CHARACTERISTICS OF FRESH MUNICIPAL SOLID WASTE

by

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ABSTRACT

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The characteristics of fresh municipal solid waste (MSW) are critical in planning, designing, operating or upgrading solid waste management systems. Physical composition, moisture content, compacted unit weight, permeability are the most important MSW characteristics to be considered in planning a system. When the landfill is operated as enhanced leachate recirculation (ELR) landfill, the physical and hydraulic characteristics are of particular interest in determining the amount of moisture to be recirculated and to design the leachate recirculation and gas collection systems.

The current study presents the physical and hydraulic characteristics of MSW collected from the working face of Denton Landfill. The results are based on 20 (twenty) 30-lb bags of MSW samples collected over two seasons: May 2009 and August 2009. It was evaluated that ten samples are adequate to provide reliable results within 90% confidence interval about mean for each sample sets.

For the MSW sample of May, 2009, the moisture content of the fresh MSW was determined to vary between 34.0% and 48.02% on wet weight basis. The unit weight varied from 27.6 lb/ft^3 to 38.55 lb/ft^3 with an average of 33.88 lb/ft^3 at initial moisture content. The hydraulic conductivity was found to be in the range of 10^{-3} cm/sec (10^{-5} to 10^{-4} ft/sec) at a density of 5.32 kN/m^3 (33.88 lb/ft^3).

For the MSW sample of August, 2009, the moisture content of the fresh MSW was determined to vary between 30.3% and 42.5% on wet weight basis. The unit weight varied from 26.4 lb/ft^3 to 50.55 lb/ft^3 with an average of 33.88 lb/ft^3 at initial moisture content. The hydraulic conductivity was again found to be in the range of 10^{-3} cm/sec (10^{-5} to 10^{-4} ft/sec) at a density of 5.32 kN/m^3 (33.88 lb/ft^3).

The overall average physical composition of the MSW of Denton Landfill is: Paper (41.27%), Plastic (17.65%), Food Waste (3.03%), Textile & Leather (4.07), Wood & yard waste (8.72%), Metals (5.36%), Glass (1.18%), Styrofoam & sponge (1.24%), Construction debris (4.78%), and Others (18.95%). Of the total weight, 57% is degradable and 43% is non-degradable. The unit weight of the solid waste was 35.85 pcf (5.63 kN/m^3) and the moisture content on wet basis is 37.45% on average. The permeability was 3.48×10^{-3} cm/sec at about 33.88 pcf density.

The composition indicated that the waste is high in Paper and Plastics content but very low in food content. The unit weight and permeability results found from present study closely comply with values published in literature but the moisture content is slightly higher.

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CHAPTER 1

INTRODUCTION

1.1 Background

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. In 2007, 250 million tons of municipal solid waste (MSW) was generated in the U.S., with approximately 54.2% of this waste buried in landfills (USEPA, 2008). While portions of this waste are recycled and composted, and converted to energy, landfills will remain a significant aspect of MSW management for the foreseeable future.

According to USEPA (2008) organic materials were the largest component of MSW. Before recycling, paper and paperboard accounted for 31%, with yard trimmings accounting for 13.2% and food scraps for 12.7%. Plastics made up 12%; metals comprised 8.4%; and rubber, leather, and textiles accounted for 7.9%. Wood was found to be 6.6% followed by glass at 4.9%. Other miscellaneous wastes comprised about 3.3% of the total waste.

Conventional MSW landfills are designed and operated in accordance with RCRA Subtitle D, which minimizes amount of moisture entering and retained in the landfill waste. The absence of nutrient i.e. moisture in the waste prolongs the decomposition and can take as much as 50 to 100 years for complete decomposition. This complicates the post closure monitoring period which is currently being set as 30 years, and future development on existing landfills. Also, due to rapid growth and urbanization of cities beyond city limits, many of these landfills are now within city limits. However, getting a suitable new location for landfilling of MSW within the city limit is becoming a predominant problem, as conventional MSW landfills may occupy an area ranging from several acres to hundreds of acres. Therefore, waste minimization or increasing the capacity of landfills within the same area is becoming a major consideration for the state agencies and federal regulatory bodies.

Accordingly, there have been substantial changes in the design and operation of landfills over the past twenty years. Though first suggested in the mid 1970s (Pohland, 1975), the concept of operating a landfill as a bioreactor or enhanced leachate recirculation (ELR) landfill has recently received increased attention (Pacey et al., 1999). An ELR landfill is operated to enhance refuse decomposition, gas production, and waste stabilization.

An ELR landfill operates to rapidly transform and degrade the organic matters within the MSW stream. A major aspect of ELR landfill operation is the addition of liquid and recirculation of collected leachate back through the refuse mass. The idea of liquid addition differs from the conventional landfill approach, where the objective was to minimize moisture intrusion into the landfill.

There are several benefits associated with the operation of landfills as bioreactors, including:

1. More rapid settlement which results in increased effective refuse density and air space as presented in Figure 1.1
2. In-situ leachate treatment and the reduction of leachate handling cost ,
3. Increased gas production which can improve the economics of energy recovery,
4. The rapid stabilization of a landfill to a more environmentally benign state, and
5. Acceleration of refuse decomposition which may shorten the regulated post closure monitoring period and reduce the overall cost of the landfill.

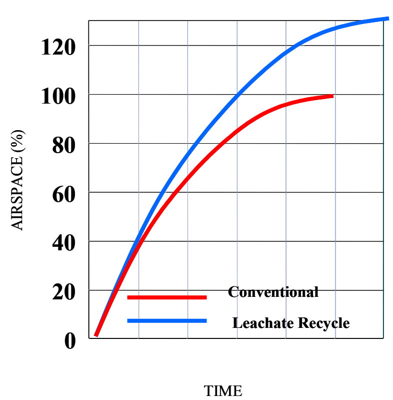

Figure 1.1 Increased Air Space in Bioreactor or ERL Landfill

As a result of these benefits, there has been a significant increase in the number of landfills that are being operated with leachate recycle. A review of literature in 1993 identified less than 20 leachate recirculating landfills located in US, Germany, UK, and Sweden. By 1998, over 200 landfills were practicing leachate recirculation with little engineering input to design and operation (Reinhart et. al., 2002).

1.2 Problem Statement

The design and operation of a landfill as ELR, however, raises some concerns for stability analysis. Kavazanjian (1999) reported that the advent of ELR landfills, in which liquids are re-circulated by injection into the waste mass, not only raises questions about changes in mechanical properties but also heightens concerns about the stability of saturated waste. The physical properties of MSW are expected to change with the increasing moisture content. These changes must be considered during the design phase to ensure slope and cover stability. However, it is important to characterize the fresh MSW coming to landfill to have an understanding of the changes with time and decomposition in an ELR landfill.

Municipal solid waste is a highly heterogeneous material which varies widely from place to place and time to time. The characteristics are influenced by many factors, such as, weather, geographic location, food habit, income level, economy, etc. The properties differ not only from country to country but also within different landfills of the same place. It also changes with time as the habits and, socioeconomic condition change. On top of that, the characteristics of the same waste changes with age and decomposition. Therefore it is very important to characterize the waste coming to each landfill individually.

The characteristics of Fresh municipal solid waste (MSW) are crucial in planning, designing, operating or upgrading solid waste management systems. At present there are mainly three types of waste management systems: incineration, composting and landfilling. Knowing the basic physical and hydraulic properties is the first step in selecting the appropriate option and also in designing the chosen facility. In case of operation of enhanced leachate recirculation (ELR) landfills, the physical and hydraulic characteristics are of particular interest in determining the amount of moisture to be recirculated, the expected rate and volume of gas generation to design the leachate recirculation and gas collection systems.

The major physical properties of municipal solid waste include physical composition, degradable percentage, natural moisture content, compacted unit weight, and the most important hydraulic property is hydraulic conductivity.

1.3 Objectives

The current study was undertaken as a part of the project “Performance Monitoring of Leachate Recirculation Systems in ELR Landfill” for the landfill of City of Denton, Texas. The objectives of the original project are to obtain the physical properties, the moisture data for both fresh waste and existing waste, the gas composition data, etc required to evaluate the performance of leachate recirculation systems in enhanced leachate recirculation (ELR) landfill. However, the baseline MSW characteristics are important to evaluate the effect of leachate recirculation on the changes in physical and engineering characteristics of MSW.

The current study was about obtaining the physical and hydraulic characteristics of the solid waste in question. The specific objectives of the present study can be listed as follows:

1. Collection of MSW Sample from the working face of Denton Municipal Landfill, Texas
2. Determination of Number of Sample to be collected for the computed results to be representative.
3. Determination of Physical Composition for the fresh MSW.
4. Determination of Degradable and Non-Degradable percentage for the Fresh MSW.
5. Determination of Moisture Content for the same.
6. Determination of Permeability of the waste.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

According to Pichtel (2005) solid Waste is defined as "garbage, refuse, sludges, and other discarded solid materials resulting from industrial and commercial operations and from community activities. It does not include solids or dissolved material in domestic sewage or other significant pollutants in water resources, such as silt, dissolved or suspended solids in industrial wastewater effluents, dissolves materials in irrigation return flows or other common water pollutants".

Municipal Solid waste (MSW), also known as domestic waste, or household waste, is the waste generated within a community, not only from households but also from commercial, institutional, industrial, and municipal sources. MSW is highly heterogeneous. It includes durable goods like electronic appliances, non-durable goods like newspapers, containers & packaging, food wastes, yard wastes and miscellaneous inorganic wastes (Pichtel, 2005).

According to Texas Natural Resource Conservation Commission (TNRCC) relatively few detailed waste characterization studies have been conducted across the United States. Based on TNRCC (1995) 63% of MSW typically generated in Texas is residential, and 37% is commercial/ institutional, which very closely parallels the national figures in the EPA study. In Texas, 73.3% is typical MSW, 16.7% is C&D waste, 7% is industrial waste, and 3.0% is Sludge/ septage. The components other than the typical MSW may enter the MSW stream if not classified as hazardous waste.

2.2 Physical Composition

Physical composition of MSW indicates the amount of different types of materials present in the total waste stream. There are several ways of determining the composition of municipal solid waste (Vesilind et al., 2002). For example, (1) On national level, data from published industry production statistics can be used for estimating waste composition. This method is known as input method. (2) Again it can be estimated by manual sorting of representative samples. (3) The composition can be determined by photogrammetry which involves photographing a representative portion of refuse and analyzing the photograph (Vesilind et al., 2002).

Waste composition studies are essential tools for solid waste management, though often the lack of consistent procedure and underfunding cause data to be inaccurate and imprecise. Also an insufficient number of samples are obtained, sampling events are not representative of seasonal and economic changes, contamination is not accounted for, and the study is not repeated in response to changes in the community (Vesilind et al., 2002).

According to Sharma & McBean (2007) the percentages of waste within individual categories are important information for planning solid waste management programs. These include evaluation of recycling programs, quantification of degree of success of exclusion of banned items from waste stream, quality of waste to be used as feedstock to an incinerator, quantification of organics to evaluate biogas possibilities, etc.

