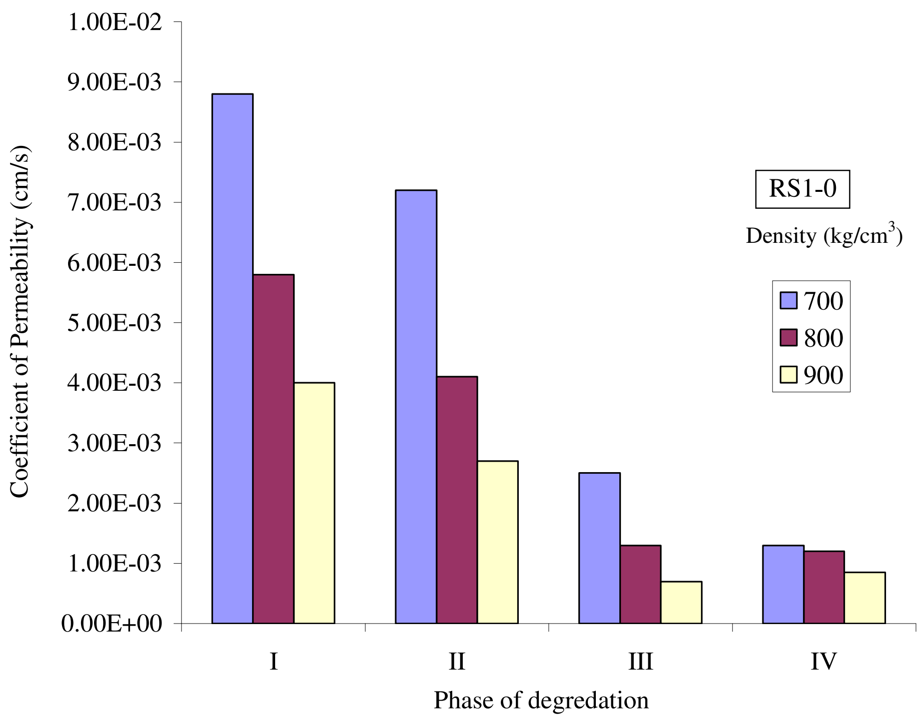


Figure 4.18 Interpolated values of permeability at a given density

The permeability results when plotted against their corresponding densities gave an agreeable relation with the test results of vertical permeability against dry unit weights by Powrie and Beaven (2005). Figure 4.19 gives the comparison of trend of the results obtained in the current research with the values vertical permeability obtained by Powrie and Beaven (2005).