Sharma & McBean (2007) developed a statistics based approach for evaluation of the minimum number of samples to be sorted to get a representative composition. They studied the change in 90% confidence interval with the increase in number of samples and reported that after the decrease in confidence interval is not significant after 5 sampling. The authors indicated that increasing the number of sample beyond that point will not improve the results significantly. According to their findings, the minimum number of sample to be sorted is site specific and evolves during the sampling. As the order of sampling (which is random) also can influence the number, a minimum of ten numbers of samples need to be considered to get past the initial instability. The confidence interval about mean with number of sorts is presented in Figure 2.1.

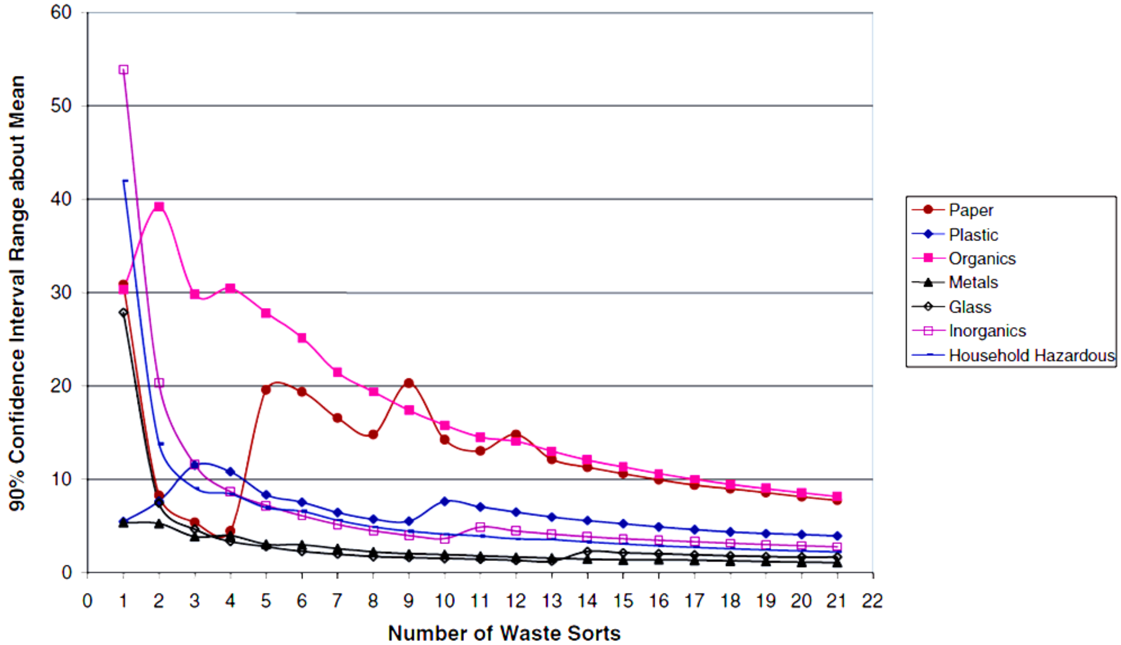

Figure 2.1 90% Confidence Interval about Mean vs. Number of Waste Sorts (Sharma & McBean 2007)

Numerous published documents reporting the physical composition of MSW of different places all over the world are available in the literature. Some of them are summarized below.

Gabr and Valero (1995) evaluated the engineering properties of 15 to 30 years old municipal solid waste. According to the authors, for aged waste, based on age, the percentage of food, garden and paper waste becomes almost 0, while the composition becomes mostly textile, ash, rock and soil. The Composition presented by them is: Food Waste (0%), Garden Refuse (0%), Paper Products (2%), Plastic & Rubber (13%), Textiles (13%), Wood (9%), Metal Products (10%), Glass, Ceramics (10%), Ash, Rock, and Soil (33%).

Yousuf & Rahman (2007) worked on fresh municipal solid waste of Dhaka city and provided with a detailed composition of MSW from different sectors and different income groups as presented in Table 2.1

Xiang-rong et al. (2003) has reported the main ingredients of the MSW in Tianziling Landfill as plastic (0-20%), inorganic (50-100%), organic & impurities (0-20%) and minerals.

Table 2.1 Physical Composition of waste of Dhaka City (Yousuf & Rahman, 2007)

Season	Source Category	Income level/ source	Composition (%)					
			paper	Food waste	Wood & grass	plastics	Sand & dust	Others
Dry season	Domestic waste by income group	Upper	12	49	21	2	1	15
		Middle	6	80	0	1	1	13
		Lower	4	71	1	2	17	5
		Average	7	66	7	2	6	11
	Business waste	Restaurants	2	97	0	0	0	1
		Shop/hotel	4	89	1	1	0	5
		Market	5	53	23	3	6	9
		Public facilities	35	19	25	0	14	7
		Average	12	65	12	1	5	7
	Street waste		2	4	10	0	73	11
Wet season	Domestic waste by income group	Upper	13	64	8	6	0	9
		Middle	10	72	4	8	0	7
		Lower	8	69	10	4	4	5
		Average	10	68	7	6	1	7
	Business waste	Restaurants	3	96	0	1	0	0
		Shop/hotel	8	89	0	2	0	2
		Market	3	67	16	1	4	8
		Public facilities	31	19	14	11	20	4
		Average	11	68	8	4	6	4
	Street waste		1	11	16	1	60	10

Reddy et al. (2009) determined the geotechnical properties of fresh MSW collected from the working face of Orchard Hills Landfill. They presented the composition based on both components and degradability, which can be found in Table 2.2.

Landva & Clark (1990) studied the MSW of landfills across Canada. According to them, augur drilling by solid stem 130 mm augur (140 mm bit) is the most suitable method for sampling both old and new waste fill. They also gave a very thorough classification system for municipal solid waste in their published work. Landva & Clark (1990) suggest that the range of percentage weight of different components of MSW are: Food Waste (5-42), Garden Refuse (4-20), Paper products (20-55), Plastic, rubber (2-15), textiles (0-4), Wood (0.4-15), Metal products (6-15), Glass & Ceramics (2-15), and Ash, rock & dirt (0-15).

Table 2.2 Typical Composition of Fresh MSW at Orchard Hills Landfill (Reddy et al., 2009)

Category	Waste type	Waste composition (% by wet mass)	
Easily biodegradable	Cooking waste	6.6	6.9
	Garden waste	0.3	
Medium Biodegradable	Paper	8.2	24.6
	Cardboard	13.3	
	Food carton	0.0	
	Sanitary waste	3.1	
Hardly biodegradable	Textiles	5.8	19.2
	Nappies	1.7	
	Wood	11.7	
Inert waste	Metal	4.4	29.2
	Plastic bottles	5.7	
	Other plastics	5.3	
	Special waste	0.0	
	Medical waste	0.1	
	Other waste	3.5	
	Inert waste	5.8	
	Glass	4.4	
Residual fines	Fines (<20 mm)	20.1	20.1

Gomes et al. (2005) presents a study on different aged wastes from the same landfill. In case of pre-selected and treated waste collected from a closed landfill, the physical composition of this waste is given as: plastic (37.4%), textile (33.3%), soil (11.2%), metal (10.2%), wood (2.8%), rubber (1.3%), paper (0.9%), other organics (0.1%), and larger part of non-classifiable.

Hogland et al. (2004) determined physical and chemical properties of MSW to evaluate the stage of degradation of buried waste. The physical composition has been determined at different depths of the waste for two landfills and can be found in Table 2.3.

Hristovski et al. (2007) conducted a short one week study in summer on the residential waste of Veles, Macedonia. The study area is representative of upper end of low income to lower end of middle income community. In this study, the commercial or agricultural wastes were not considered. The average composition of the solid waste was found to be as follows: organic

(23.99%), paper (24.47%), glass (7.19%), soft plastic (4.49%), hard plastic (2.51%), cans (1.32%), other scrap metals (4.78%), garden waste (8.7%), other (23.36%).

Table 2.3 Weight Composition (%) of Unsorted Waste Excavated from Different Depths (Hogland et al., 2004)

	Måsalycke landfill				Gladsax landfill	
	0.5–2 m	2–4 m	4–6 m	6–8 m	5–6 m	6–7 m
Paper	7.31	21.06	4.97	5.57	1.73	2.80
Plastic	8.12	3.86	5.27	2.50	0.27	3.98
Diapers	0.07	2.05	0.00	0.00	0.00	0.00
Textiles	1.3	4.1	0.40	3.40	0.27	1.11
Rubber	0.07	1.78	0.07	0.28	0.00	0.00
Leather	0.00	0.00	0.10	0.00	0.00	0.00
Glass, ceramics	0.32	0.32	0.22	0.25	0.33	1.53
Metals	2.09	1.11	2.18	1.52	1.56	1.25
Food waste	0.32	0.78	0.55	0.25	0.00	0.00
Electronics	0.00	0.00	0.00	0.01	0.00	0.45
Garden waste	0.22	0.46	1.96	1.82	0.00	0.47
Wood	11.59	10.97	11.94	5.25	2.29	1.15
Stones	27.41	3.53	10.55	13.31	15.49	22.71
Hazardous waste	0.45	0.00	0.03	0.34	0.00	0.00
Soil-type	40.74	49.99	61.73	65.51	78.06	64.54
Sample weight (kg)	5201.6	74.2	133.6	173.4	81.1	84.9

Gómez et al. (2009) provides with a very through methodology for determining the composition of municipal solid waste. The variation in composition based on different parameters like season, socio-economic conditions, etc. are also reported in the paper. For this study, a total of 1687 samples were collected directly from households for seven consecutive days. It was determined that people with lower income generate less amount of waste. Also, the authors reported that waste generation is least in the colder seasons. The weighted average of the composition of MSW of Chihuahua, Mexico is reported as follows: Organic (45%), Paper (17%), Plastic (13%), Glass (5%), Metal (3%), and Others (16%).

Saeed et al. (2009) presented the results on a study on municipal waste generation and recyclable materials potential in Kuala Lumpur, Malaysia. According to the authors, the contributions of different sectors in total waste generation in the city are as follows: residential

(48%), street cleaning (11%), commercial (24%), institutional (6%), construction and industrial (4%), and landscape (7%). The municipal solid waste composition of Kuala Lumpur as of year 2000 is reported here as: Organic (68.67%), paper (6.43%), plastic (11.45%), glass (1.41%), metal (2.71%), textile (1.5%), wood (0.7%), and others (7.13%). The waste compositions of different years since 1975 till 2000 are also reported here, though no trend in the compositional variation is evident from Saeed et al. (2009).

Minghua et al. (2009) presented the characteristics of MSW in Pudong city of China. The study area is representative of year round pleasant climate with an average annual temperature of 16.2^{o}C and an annual rainfall of 1183 mm. The area is characterized by both urban and suburban areas. The physical composition of the solid waste of the city is as follows: Food waste (48%), plastic (33%), fruit (7%), paper (4%), textile (3%), glass (3%), and wood (2%).

Sharholy et al. (2007) conducted a study to determine the quantitative and qualitative characteristics of MSW of Allahabad city of India. Of the total MSW stream, 40% comes from households, 27.2% from restaurants and the rest from other sources. The results were obtained based on 20 randomly collected samples. The study determined that MSW contains 45.3% organic matter and 40% miscellaneous materials like brick, fine dust, rubber, wood, leather, waste water, etc. and very low percentage of glass, paper, plastic, metals etc. The composition has been presented as follows: Paper (3.6%), cardboard (1.09%), metals & tin cans (2.54%), glass (0.73%), food waste (45.3%), textile rags (2.22%), plastic bags (2.86%), miscellaneous (41.66%).

Burnley (2007) studied the MSW of United Kingdom, and stated that composition of household municipal solid waste is a function of size & age profile of household, waste container provided by the local authority, and socio-economic classification of the household. The trend of composition has changed from 1930 to 1980: Plastic appeared in mid 1960's and kept on increasing till then, fines and ash content has reduced, and paper content has increased. More affluent households tend to produce more waste. Waste amount decreases in winter, but no other seasonal trend is there. Garden waste is found to be 54% to 134% more in summer time. The detail composition determined by the authors is presented in Table 2.4. The authors also provided the composition of commercial waste separately, which is presented in Table 2.5.

Table 2.4 Composition of municipal solid waste in Wales (Burnley, 2007)

Waste category	Percentage
Newspapers and magazines	9.0
Recyclable paper	2.1
Cardboard boxes/containers	5.1
Other paper and card	4.8
Refuse sacks and carrier bags	1.3
Packaging film	1.3
Other plastic film	0.2
Dense plastic bottles	1.7
Other packaging	1.5
Other dense plastic	1.3
Textiles	1.8
Shoes	0.4
Disposable nappies	2.3
Wood	2.8
Carpet and underlay	1.5
Furniture	1.5
Other miscellaneous combustibles	3.6
Packaging glass	5.3
Non-packaging glass	0.5
Garden waste	12.7
Kitchen waste	15.7
Other organic wastes	2.1
Ferrous metal food/beverage cans	1.7
Other ferrous metal	3.1
Non-ferrous food and beverage cans	0.3
Other non-ferrous metal	0.5
White goods	0.8
Large electronic goods	0.2
TVs and monitors	0.3
Other WEEE	0.7
Lead/acid batteries	0.2
Oil	0.1
Identifiable clinical waste	0.2
Other potentially hazardous	0.3
Construction and demolition waste	5.2
Other non-combustible material	2.8
Fines	5.2

Table 2.5 Composition of Commercial Waste (Burnley, 2007)

Material	Weight percentage
Paper and card	41
Film plastics	4
Dense plastics	6
Textiles	1
Miscellaneous (combustible)	7
Miscellaneous (non-combustible)	2
Glass	4
Organic waste (food, garden waste)	27
Ferrous metal	4
Non-ferrous metal	1
Unclassified fine material (<10 mm)	1

According to Damghani et al. (2008) total solid waste stream of Tehran consists of 97% municipal solid waste and 3% other wastes like, hospital, industrial and construction& demolition wastes. Of the total municipal solid waste 62.5% comes from households. The solid waste characteristics of this area is representative of hot and dry climate with maximum, minimum and mean air temperatures being 38.7, -7.4 and 18^{o}C respectively. The major element of the waste here is stale bread. The detailed seasonal composition as reported by the authors is presented in Table 2.6.

Table 2.6 Composition of household solid waste in Tehran (%) in different seasons of 2005 (Damghani et al., 2008)

Season	Stale bread	Plastic	Paper and cardboard	Metal	Glass	PET	Others
Spring	42.4	9.8	20.1	8.8	1.5	1.1	16.3
Summer	44.1	10.7	20.2	8.8	1.6	0.7	13.9
Autumn	43.1	10.1	24.5	8.5	1.6	0.8	11.5
Winter	40.7	11.5	24.5	9.9	1.9	1.1	10.5
Average	42.6	10.5	22.3	9.0	1.6	0.9	13.0

Guermoud et al. (2009) studied the municipal solid waste of Mostaganem city of western Algeria, which is representative of an industrialized developing country. In this paper they reported the solid waste composition of Mostaganem at different years, which shows the trend of change in composition with time (Table 2.7). They also reported compositions of solid waste of some world cities for comparison which is presented in Table 2.8. The authors reported that organic matter content is higher in developing countries (about 60%) than in industrial countries (about 30%).

Table 2.7 Evolution of MSW Composition in Mostaganem City (Guermoud et al., 2009)

Categories	1983	2001	2004
Organic matter	78.0	77.5	64.6
Cardboard	12.6	13	15.9
Plastics	2.7	7.5	10.5
Metals	2.2	1.5	1.9
Glass	1.1	0.5	2.8
Textiles	3.4	–	2.3
Diverse	–	–	2.0

Table 2.8 Composition (%) of MSW in Some World Cities (Guermoud et al., 2009)

Country	City	Organic matter	Cardboard	Plastics	Metals	Glass
Morocco	Agadir	65–70	18	2–3	5.6	0.5–1
Jordan	Amman	63	11	16	2	2
Turkey	Istanbul	36.1	11.2	3.1	4.6	1.2
Tunisia	Tunis	68	11	7	4	2
Mauritania	Nouakchott	4.8	6.3	20	4.2	4
Guinea	Labe	69	4.1	22.8 (+textile)	1.4	0.3
France	Paris	28.8	25.3	11.1	4.1	13.1
Portugal		35.5	25.9	11.5	2.6	5.4
Greece	Palermo	31.7	23.1	11.8	2.7	8.3
Canada	Toronto	30.2	29.6	20.3	2.1	2

Kumar et al. (2009) studied the status of municipal solid waste management of different cities and towns in India and came up with the following findings. According to them, quantity and composition of MSW bears a consistent correlation with the average standard of living. To collect representative samples from different zones of the cities, they collected MSW samples from bins for 5 consecutive days. They mixed, quartered repeatedly until the sample size was 12.5 kg. The average waste consists of 30-45% organic matter, 6-10% recyclables, and the rest of it is inert matter. The research revealed that, all metals, unsoiled paper, plastic, glass, cardboard etc. are recycled by the householders themselves or by rag pickers, so by the time the waste reaches community bins, it contains very little recyclables and contains mainly vegetable/fruit peelings, scraps of soiled paper and plastics, used toiletries, etc.

According to Moghadam et al. (2009) waste production and composition depends on socio economic condition, stage of development, climatic condition and geographic location of the area. The authors also reported that the quality of municipal solid waste changes with people's lifestyle. The average compositions of MSW of Rasht city, Iran for different years are reported here in Table 2.9. According to the authors, high organic content is a characteristic of MSW of developing countries (Turkey (43 – 64%), India (40-60%), Jordan (54-78%), and Nigeria (52-65%)).The researchers evaluated that, though percentage of organic waste in the MSW is very high in Rasht city, it is gradually decreasing with time. On the other hand percentage of plastic is increasing.

Table 2.9 Composition of MSW in Rasht, Iran (Moghadam et al., 2009)

Components (%)	1995	1998	2007
Food wastes	88.4	88.3	80.2
Paper and cardboard	3.5	3.5	8.7
Metals (all types)	0.6	0.6	0.7
Textiles	2.0	2.5	0.4
Glass	0.7	0. 9	0.2
Rubber and plastics	3.5	3.2	9
Wood	0.1	0.2	0.4
Construction waste	0.1	0.1	–
Others	1.1	0.7	0.4

Batool & Ch (2009) studied the municipal solid waste of Lahore of Pakistan which is representative of temperature range of 2 to 40^{o}C and 628.8 mm of rainfall per year. For this study, they sampled a total of 360 households covering all three economic classes: low, middle, and high income. Samples were collected randomly and continually from both these sources and disposal sites. Their samples also covered all seasons. Of the total waste generated, 67.02% is organic waste. The composition of waste by weight as reported in this paper is as follows: paper

(5.04%), glass (2.19%), ferrous metal (0.02%), non-ferrous metal (0.47%), film plastic (12.94%), rigid plastic (5.55%), organics (67.02%), textiles (1.00%), and others (5.77%).

Ngoc & Schnitzer (2009) studied the solid waste management of Southeast Asian countries and determined that the higher the economic prosperity the higher is the percentage of urban population and the greater is the amount of solid waste produced. According to the authors, waste composition is a function of geographic location, population, standard of living, energy source and weather. The researchers presented the waste compositions of different Southeast Asian countries along with those of USA and European countries in this paper which is presented in Table 2.10. According to this research, highly urbanized cities generate high percentage of organic and mixed organic wastes (55-70%) with about 10-16% plastic, 4-10% glass and 4-12% metals. Plastic, paper, glass, rubber and ferrous components of MSW are considered recyclable and average recycling rates for Southeast Asian countries are as follows: high income countries (44.3%), middle income countries (12%) and rest of the countries (8-12%).

Table 2.10 Composition of municipal solid waste in Southeast Asian Nations (Ngoc & Schnitzer, 2009)

Country	Waste composition (%)						Waste generation rates (kg/cap/day)
	Organic	Paper	Plastic	Glass	Metal	Others	
Brunei	44	22	12	4	5	13	0.66
Cambodia	55	3	10	8	7	17	0.52
Indonesia	62	6	10	9	8	4	0.76
Laos	46	6	10	8	12	21	0.55
Malaysia	62	7	12	3	6	10	0.81
Myanmar	54	8	16	7	8	7	0.45
The Philippines	41	19	14	3	5	18	0.52
Singapore	44	28	12	4	5	7	1.1
Thailand	48	15	14	5	4	14	0.64
Vietnam	60	2	16	7	6	9	0.61

Owens & Chynoweth (1993) studied MSW collected from two sources: Sumter county and Levy county of Florida. The authors prepared fresh, dried and digested subsamples from waste of both the sources. According to them, paper is normally the largest component of solid waste which can compose 30-50% of MSW; again yard waste can be up to 20% of solid waste.

The researchers presented the composition of fresh MSW on dry weight basis. For Sumter county the composition is as follows: paper (43.7%), corrugated (4.8%), plastic (11.2%), yard waste (3%), and miscellaneous (37.3%). For Levy county the composition is as follows: paper (85-91.3%), Corrugated (7%), plastic (0-0.8%), yard waste (0-1.6%), and miscellaneous (1.8-7.2%).

Elagroudy et al. (2008) worked on waste settlement in bioreactor landfills and presented the composition of municipal solid waste as, food (35%), vegetables (26%), paper (10%), and plastics (6%), textiles (3%), and bio-solids (20%).

According to Han et al. (2006) the composition of MSW on percent wet weight basis are as follows: paper (40%), plastic (11%), yard waste (20%), glass (4%), and food waste (25%).

Zhen-shan et al. (2009) have presented an overview of the municipal solid waste of Beijing City. The composition of MSW of Beijing for years 1989 through 2006 as given by the authors has been tabulated in Table 2.11. It is noticeable that, the percentage of food waste has increased remarkably with time. According to them, Nepal and Rasht have also high percentages of food and the values are 70% and 80.2% respectively. Food waste percentage is 52.4 for Mexico and 38.83 for Singapore which is somewhat less. For England and Macao the percentage is low and values are 20.2% and 14.5% respectively.