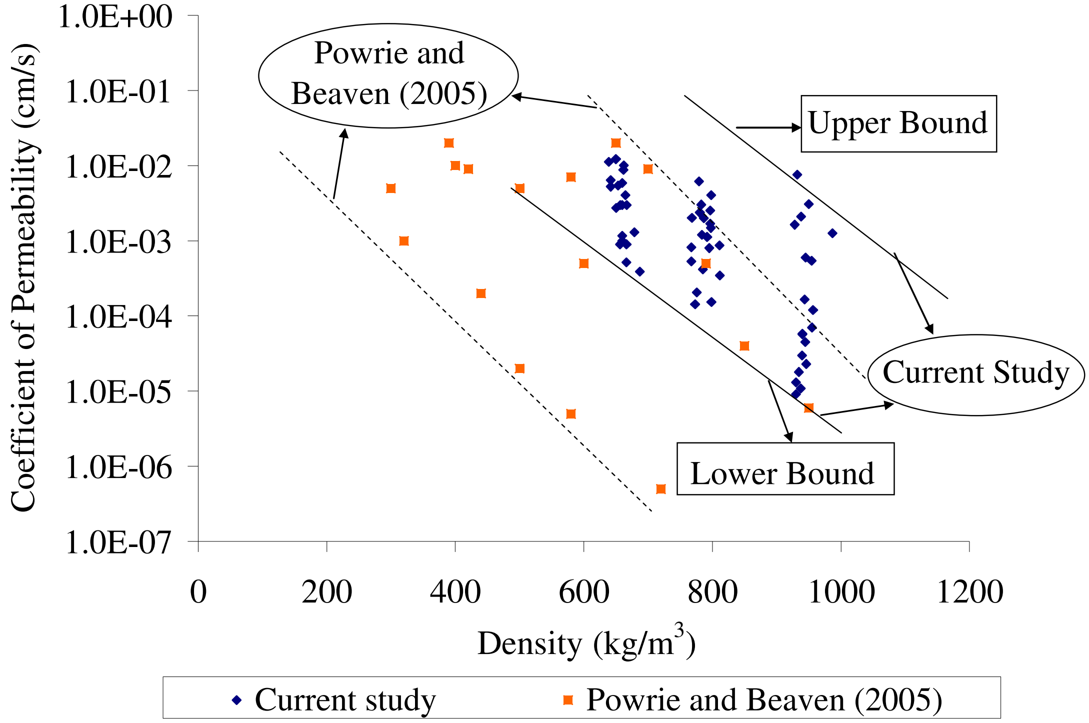


Figure 4.19 Comparison of values obtained in the current study and values of vertical permeability with dry density obtained by Powrie and Beaven (2005)

4.4.4.5 Effects of Cover Soil

There is an overall decrease in permeability with increase in percentage soil. The trend is the same at each phase of degradation. The variation in coefficient of permeability for the samples at each phase of degradation with varying percentages of soil are presented in Figure 4.20 to Figure 4.27.

The average percentage decrease in permeability for samples at each phase of degradation for different percentages of soil and density are given in Table 4.7 to Table 4.10. The Percentage decrease in permeability is cumulative when there is combined effect of both increase in density and increase in percentage of soil.

The variability in the permeability of MSW can be attributed to the change in orientation and size of flow path which is the function of size, shape and properties the individual constituent. Also, the percentage of fines increase with the increase in percentage of the soil contributes to a further decrease in coefficient of permeability. The decrease in the order of permeability with addition of soil and increase in density is in the order of 10^{-2} cm/s as the waste degradation proceeds from phase I to phase IV.

Table 4.7 Percentage decrease in coefficient of permeability for phase I sample with Percentage of soil and density.

Percentage of soil / Density Kg/m^3	Decrease in Permeability (%)	
	20% soil	30% soil
700	10.22	56.25
800	55.17	70.68
900	72.5	87.5

Table 4.8 Percentage decrease in coefficient of permeability for phase II sample with Percentage of soil and density.

Percentage of soil / Density Kg/m^3	Decrease in Permeability (%)	
	20% soil	30% soil
700	16.67	64.58
800	58.53	75.85
900	75.92	88.88

Table 4.9 Percentage decrease in coefficient of permeability for phase III sample with Percentage of soil and density.

Percentage of soil / Density Kg/m^3	Decrease in Permeability (%)	
	20% soil	30% soil
700	4	40
800	11.5	69.23
900	42.85	80

Table 4.10 Percentage decrease in coefficient of permeability for phase IV sample with Percentage of soil and density.

Percentage of soil / Density Kg/m^3	Decrease in Permeability (%)	
	20% soil	30% soil
700	40.76	61.69
800	66.66	85.83
900	81.76	94.11

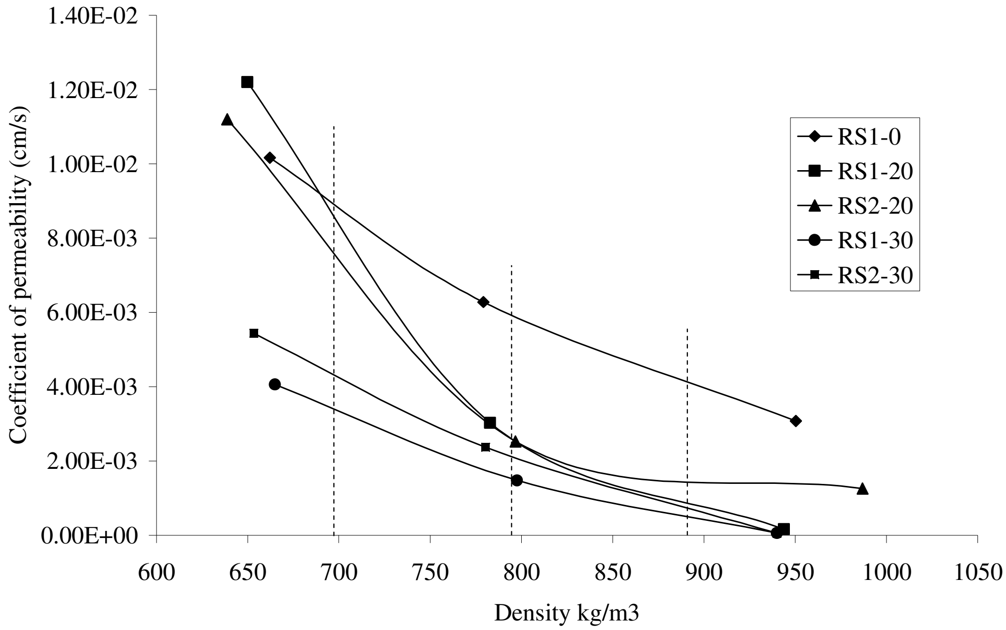


Figure 4.20 Changes in permeability with percentage soil for Phase I

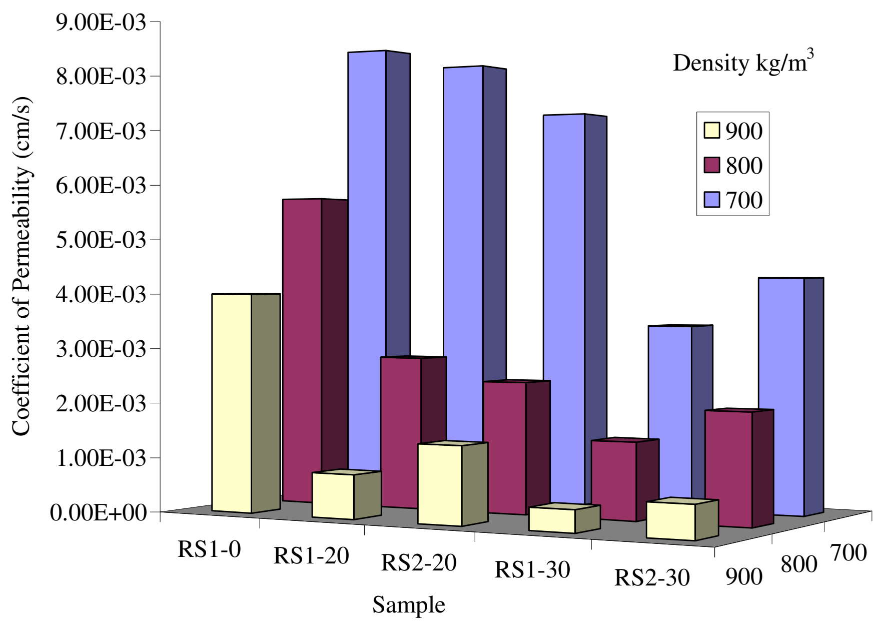


Figure 4.21 Change in permeability with percentage soil for Phase I at a given density