Table 2.11 Composition of MSW in Beijing City, 1989–2006 (Zhen-shan et al., 2009)

Composition (%)	1989	1990	1995	1998	2000	2001	2002	2005	2006
Food	32.6	24.89	35.96	37.12	44.15	39	45.77	54.55	63.39
Plastic	1.88	5.08	10.35	10.35	13.61	10.35	15.49	11.26	12.7
Construction debris	4.79	4.11	1.5	1.11	0.88	10.93	14.59	19.62	0.62
Dust	47.2	52.22	10.92	5.64	2.02		0.89		5.87
Wood	1.17	4.13	8.32	9.12	7.47	–	2.92	3.04	1.78
Glass	3.79	3.10	10.22	10.70	6.34	18.18	6.45	1.51	1.76
Paper	6.04	4.56	16.18	17.89	14.28	18.18	4.32	7.55	11.07
Textiles	1.74	1.82	3.56	4.11	9.58	3.56	8.8	1.83	2.46
Metal	0.76	0.09	2.96	3.34	1.17	2.96	0.71	0.54	0.27
Other	0.2	–	–	–	0.5	2	0.06	–	0.08

Maystre & Viret (1995) discussed sampling and analytical techniques to characterize solid waste and defined what a representative sample is. According to them, while sorting, if fine indeterminable material can be reduced to less than 2%, direct hand sorting can give good estimate of composition. The authors also concluded that, socio economic status does not significantly affect composition but housing type does. The MSW composition of Geneva as mentioned by them is elaborate and comprises of 52 categories (Table 2.12).

Table 2.12 Composition of 52 Waste Categories Analyzed in MSW from Geneva (Maystre & Viret, 1995)

Class or material	Composition (by % weight)	Class or material	Composition (by % weight)
Vegetable and food stuffs	26.1	iron scraps	1.6
Meat scraps	1.7	PVC bottles	0.6
Natural tissues	0.6	polyethylene bottles	0.6
Synthetic tissues	0.7	solid molded boxes	0.5
Nylon stockings	0.1	rubbish bags	1.1
Unweaved sanitary	0.2	supermarket bags	0.6
Disposable nappies	3.3	over-packing	1
Various textiles	0.5	plastics from foodstuffs	1.2
Glass	9.6	rigid pots (yogurts)	0.9
Newspaper	12.1	polystyrene	0.2
Packing paper	1.1	plastic scraps	1.9
Other paper	11.6	cigarette packets	0.2
Other cardboard	3.2	Tetra brik without Al	0.4
Packing cardboard	3.2	Tetra brik with Al	0.7
Household aluminum	0.2	packaging composites Al+plastic	0.1
Aluminum aerosols	0.1	packaging composites Al+plastic+paper	0.1
Aluminum tubes	0.1	packaging composites Al+paper	0.2
aluminum pastry trays	0.1	paper+paraffin wax	0.3
aluminum covers	0.1	cardboard+paraffin wax	0.1
aluminum beverage cans	0.2	batteries	0.2
aluminum scraps	0.1	medications packaging	0.2
non-ferrous metals	0.3	electronic material	0.3
iron food cans	1.3	toxins	0.6
iron covers	0.2	wood-leather-rubber scraps	1.7
iron aerosols	0.1	inert material	5.7
iron beverage cans	0.1	others	2.4

Sujauddin et al. (2008) studied the characteristics of household solid waste of Chittagong, Bangladesh. For this study, the researchers collected solid waste directly from 75 selected households, 15 from each of 5 socio-economic categories. Waste generation rate was found to with the increase in household income. The compositions of MSW for different socio-economic groups are presented in this study. The average composition as mentioned by the authors are: paper (3%), pack (9%), can (9%), plastic (2%), glass (5%), and rocks (6%), all categorized as non-compostable; among the compostable components, textile (1%), vegetable (62%), and wood (3%). Composition indicates that the largest component of household solid waste is vegetable or food waste comprising about 62%, and this component increases from high income to low income households.

According to the study by Hudson et al. (2004) plastic film is visually a prominent component of the waste and the putrescible waste content is very low for household waste. The composition reported here is: paper/cardboard (42.3%), plastic film (7.9%), dense plastic (5.3%), textiles (3.5%), miscellaneous combustibles (4.9%), miscellaneous non-combustibles (2%), glass (4.5%), ferrous metal (2.2%), non-ferrous metal (0.8%), putrescible (2%), less than 10 mm sized (24.7%).

Koukouzas et al. (2008) presented a case study of MSW for Western Macedonia. According to their findings, about 20% of the total waste here is non-combustible. The composition of MSW on wet weight basis is as follows: Organics (43%), paper (22%), plastics (15%), aluminum (1%), iron (3.5%), inert (2%), glass (5%), others (8.5%).

Sha'Ato et al. (2007) presented the characteristics of MSW of Nigeria as determined over a ten days period for waste collected from 100 households, 11 businesses, 5 institutions and 5 industries. Here 82% of the solid waste comes from households and the rest from the other above mentioned sectors. . The composition of different MSW as mentioned by them can be found in Table 2.13. It shows that, there is more putrescible waste in the household waste stream than in the non-household waste stream.

Table 2.13 Typical composition of solid waste in Makurdi urban area by generator (Sha'Ato et al., 2007)

Waste source	Waste category (%)							
	Putrecibles	Plastics/ cellophane	Paper	Metals	Glass	Textiles	Fines	Misc.
	food remnants, fresh and decaying leaves, vegetation			mostly cans and bottle caps; few ferrous metal and aluminum items			ash, dust and sand	
low density area	57.5	6.1	4.3	2.5	2.3	2.9	21	3.4
medium density area	53.7	7.1	4.1	2.01	1.7	2.4	27.1	1.7
high density area	36.4	8.04	2.59	1.75	0.86	3.67	41	5.73
commercial premises	27.9	10.2	10.9	3.4	6.9	1.2	36.4	3.1
institutional premises	44.8	5.9	8.9	0.9	1.2	0.3	36.4	3.1
small/medium scale industry	23.4	7.01	2.1	0.7	0.1	6.1	31.7	28.9
market	36.1	6.8	3.2	1.1	0.1	1.9	48.7	2.01

Otoniel et al. (2008) conducted a study to find out the generation rate and composition of household hazardous solid waste produced at residences of UK. According to this research, 1.6% of total municipal solid waste is household hazardous waste. This waste of UK is composed of aerosols (26%), paints (17%), oils (15%), batteries (14%), and bleaches (10%).

Hazra and Goel (2009) presented the physical properties of solid waste of Kolkata, India. Of the total waste, 34.2% comes from households, 22.8% from street sweepings, 6.32% from different institutions, and 36.3% from commercial and market spaces. The compositions of the waste for the years 1970 and 1993 are presented in Table 2.14. 45.1% of the total waste is biodegradable.

Table 2.14 Physical composition of MSW of Kolkata in 1970 and 1993 (Hazra & Goel, 2009)

Component	% by weight	
	1970	1993
paper	3.18	6.25
rags	3.60	5.73
ash and earth	33.59	17.18
ignited coal	8.08	2.46
earthen ware	6.65	4.15
coconut shell	4.96	9.22
stone	1.36	0.39
iron and other metals	0.66	0.42
bones	0.42	4.00
leather	0.86	1.07
plastic	0.65	1.67
glass	0.88	1.50
vegetable matter	13.05	11.76
garbage	16.05	29.42
hay and straw	6.31	3.34

By Hernández-Berriel et al. (2008) 64.4% of the waste was defined as biodegradable, 49.5% as readily degradable and the 13% as non-degradable for El. Socavón, Mexico. Here 49.76% of total waste is organic. The percentage wet weights of different components as reported by the authors are: food waste (49.7), plastic (23.4), paper & cardboard (13.1), others (4.8), glass (4.7), metal (1.9), textiles (1.6), yard trimmings (0.9).

Sakai (1996) defined municipal solid waste as a complicated physical composition. Waste compositions of different cities of Japan as mentioned by the authors for year 1989 are summarized in Table 2.15. They also presented how physical composition differs in weight basis and volume basis. The example of City of Kyoto can be found in Figure 2.2. The figure indicates that for paper and plastic, proportion surges in volumetric ratio.

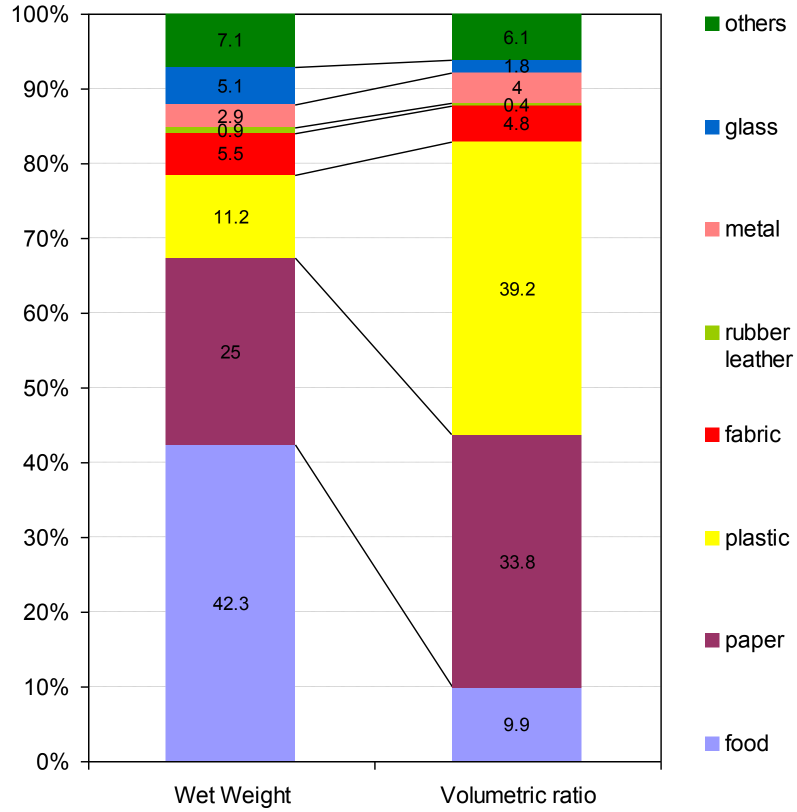

Figure 2.2 Physical Composition of Waste: Comparison between Weight Ratio and Volumetric Ratio (Sakai, 1996)

Table 2.15 Physical Composition of Japan's MSW, Records of 1989 (Sakai, 1996)

Components	City		
	Sapporo (% wet basis)	Yokohama (% dry basis)	Osaka (% wet basis)
Paper	25.2	40	35.7
Kitchen waste	46.6	9.8	6.5
Fabric	2.4	4.2	5.9
Wooden waste	1.7	5.8	5.2
Plastics	12.5	14.8	20.3
Rubber, leather	-	-	-
Metal	3.7	5.7	5.3
Glass	7.1	13.2	7.1
Ceramic	-	-	2.7
Soil and rubbish	0.8	6.5	-
Moisture Content	-	-	46%

The research by Henry et al. (2006) provides with the municipal solid waste composition of three socioeconomic classes of Kenya, which is representative of a low-income developing country. The composition reported by the authors is presented in Table 2.16.

Table 2.16 Composition of MSW Disposed by Three Groups in Nairobi (1999) (Henry et al., 2006)

MSW component	% Composition		
	High income	Middle income	Low income
Food	52	50	57
Paper	17.3	17	16
Textiles	2.7	3	2
Plastic	11.8	14	12
Grass/wood	6.7	8	2
Leather	0.9	1	1
Rubber	1.5	1	2
Glass	2.3	2	2
Cans	1.7	2	1
Other metals	0.9	1	0
Others	2.7	7	4

According to Sharholy et al. (2008) the quantity of MSW generation depends on a number of factors such as food habits, standard of living, degree of commercial activities, and seasons. The composition for MSW of India at generation sources and collection points has been determined on a wet weight basis and it consists mainly of a large organic fraction (40–60%), ash & fine earth (30-40%), paper (3-6%), and plastic, glass and metals (each less than 1%). According to the authors, characteristics of MSW change with population density and also relative percentage of organic waste in MSW is generally increasing with the decreasing socio-economic status. In the waste, percentage recyclable was very low as rag pickers segregate and collect them at generation sources, collection points and disposal sites.

Bai & Sutanto et al. (2002) present an overview of the current solid waste management situation in Singapore which is representative of hot (average temperature 24.7 to 31.3^{o}C) and humid (84.4% humidity and annual average rainfall 2134 mm) climate. Typical composition of MSW of Singapore for the years 1997 to 2000 is given in Table 2.17. It indicates that the composition is relatively stable over time.

Table 2.17 Solid Waste Composition in Singapore (Bai & Sutanto, 2002)

Composition (%)	Year			
	1997	1998	1999	2000
food waste	38.81	38.80	38.80	38.83
paper/cardboard	20.60	20.60	20.60	20.60
plastics	5.79	5.80	5.80	5.80
construction debris	4.51	4.50	4.50	4.50
wood/timber	8.91	8.90	8.90	8.90
horticulture waste	2.70	2.70	2.70	2.70
earth spoils	2.70	2.70	2.70	2.70
ferrous metal	2.70	2.70	2.70	2.70
non-ferrous metals	0.50	0.50	0.50	0.50
used slag	4.29	4.30	4.30	4.30
sludge	1.80	1.80	1.80	1.80
glass	1.10	1.10	1.10	1.10
textile/ leather	0.90	0.90	0.90	0.90
scrap tyres	0.20	0.20	0.20	0.20
others	4.51	4.50	4.50	4.50

Yu & Maclaren (1995) characterized industrial-commercial and institutional waste of Toronto, Canada. The analysis was done based on 1 sample from each of 111 companies of 9 different categories. The composition of this MSW as computed by direct analysis is as follows: Paper (24.7%), Paperboard (22.3%), Ferrous metal (5.9%), Non-ferrous metal (0.9%), Plastics (13.3%), Glass (2.8%), Rubber (0.4%), Leather (0%), Textile (4.5%), Wood (7.5%), Vegetation (1..4%), Fine (0.3%), Special (0.6%), Construction Material (4.6%), and Food (10.7%).

Abduli (1995) studied the solid waste of Tehran. The physical compositions of waste of Tehran for years 1983, 1991, and 1992 have been reported in this study. The percent composition for the year 1992 has been reported as: Organics (73.6), Paper & cardboard (8.3), Plastics (4.8), Glass (2.7), Textile (2.2), Metals (1.3), Bone (1.7), Construction debris (1), Wood (0.9), Rubber (0), and Others (1.3).

Oweis & Khera (1998) summarized the waste composition of different countries, which can be found in Table 2.18.

Table 2.18 Typical Municipal Waste Composition (Oweis & Khera, 1998)

Country/ City	Component (% by weight)								
	metals	paper & paper board	plastics	rubber, leather, wood	textile	food and yard waste	glass	non-food inorganic	other
Australia		37				45		18	
Switzerland	6	32	13	4	3	33	9		
Beijing	1	5	1	1		45	1	46	
Italy	3	22	7			42	7		19
Canada	6	39	5	1	4	34	6	2	3
Hong Kong	3	33		7	10	15	10	22	
Sweden	3	40	9	1	3	30	7		7
Japan		38	8	12	18		24		
Korea	3	10		4			74	7	2
Madras India		14				56		30	
France	5	30	6		4	25	12		18
Singapore	7	32	3	7	4	36	4	7	
Spain		14				50		21	
Taiwan	2	8		3	4	25	3	55	
UK	8	30		1	2	16	8	35	
West Germany	5	31		4	2	16	13	29	

Manassero et al. (1997) also summarized the composition of solid waste of different cities (Table 2.19).

Table 2.19 MSW Components as Weight Percentage for Different Cities (Manassero et al., 1997)

City (Country)	Component (% by weight)							
	Metals	Paper & cardboard	Plastic	Leather, wood, rubber	Textiles	Putrescible materials	Glass	Others
Bangkok (Thailand)	1	25		7	3	44	1	19
Nairobi (Kenya)	3	12	5			74	4	2
Hong Kong	3	3		7	10	15	10	22
New York (USA)	5	22		3		20	6	46
Geneva (Switzerland)	2.5	31	9.5	4	5	28	9	11
Athens (Greece)	4	19	7	4		59	2	5
Cochabamba (Bolivia)	1	2	3	1		71	1	21
Wollongong (Australia)	3	16	20			58	2	1

2.3 Unit Weight

Unit weight of municipal solid waste is indicative of the compactness of the waste. It indicates the amount of waste present in a certain volume. The unit weight of refuse can vary widely because of the large variations in the waste constituents, state of decomposition, degree of control during placement such as thickness or absence of daily cover, amount of compaction, total depth of landfill, the depth from which the sample is taken, etc. (Oweis & Khera, 1990).

Various values of unit weight have been suggested for solid waste by different researchers. Some of them are presented here.

According to Vesilind et al. (2002) MSW has a highly variable bulk density, depending on the pressure exerted on it. When, MSW is placed loosely in a trashcan by a homeowner it might be between 150 and 250 lb/yd^3, and can be up to 300 lb/yd^3 if pushed into the can. In the collection truck, the density increases up to 600 to 700 lb/yd^3. Once compacted with machinery in landfill, it can reach up to 1200 lb/yd^3. If cover soil is included, the value can range from 700 to even 1700 lb/yd^3.

Gabr and Valero (1995) evaluated the engineering properties of 15 to 30 years old municipal solid waste. According to them, the Mean specific gravity of MSW is 2.0. The dry unit weight varies from 7.4 to 8.2 KN/m^3 while the maximum dry unit weight of solid waste can be 9.3 KN/m^3 at an optimum moisture content of 31%.

Yousuf & Rahman (2007) reported the average bulk density for municipal solid waste of Dhaka City, Bangladesh for wet season to be 0.23 ton/m^3 and for dry season to be 0.24 ton/m^3.

Xiang-rong et al. (2003) have reported the geotechnical behaviors of the MSW in Tianziling Landfill. The authors suggested that unit weight of MSW increases from 8 KN/m^3 to 16.8 KN/m^3 as depth increases. They also reported that the presence of plastic and branch in MSW decreases unit weight while gravel in daily cover does the opposite. The researchers indicated that specific gravity of MSW is somewhat lower than soil and ranges from 1.96 to 2.62.

For fresh MSW collected from the working face of Orchard Hills Landfill, under confinement, the dry unit weight varies from 600 kg/m^3 to 620 kg/m^3, while maximum dry density at optimum moisture content is 420 kg/m^3 (Reddy et al. 2009).

By in situ unit weight measurement, Landva & Clark (1990) found that for MSW of landfills across Canada, the unit weight value ranges from 6.8 to 16.2 KN/m^3. They also suggested that the unit weight of the cover soil needs to be measured separately. The authors mentioned that, plate load tests carried out for 10 to 15 minutes gives idea about the density or degree of compaction of the waste fill. This test gives results in terms of ratio of applied pressure to settlement, which can vary from 1 MPa/m in case of poor compaction to 15 MPa/m in case of good compaction or better gradation or thicker good compacted cover. They also reported the unit weight of different components of typical MSW, which can be found in Table 2.20.

Table 2.20 Typical Unit Weight of Refuse (Landva & Clark, 1990)

Category	Unit weight (KN/m^3)	
	Dry	Saturated
Food waste	1.0	1.0
Garden refuse	0.3	0.6
Paper products	0.4	1.2
Plastic, rubber	1.1	1.1
Textiles	0.3	0.6
Wood	0.45	1.0
Metal products	6.0	6.0
Glass & ceramics	2.9	2.9
Ash, rock & dirt	1.8	2.0

Hogland et al. (2004) determined that no reliable trend of variation exists in density of different layers of buried waste.

From the short one week study conducted by Hristovski et al. (2007) in summer on the residential waste of Veles, Macedonia, the uncompacted and compacted specific weights were found to be 140.5 kg/m^3 and 223 kg/m^3 respectively.

Chen et al. (2009) suggests that the unit weight of solid waste of Qizhishan landfill, China varies from 5 KN/m^3 to 15 KN/m^3, increasing bi-linearly with depth. According to the authors unit weight increases at an increased rate from 0 m to 22 m; then the rate of increase decreases at greater depths.

According to Guermoud et al. (2009), the density of the waste is higher in developing countries (0.35 to 0.5 ton/m^3) than in industrial countries.

Elagroudy et al. (2008) worked on MSW in bioreactor landfills and reported the initial density of solid waste as 532 kg/m^3.

Hettiarachchi et al. (2009) also studied bioreactor landfill. The authors reported the compaction dry density of MSW to be 500 kg/m^3. They also reported that wet density of waste can vary in an approximate range of 825 to 1125 kg/m^3 and maximum density at the bottom of landfill after 25 years can be 1125 kg/m^3.

From the study of Han et al. (2006) it was found that the compacted bulk density near top during landfilling is 647.9 kg/m^3, whereas the average waste density of landfill is 999.6 kg/m^3 for the Sandtown Landfill of Delaware.

Maystre & Viret (1995) stated that the specific weight of solid waste in collection bags lies between 0.08 to 0.12 kg/liter for Geneva, Switzerland, though no value was given for the same in landfills.

Sha'Ato et al. (2007) reported the bulk density of MSW of Nigeria as determined over a ten days period for waste collected from 100 households, 11 businesses, 5 institutions and 5 industries. Average bulk densities for the household and non-household solid wastes were reported as 287 kg/m^3 and 200 kg/m^3 respectively.

Abduli (1995) studied the solid waste of Tehran and reported the values of waste properties for several years. The densities of the wastes for years 1983, 1991 and 1992 were mentioned as 297, 320 and 400 kg/m^3 respectively.

The study by Hudson et al. (2004) focuses on quantifying the changes in density of saturated solid waste resulting from increases in vertical stress. Apparent densities of fresh and aged solid waste with stress level as determined by the researchers are listed in Table 2.21.

Table 2.21 Variation in Particle Density with Applied Stress (Hudson et al., 2004)

Raw Domestic waste		Aged Domestic Waste	
Average Stress at end of stage	Average apparent particle density	Average Stress at end of stage	Average apparent particle density
kPa	t/m^3	kPa	t/m^3
34.00	0.88	35.00	1.64
65.00	0.97	67.00	1.62
120.00	1.02	123.00	1.64
241.00	1.17	239.00	1.69
463.00	1.30	458.00	1.86

Hazra and Goel (2009) reported the average density of the waste of Kolkata, India to be 600 kg/m^3 as compared to 95 kg/m^3 for an average American city.

The density of municipal solid waste of Mexico has been reported as 400 kg/m^3 by Hernández-Berriel et al. (2008).