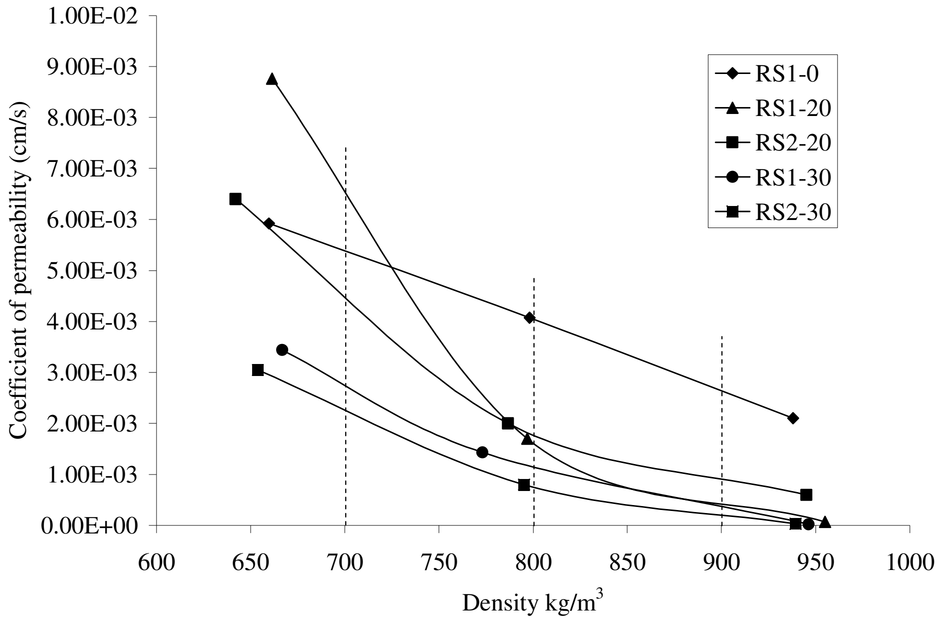


Figure 4.22 Changes in permeability with percentage soil for Phase II

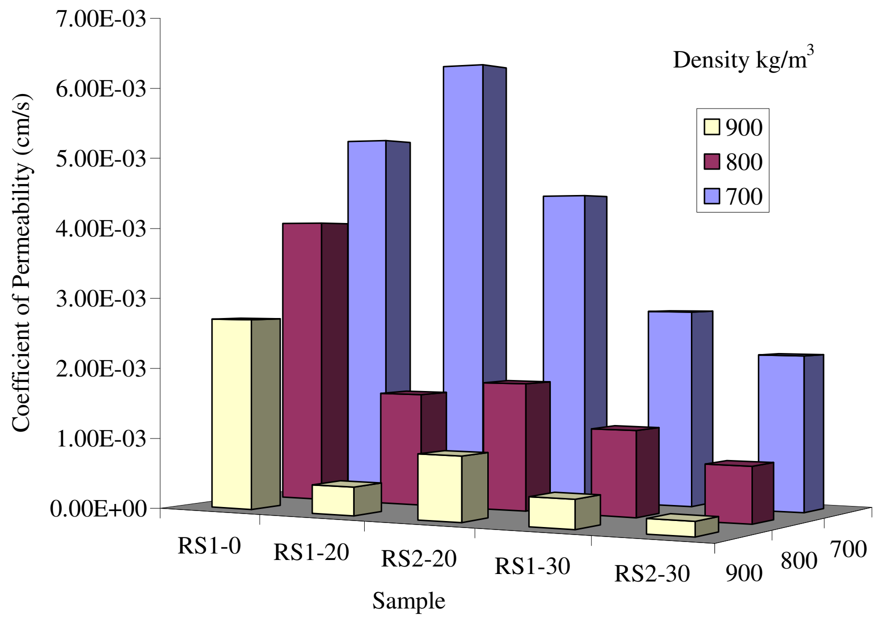


Figure 4.23 Change in permeability with percentage soil for Phase II at a given density