According to Bleiker et al. (1995) the refuse at the bottom of the landfill gets compacted both immediately upon placement and over time as landfill development progresses vertically. As a result, density of refuse at bottom is much greater compared to top. According to the authors, if effective stress increases from 21 kPa to 441 kPa, refuse density increases from 685 to 1345 kg/m^3. They also summarized typical landfill densities as suggested by different researchers (Table 2.22).

Table 2.22 Typical Landfill Densities (Bleiker et al. 1995)

Source	Density (kg/m^3)	
Landva & Clark (1990)		694-1653
Oweis & Khera (1986)	old refuse	1122-1286
	during active landfilling	673
Sowers (1973)		600
Ham & Bookter (1982)	1.2 m of refuse	458
	1.4 m of refuse	491
Lukas (1992)	poor compaction	321
	good compaction	642
	best compaction	963

Gharabaghi et al. (2008) reported that according to Grisolia et al. (1995) unit weight of MSW can range from 6 to 7.4 KN/m^3. They studied two landfills of Brazil. The apparent density of waste of Muribeca landfill, which is a partially engineered landfill, is about 850 kg/m^3 and the unit weight is 14.7 KN/m^3. The same for Cruz das Almas landfill, representative of an open dump, were reported as 450-600 kg/m^3 and 8.8 kN/m^3 respectively.

Yu & Maclaren (1995) characterized the industrial, commercial and institutional wastes of Toronto, Canada. The authors reported the unit weights of different components of MSW at source (Table 2.23).

Table 2.23 Composition and Density Estimate of IDI MSW (Yu & Maclaren, 1995)

Components	Density (kg/m^3)	
	Trash can	Compactor
Paper	77	350
Paperboard	26	337
Ferrous metal	120	270
Non-ferrous metal	32	178
Plastics	38	198
Glass	390	1293
Rubber	102	175
Leather	29	191
Textile	29	191
Wood	360	444
Vegetation	300	720
Fine	60	480
Special	32	178
Construction materials	360	444
Food	300	930

Zekkos et al. (2006) stated that individual landfills have a characteristic MSW unit weight profile which is a function of waste composition, compaction, cover soil placement, liquids management and confining stress. They developed a hyperbolic unit weight profile applicable for conventional landfills with moisture content at or below field capacity. The model is shown in Figure 2.3. According to the authors, in situ large scale method is most reliable approach for evaluation of unit weight of MSW. They provided unit weight values suggested by various researchers as summarized in Table 2.24. They also reported that unit weight varies proportionately with moisture content.

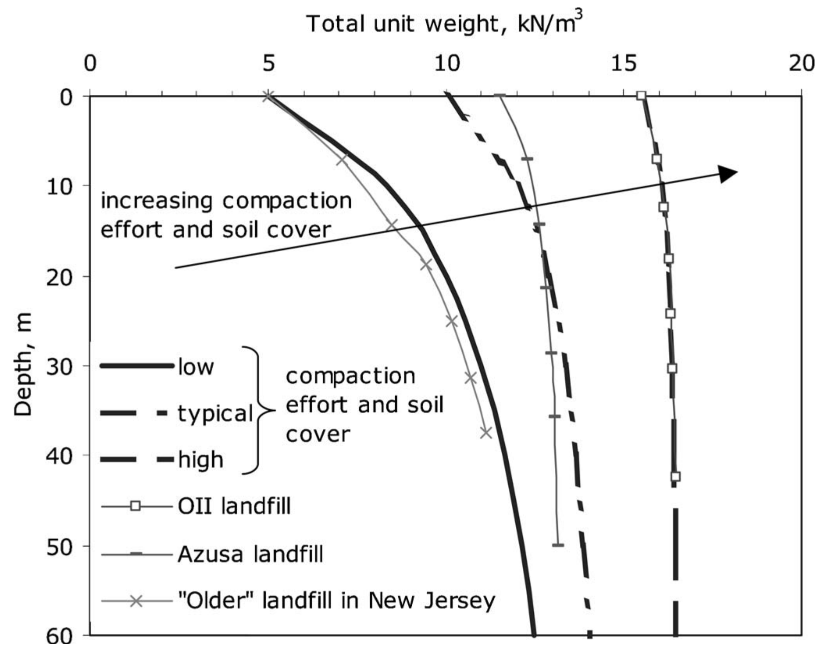

Figure 2.3 Unit Weight Profile (Zekkos et al., 2006)

Table 2.24 Unit Weight of MSW (Zekkos et al., 2006)

Source	Unit Weight (kN/m^3)	
Fassett (1993)	Poor compaction	3
	Good compaction	17
Zekkos et al. (2005b)		3-20
Landva & Clark (1986)		8-17
Kavazanjian (1995)	at surface	6
	at 45 m depth	13
Kavazanjian (1996)	at surface	10-13
	at 30 m depth	13-16
Biorector		20
Submerged condition		14.5-16

According to Dixon & Jones (2005) initially for fresh MSW, unit weight is a function of composition, daily cover, and degree of compaction, but later on for older waste, it is affected by depth of burial, degree of decomposition and climatic condition. With degradation, unit weight increases. The range of unit weight for poor, moderate and good compaction has been reported as 3.0-9.0, 5.0-7.8, 8.8-10.5 KN/m^3 respectively. The bulk unit weights for different countries have also been mentioned by the authors. Those are listed in Table 2.25. Also, leachate recirculation causes bulk unit weight to increase.

Table 2.25 Bulk Unit Weight of MSW for different Countries (Dixon & Jones, 2005)

Country	Bulk unit weight (KN/m^3)	
United Kingdom		6-8
Belgium		5-10
France	Fresh MSW	7
USA	Fresh MSW	6-7
	Degraded MSW	14-20

Oweis & Khera (1998) reported unit weights of different types of landfills as presented in Table 2.26.

Table 2.26 Unit Weight of Different Types of Landfill (Oweis & Khera, 1998)

Type and State of Municipal Waste	Total Unit Weight	
	lb/ft^3	kN/m^3
Poor compaction	18-30	2.8-4.7
Moderate to good compaction	30-45	4.7-7.1
Good to excellent compaction	45-60	7.1-9.4
Baled waste	37-67	5.5-10.5
Shredded and compacted	41-67	6.4-10.5
In situ density	35-44	5.5-6.9
Municipal waste from Canada	43-89	6.8-14
Active landfill with leachate mound	42	6.6
Northeast US active landfill	30-40	4.6-6.3

According to Manassero et al. (1997) the unit weight varies throughout the landfill and is difficult to determine because of variability in composition, method of placement, induced ageing, depth and local moisture content. The authors summarized different values of unit weight found in literature (Table 2.27) and suggested that the possible range is 3 to 14 kN/m^3.

Table 2.27 Unit Weight of Domestic Waste (Manassero et al. 1997)

Source	Unit Weight (kN/m^3)
Fungaroli et al. (1979)	1.1-4
Koriates et al. (1983)	8.6
Oweis & Khera (1986)	6.45
Oweis et al. (1990)	6.45
	9.4-14
	6.3-9.4
Landva & Clark (1990)	10.1-14.4
Gabr & Valero (1995)	
Blengino et al. (1996)	9-11
Manssero (1990)	8-10
Beaven & Powrie (1995)	5-13
Brandl (1990)	11-14
	13-16
Brandl (1994)	9-12
	9-12
	13-17

2.4 Moisture Content

The moisture content of solid waste is useful information for estimating heat content, landfill sizing, and transport requirements (Pichtel, 2005). Moisture content becomes important when the refuse is processed into fuel or when it is fired directly. As transfer of moisture takes place within the waste in the garbage can and truck, the moisture content at component level changes with time (Vesilind et al., 2002). Moisture content is more commonly expressed as the percentage of wet weight of the material.

According to Vesilind et al. (2002) the moisture content of loose refuse is about 20% if there has not been a rainstorm before collection. During the rainy weather the moisture content can go as high as 40% on wet basis.

For most MSW in the United States, the moisture content will vary from 15 to 40% on wet basis, depending on composition, season of year, and the weather conditions (Pichtel, 2005).

Gabr and Valero (1995) worked on 15 to 30 year old MSW and reported that the moisture content can vary from 30% at surface to as high as 130% at greater depths.

Yousuf & Rahman (2007) reported the moisture content of fresh MSW of Dhaka city to be very high ranging from 65% to 80%.

According to Xiang-rong et al. (2003) moisture content gradually decreases with depth from 60% to 20% with an average of 30% for Tianziling Landfill.

Reddy et al. (2009) determined the geotechnical properties of fresh MSW collected from the working face of Orchard Hills Landfill and reported the dry gravimetric moisture content to be 44%.

The research of Landva & Clark (1990) indicates that the moisture content increases with increasing organic content and can be up to 120% for Landfills across Canada.

The moisture content of the fresh waste was reported to be 61% while that of three year old waste as 117% by Gomes et al. (2005).

Kumar et al. (2009) studied the status of municipal solid waste management of different cities and towns of India based on their populations. The moisture contents determined by the authors are tabulated in Table 2.28.

Table 2.28 Moisture Content of MSW of Different Cities of India (Kumar et al., 2009)

Population of the city (million)	Compostable fraction (%)	Moisture Content (%)
<0.1	29 – 63	65
0.1 to 0.5	29 – 63	65
0.5 to 1	35 – 65	17 – 64
1 to 2	39 – 54	25 – 65
> 2	40 – 62	21 – 63

Sharholy et al. (2007) conducted a study on MSW of Allahabad city of India and reported the moisture content as 25.86%.

Hogland et al. (2004) determined moisture content of mixed unsorted waste to be around 30% by weight and found it to be more or less constant at different depths.

Gawande et al. (2003) measured the moisture content of bioreactor landfill as a function of electrical resistance between two electrodes embedded in granular surface and reported that the value is higher than 35% wet weight basis.

Guermoud et al. (2009) reported moisture content of different components of MSW of Mostaganem city of western Algeria, which is representative of an industrialized developing country. The reported values are 58.9%, 9.5%, and 3.7% for organic matter, cardboard, and plastic respectively.

Elagroudy et al. (2008) reported the moisture content of bioreactor landfill to be 67%.

As suggested by Hettiarachchi et al. (2009), volumetric moisture content of dry landfills can vary from 5% to 30%. The authors also suggested that the final moisture content at the bottom layer can be approximately 39%.

The moisture content of the waste of Beijing has been suggested as 61.21%, by Zhen-shan et al. (2009).

Han et al. (2006) conducted a study on the seasonal variation of moisture in a landfill. The researchers used Partitioning Gas Tracers Test (PGTT) method for moisture content determination and compared the method with other indirect methods as neutron probe, time domain refractometry, electrical conductivity, and electromagnetic slingram. By PGTT tests conducted in the same location of Central Solid Waste Management Center in Sandtown, Delaware over a 12- month period, it was found that the moisture content ranges from 0 to 24.7%, whereas gravimetric measurements in excavated pits yielded the same to be 26.5%. This is very close. According to the authors, the other indirect methods are unsuccessful in producing such accurate results as they have the drawback of only point measurement.

Sha'Ato et al. (2007) provides with the moisture content of MSW of Nigeria as determined over a ten days period for waste collected from 100 households, 11 businesses, 5 institutions and

5 industries and according to the authors, the moisture content values for household and non-household solid wastes on wet weight basis are 26.8% and 22.7% respectively.

Maystre & Viret (1995) classified the MSW of Geneva into 52 components and reported the moisture content of each individual component. The results are presented in Table 2.29.

Table 2.29 Moisture Content of 52 Waste Categories Analyzed in MSW from Geneva, (Maystre & Viret, 1995)

Class or material	Humidity (% by weight)	Class or material	Humidity (% by weight)
Vegetable and food stuffs	73.9	iron scraps	3
Meat scraps	45	PVC bottles	5.9
Natural tissues	20.5	polyethylene bottles	6
Synthetic tissues	23.1	solid molded boxes	7.2
Nylon stockings	11.4	rubbish bags	3.8
Unweaved sanitary	36	supermarket bags	23.7
Disposable nappies	53.4	over-packing	6.4
Various textiles	23.1	plastics from foodstuffs	8.7
Glass	0.5	rigid pots (yogurts)	18.8
Newspaper	17	polystyrene	11.3
Packing paper	20.4	plastic scraps	7
Other paper	16.6	cigerette packets	17.7
Other cardboard	28.9	Tetra brik without Al	6.5
Packing cardboard	17.2	Tetra brik with Al	9.6
Household aluminum	30.3	packaging composites Al+plastic	12.1
Aluminum aerosols	-	packaging composites Al+plastic+paper	12.8
Aluminum tubes	24.7	packaging composites Al+paper	13.6
aluminum pastry trays	21.1	paper+paraffin wax	17.3
aluminum covers	27.4	cardboard+paraffin wax	19.5
aluminum beverage cans	15.6	batteries	3
aluminum scraps	10	medications packaging	8.7
non-ferrous metals	7	electronic material	3
iron food cans	7.4	toxins	8
iron covers	3.1	wood-leather-rubber scraps	15
iron aerosols	5	inert material	27.5
iron beverage cans	3.2	others	36.9

According to Bai & Sutanto et al. (2002) moisture content on wet weight basis for the waste of Singapore ranges from 30% to 60% with an average of 48.60%, which is considerably higher as compared to 20% for USA.

Hudson et al. (2004) reported the moisture content of solid waste to be 32.5% on wet weight basis.

Hazra and Goel (2009) presented the physical properties of solid waste of Kolkata, India. They reported the average moisture content of this waste as 60%.

Sakai (1996) reported the moisture content on percentage wet weight basis for Osaka, Japan to be 46%.

Abduli (1995) studied the solid waste of Tehran. The authors reported the moisture content of MSW as 52.7%.

The research by Kumar et al. (2009) is about the ability of using resistance based sensors to measure in situ moisture content. The study was conducted in a bioreactor landfill of Florida. The moisture content values were obtained using both resistivity method and gravimetric method. To determine the gravimetric moisture content, 5 to 10 kg of waste were oven dried at 102^{o}C over duration until the sample weight was stabilized. Moisture content values both before and after recirculation have been reported by the authors (Table 2.30).

Table 2.30 Moisture Content of Bioreactor Landfill (Kumar et al., 2009)

Moisture content (wet wt. basis)	By Resistivity	By Gravimetric method
Initial: before recirculation	27.40%	23%
Final: after recirculation	44.40%	45%

Zekkos et al. (2006) determined the moisture content of four different landfills and determined that moisture content usually ranges from 10 to 50% on dry basis.

According to Manassero et al. (1997) most of the domestic landfills of Untied States have moisture content varying from 15 to 40%, which depends on the composition of waste, the season of the year, and natural humidity and rain conditions. In regions where evapotranspiration is more than precipitation, the typical moisture content is 25%. The moisture content values can increase from 30% at surface to 130% at greater depth. For fresh uncompacted waste, moisture content is about 22.5% which can increase to around 55% for 1-5 year old compressed waste.

2.5 Permeability

According to Pichtel (2005) the hydraulic conductivity of compacted waste is a physical property that strongly influences the movement of liquids (especially leachate) and gases in a landfill. Dense materials such as sludges tend to resist rainfall infiltration and promote runoff from a landfill cell, whereas components like paper and yard waste due to large particle size and consequently large void space, exhibit little resistance to rainfall infiltration (Pichtel 2005).

According to Oweis & Khera (1990) laboratory measurements of hydraulic conductivity of MSW is not a routine step in an investigation program and often field pumping test may be necessary for a proper determination of hydraulic properties of refuse. Based on laboratory test values, hydraulic conductivity may vary from $7x10^{-4}$ cm/sec (for dense, unit weight 71 pcf) to $15x10^{-3}$ cm/sec (for loose, density 35.8 pcf).

Gabr and Valero (1995) evaluated the engineering properties of 15 to 30 years old municipal solid waste. According to the authors, the permeability of aged waste varies from 10^{-3} to 10^{-5} cm/sec, but the change does not follow any particular trend.

Hossain et al. (2009) conducted a research to compute permeability based on 4 lab scale bioreactors representing 4 stages of decomposition. The study was conducted on waste collected from transfer stations of Texas. The moisture content was fixed at 55%, temperature at 22-29^{o}C, and recirculation was done 4 days a week. Based on the test results, the authors evaluated that permeability of MSW in bioreactor decreases from 10^{-2} cm/s to 10^{-4} cm/s with decomposition, with density being the same. Also, increase in density results in decrease in permeability. The authors concluded that instead of using one average value for the full landfill height and time, variation of permeability should be considered.

Durmusoglu et al. (2006) studied the scaling effect on permeability of MSW. In this study the researchers used ten years old MSW sample. In case of large scale permeability test, it was noted that, permeability decreases as density increases, though in case of small scale test, the permeability was found to be the same. The authors determined that permeability value found from large scale test ($4.7x10^{-6}$-$1.0x10^{-5}$ m/sec) is less than that from small scale test ($2.35x10^{-6}$-$1.24x10^{-4}$ m/sec), though they suggest that this should have been the opposite.

Hettiarachchi et al. (2009) reported that permeability of bioreactor landfills can vary from 10^{-12} to 10^{-14} m^2.

Bleiker et al. (1995) conducted a study on landfill settlement and the effect on hydraulic conductivity. According to the authors the refuse at the bottom of the landfill gets compacted both immediately upon placement and over time as landfill development progresses vertically. As a result permeability of waste at bottom is much less compared to top. According to them, if effective stress increases from 21 kPa to 441 kPa, hydraulic conductivity decreases from $8.1x10^{-5}$ to $4.8x10^{-5}$ m/s. The refuse density and corresponding hydraulic conductivity as proposed by other researchers have also been summarized (Table 2.31) by the authors.

Table 2.31 Refuse Hydraulic Conductivity (Bleiker et al., 1995)

Source	Unit Weight (kg/m^3)	Hydraulic Conductivity (m/s)
Fungaroli & Steiner (1979)	574	$10^{-3.8}$
	787	$10^{-4.3}$
	838	$10^{-4.5}$
	1140	$10^{-5.2}$
Hentges et al. (1993)	lightly compacted	$10^{-2.7}$
	highly compacted	$10^{-4.2}$

Dixon & Jones (2005) discussed some physical properties of MSW and the different factors affecting them. In case of hydraulic properties, placement of waste in layers and the use of daily cover soil result in waste bodies having a structure of sub-horizontal layers which, results in higher permeability in the horizontal direction. Permeability is also controlled by stress level. For fresh MSW, permeability reduces from 10^{-5} to 10^{-8} m/s if depth of burial changes from 0 to 60 meters.

Chen & Chynoweth (1995) studied the hydraulic conductivity of compacted solid waste, and evaluated that hydraulic conductivity is time dependent. They conducted large scale constant head hydraulic conductivity tests in the lab and concluded that the temporal profile of hydraulic conductivity of MSW has three distinct phases: at first hydraulic conductivity declines very sharply in the first few days, then it increases almost as sharply, then in the third stage, it finally declines gradually. The stages can be clearly seen in Figure 2.4. They also found out that density and composition of MSW significantly affects permeability but hydraulic gradient does not. Hydraulic conductivity shows a logarithmic relationship with density and the values are listed in Table 2.32.

Table 2.32 Hydraulic Conductivity vs. Waste Density (Chen & Chynoweth, 1995)

Density (kg/m^3)	Hydraulic conductivity (cm/sec)
160	$9.6x10^{-2}$
320	$7.3x10^{-4}$
480	$4.7x10^{-5}$

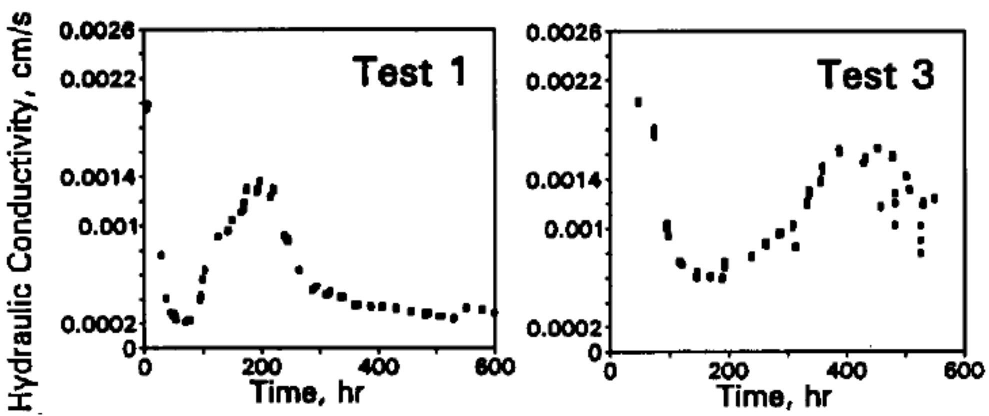

Figure 2.4 Temporal Profile of Hydraulic Conductivity (Chen & Chynoweth, 1995)

Xiang-rong et al. (2003) worked on the MSW of Tianziling Landfill, China. The authors reported that coefficient of permeability decreases with time from $4x10^{-3}$ cm/s to $2x10^{-4}$ cm/s.

According to the findings of Reddy et al. (2009) for the fresh MSW collected from the working face of Orchard Hills Landfill, permeability ranges between 10^{-5} and 10^{-4} m/s but it decreases to 10^{-8} m/s when dry density increases to 650 kg/m^3.

Manassero et al. (1997) summarized hydraulic conductivity values found in the literature (Table 2.33) and from that they concluded that a value of 10^{-5} m/s can be used as a good approximation.

Table 2.33 Hydraulic Conductivity of Domestic Waste (Manassero et al. 1997)

Source	Unit Weight (kN/m^3)	Hydraulic conductivity (m/s)
Fungaroli et al. (1979)	1.1-4	10^{-5} - $2x10^{-4}$
Koriates et al. (1983)	8.6	$5.1x10^{-5}$ - $3.15x10^{-5}$
Oweis & Khera (1986)	6.45	10^{-5}
Oweis et al. (1990)	6.45	10^{-5}
	9.4-14	$1.5x10^{-6}$
	6.3-9.4	$1.1x10^{-5}$
Landva & Clark (1990)	10.1-14.4	$1x10^{-5}$ - $4x10^{-4}$
Gabr & Valero (1995)		10^{-7} - 10^{-5}
Blengino et al. (1996)	9-11	$3x10^{-7}$ - $3x10^{-6}$
Manassero (1990)	8-10	$1.5x10^{-5}$ - $2.6x10^{-4}$
Beaven & Powrie (1995)	5-13	10^{-7} - 10^{-4}
Brandl (1990)	11-14	$2x10^{-5}$ - $7x10^{-6}$
	13-16	$5x10^{-6}$ - $3x10^{-7}$
Brandl (1994)	9-12	$2x10^{-5}$ - $1x10^{-6}$
	9-12	$5x10^{-4}$ - $3x10^{-5}$
	13-17	$2x10^{-6}$ - $3x10^{-8}$

The hydraulic properties as mentioned by Oweis & Khera (1998) are presented in Table 2.34.