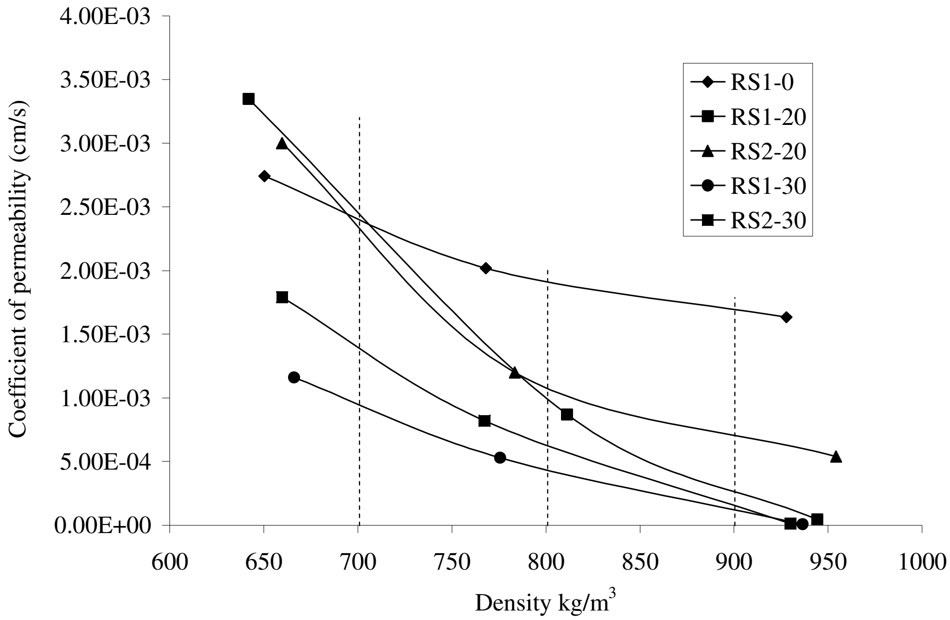


Figure 4.24 Changes in permeability with percentage soil for Phase III

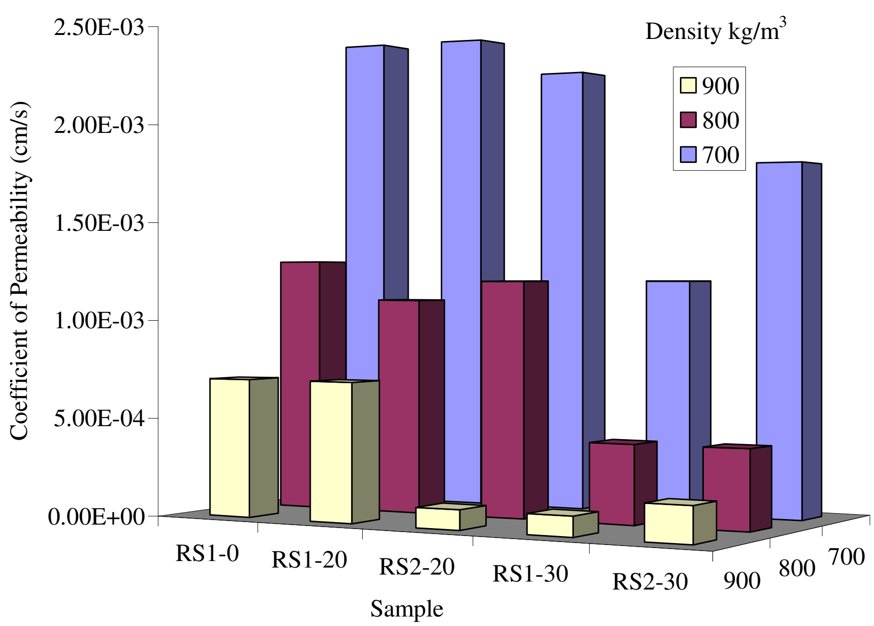


Figure 4.25 Change in permeability with percentage soil for Phase III at a given density

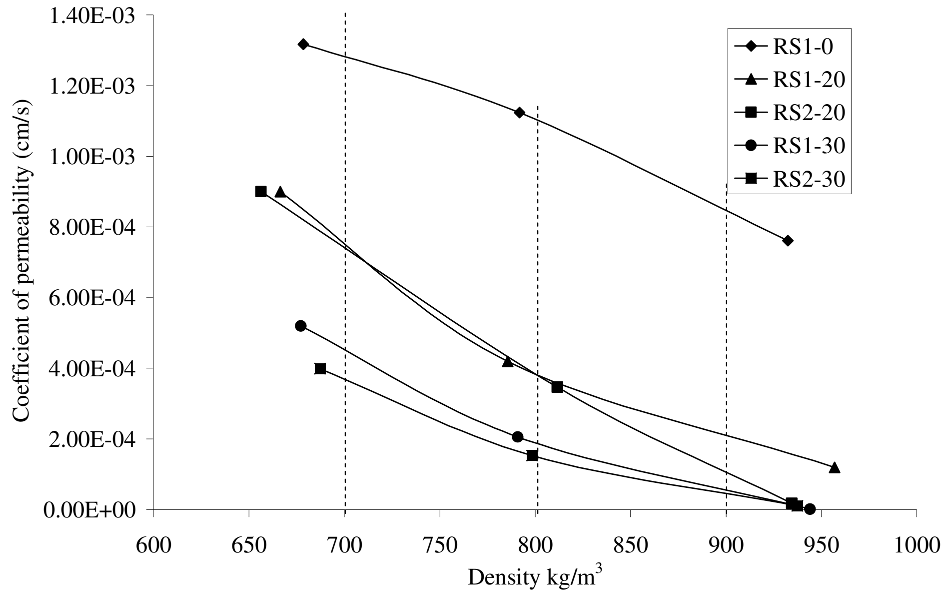


Figure 4.26 Changes in permeability with percentage soil for Phase IV

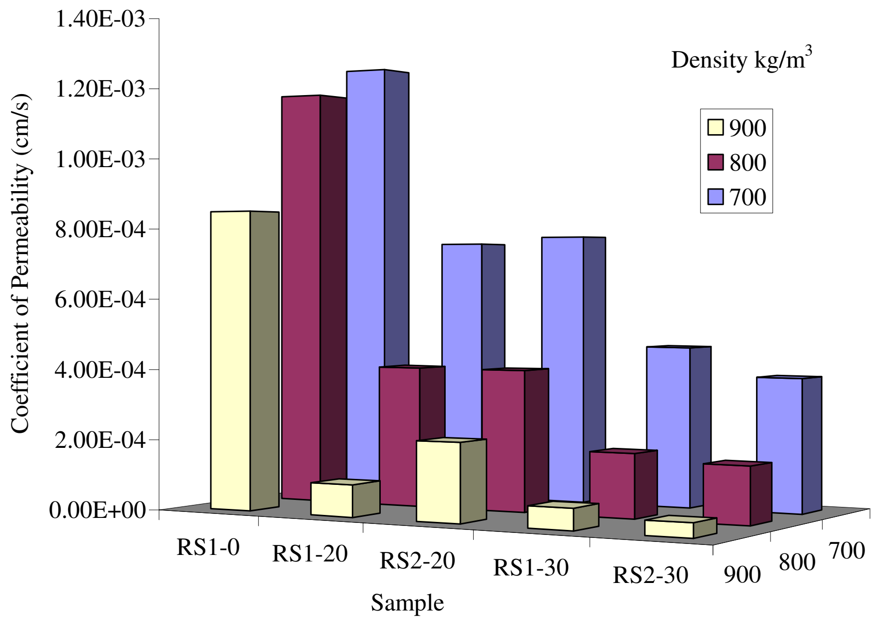


Figure 4.27 Change in permeability with percentage soil for Phase IV at a given density

CHAPTER 5

SUMMARY AND CONCLUSIONS

Permeability in municipal solid waste is mainly dependent on the pore size and geometry, which in turn varies with the size and shape of the individual particle and packing density. MSW samples representing various stages of decomposition are generated in a laboratory scale reactors operated under conditions designed to simulate decomposition in bioreactor landfills. The reactors were destructively sampled at the end of each phase of degradation based on the reactors methane production rate curve. In the current study an experimental program was designed to determine the variation of coefficient of permeability with degradation, and also to study the influence of various other parameters influencing the permeability of MSW.

The following parameters are considered for the current study.

a. Phase of Degradation

b. Packaging density

c. Percentage of soil

Tests were carried out at three different densities for the samples at different stages of degradation. Tests were also conducted with two percentages of soil so as to determine the influence of the cover soil.

The experimental results are summarized as follows:

1 Particle size analysis indicated a decrease in particle size with degradation. This phenomenon can be attributed to the disintegration of the degradable waste like paper food and textile with time.

2 The permeability of MSW at the first phase of degradation is 0.0088 cm/s at 700 kg/cm^3. As the sample degrades at the same density permeability reduced to 0.0013 cm/s. The reason for the decrease might be due to the increase in percentage of finer fraction passing US sieve no. 200 occupying the pore spaces thus decreasing the size of the flow path.

3 Density of the sample is observed to have significant affect on the permeability of MSW. Permeability decreased with the increase in density. The possible reason for the decrease might be due to the reduction in pore size and change in geometry and continuity of pores resulting in decrease in area of flow.

4 There is a decrease in voids ratio with increase in density, thus, resulting in decrease in permeability.

5 There is an overall decrease in permeability with increase in percentage soil. The trend is the same for the samples at each phase of degradation. The reason might be the increase in finer fraction filling in the void spaces.

6 The Percentage decrease in permeability is much higher when there is combined affect of both increase in density and increase in percentage of cover soil.

From the current work, the following recommendations can be given for future research.

1) Inclusion of control materials along with the MSW samples in the reactor might be useful to identify the extent of degradation.
2) Head loss along the sample during the permeability testing might be helpful to determine the influence of heterogeneity and stratification.
3) Further study on Influence of cover soils with different generally used cover soils.
4) Further study on permeability tests using leachate instead of water.

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