Table 2.34 Hydraulic Properties of MSW (Oweis & Khera, 1998)

Waste Type	Unit Weight (kN/m^3)	Permeability (cm/sec)
Baled Refuse	11.2 (dense)	$7x10^{-4}$
	7.7	$5x10^{-3}$
	8.2	$3.5x10^{-3}$
	5.6 (loose)	$15x10^{-3}$
Shredded Refuse		10^{-2}-10^{-4} (approximate 10^{-3})

Landva & Clark (1990) studied the landfills across Canada. Large scale percolation tests in excavation pits yielded permeability of $1x10-^{5}$ to $4x10^{-4}$ m/s. As MSW components are very compressible, the authors recommended that permeability be determined as a function of void ratio.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The primary objective of this study is to collect fresh municipal solid waste samples from the working face of City of Denton Landfill of Texas and to determine physical and hydraulic properties such as physical composition, unit weight, moisture content and permeability of collected MSW.

The chapter presents the methodology for sample collection and storage as well as test procedures followed for determining the physical and hydraulic properties of municipal solid waste.

3.2 Study Area: City of Denton Landfill

The City of Denton Landfill is located at 1527 S Mayhill Road of Denton, Texas (Detailed map in Appendix). The City of Denton Landfill is a Type 1 Landfill which receives Municipal Solid Waste (MSW). The Landfill has a unique liner system designed to protect groundwater. MSW going into the Landfill is compacted and covered with dirt. The compacted waste decomposes very slowly due to the lack of oxygen; this process is called anaerobic decomposition. Landfill gas is the natural by-product of the decomposition of solid waste in landfills and is comprised primarily of carbon dioxide and methane. Methane is a greenhouse gas and an important energy source.

In 2008, the Denton Landfill installed a landfill gas collection system to collect and use landfill gas as a green energy source. The system covers the entire 63-acres of current waste in place. The collected gas is directed to an electric power generator on-site which is connected to the Denton Municipal Utilities electric grid. The current capacity of the electric generator is 1.6 megawatts, powering the equivalent to approximately 1,200 homes per year. The electric power station was designed for expansion as methane gas production increases.

In 2009, the Denton Landfill received approval from the Texas Commission on Environmental Quality (TCEQ) for the recirculation of leachate and stormwater to increase landfill gas production. A leachate collection system pumps leachate back to the upper levels of the waste pack. This process speeds up the decomposition of waste which increases methane gas production and recovery. This unique effort to utilize methane emissions provides significant energy, economic and environmental benefits. (Source: City of Denton, 2010)

3.3 Sample Collection

MSW samples have been collected twice from the working face of the City of Denton Landfill. The first set of samples was collected in May 2009 and the second set of samples was collected in August 2009. Each set of sample comprised of 10 bags of municipal solid waste and average weight of each bag was about 30 lbs.

The following procedure was followed to collect representative samples. First, three random locations were selected on the landfill. From first location, solid waste was scooped out by using a backhoe and placed on a clean surface. The collected samples were thoroughly mixed with the backhoe and quartered approximately equally as presented in Figure 3.1. Then one of the quarters was randomly chosen without any bias. This is illustrated in Figure 3.2. Three plastic bags were filled with MSW from the chosen quarter by grab sampling. Sampling was done without any bias, i.e., not by choosing what to take and what to discard. Each bag contained about 30 lbs of waste. This is required for the sample to be meaningful as MSW is a very heterogeneous material. These three bags were labeled as 1-a, 1-b and 1-c. The next three bags (2-a, 2-b, and 2-c) were collected from the second chosen location following the same procedure as above. Similarly from the third location waste was scooped and quartered, and the only difference is from here four instead of three bags were filled. These were designated 3-a, 3-b, 3-c and 3-d.

Similar method was adopted for sampling of the ten bags collected in August, 2009. But this time four locations were sampled and three bags were collected from each of first three locations and one large bag weighing 100 lbs was sampled from the fourth location. These bags were designated as 4-a, 4-b, 4-c; 5-a, 5-b, 5-c; 6-a, 6-b, 6-c; and 7-large.

More pictures of sample collection are provided in the Appendix.

Figure 3.1 Quartering Solid Waste with a Backhoe

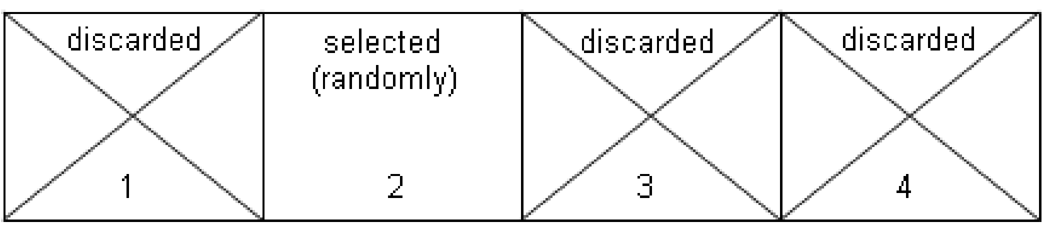

Figure 3.2 Selection of a Random Quarter for Sampling

<u>3.4 Sample Storage</u>

The collected samples were brought to the laboratory in plastic bags. All the bag samples were stored and preserved at approximately 38^{O}F (below 4^{O}C) in environmental growth chamber. The environmental growth chamber is shown in Figure 3.3. The stored samples from first batch are shown in Figure 3.4.

Figure 3.3 Environmental Growth Chambers

Figure 3.4 Stored Samples

3.5 Test Methodology

The methodology adopted for determination of each of the physical characteristics and hydraulic characteristics are described in the following subsections.

3.5.1 Determination of Physical Composition

To get the physical composition of MSW each of the bags were emptied on large plastic sheets separately and the components were manually separated into the following categories: paper, plastic, food waste, leather & textile, wood & yard waste, metals, glass, styrofoam & sponge, construction debris and others. Figure 3.5 shows a bag sample before and after sorting. Similar illustrations of other bags can be found in the Appendix A.

Figure 3.5 Physical Composition of MSW

The 'paper' category consists of all sorts of papers including cardboard packaging, newspaper, magazines, office papers, etc. All plastic containers, PET bottles, food wrappers, polythene bags, etc were placed under the category of 'plastic'. Also, rubber was not sorted separately, instead grouped together with plastic. Apart from clothes, fabrics, leathers, etc., the insulation material deriving from construction & demolition was also categorized as ‘leather & textile’. The ‘wood & yard waste’ category contained, not only branches, leaves & grass from garden trimming, but also broken pieces of wood from construction & demolition. All sorts of metals including soda cans, cutlery and dry cells were put under ‘metal’ category. Construction debris constituted of dry walls, broken brick and stone chips, tiles, paints etc. Any portion of the solid waste that could not be placed under any of the above mentioned categories, lumps of mud, and objects too small to separate were categorized as ‘others’.

The sorted components were then individually weighed, and the weights were presented as a percentage of total weight. Also the total weight in paper, food waste, leather & textile, and wood & yard waste categories were considered degradable and the rest of the total weight as non-degradable. The percentages of degradable and non-degradable portions were also determined.

3.5.2 Determination of Moisture Content

For determination of moisture content, three types of specimen can be used:

1. Grab sampling before sorting
2. Proportionately taking each component according to physical composition after sorting
3. Taking standard proctor compacted sample (proportionate to composition)

For each bag, any two types of the above mentioned samples were used for moisture content determination. For each test minimum 2 lbs of waste were taken, so that it would be more representative of the original MSW. The measured samples were then dried at 105^{o}C in the oven for 24 hours to determine the moisture loss. And the percent loss was determined on both dry weight and wet weight basis. Equations 3.1 and 3.2 were used to determine moisture content on wet weight basis and dry weight basis respectively. Figure 3.6 shows sample being dried in the oven for the determination of moisture content.

$$MoistureContent\ (wet\ basis)(\%) = \frac{weight\ of\ moisture loss}{weight\ of\ moist\ waste} \times 100\% \qquad (3.1)$$

$$MoistureContent\,(dry\,basis)(\%) = \frac{weight\ of\ moisture\,loss}{weight\ of\ dry\,waste} \times 100\% \qquad (3.2)$$

Figure 3.6 Sample Placed in Oven for Determination of Moisture Content

3.5.3 Determination of Compacted Unit Weight

To determine compacted unit weight at natural moisture content, municipal solid waste was compacted as per Standard Proctor Compaction. A larger sized compaction mold with 6 inch inside diameter, 6.1 inch height, with a volume of 1/10 cubic feet with detachable collar was used. The mold was filled with three layers of solid waste up to the rim. A 5.5 lb hammer with 2 inch face was dropped 75 times for a fall height of 12 inch on each of 3 MSW layers to attain required compaction. The use of 75 blows instead of 25 was determined based on the compaction energy per volume.

$$Energy\ transferred\ in\ standard\ proctor\ test, E = n \times h \times \frac{P}{V}$$

Where, n = number of blows, h = fall height, P = weight of hammer and V = volume of the mold. P and h are equal for the regular sized and larger mold. For E to be same for both cases, n/V should be equal. As the volume of the mold (V) for the current study is three times larger, the number of blows (n) should also be three times more per layer.

Weight of mold was measured both before and after filling with waste. Equation 3.3 illustrates how to calculate compacted unit weight of solid waste. Figures 3.7 and 3.8 illustrate the sample preparation for unit weight determination.

$$UnitWeight\ (lb/ft^3) = \frac{weight\ of\ compacted\ waste\ inside\ mold\ (lb)}{Volume\ of\ mold\ (ft^3)} \tag{3.3}$$

Figure 3.7 Sample being Compacted at First Layer

Figure 3.8 Fully Compacted MSW in Compaction Mold

3.5.4 Determination of Permeability

Compaction permeameter with inside diameter 6 inches and a volume of 1/15 cubic feet was used to conduct constant head permeability test to determine permeability. As permeability is affected by density, all the tests were conducted at about the same density of solid waste. A density of 33.88 pcf was chosen based on the average unit weight found from the bag samples of first batch. Keeping 0.4 inches empty space at the top of the mold for the accommodation of porous stone and spring, rest of the space was uniformly filled with 2.26 lb of fresh MSW (Figure 3.9) to maintain the desired density with any amount of compaction effort that was required.

Figure 3.9 Measuring Sample for Permeability

Then the mold was carefully taken out from compaction base plate and was placed on permeameter base with porous stone and O-ring. Then the collar was removed and the porous stone and spring were placed on top of the compacted waste, as shown in Figure 3.10. Then the top plate was placed along with another O-ring and screwed very tightly, so that no water can seep out through the gaps. The entire setup is shown in Figure 3.11.

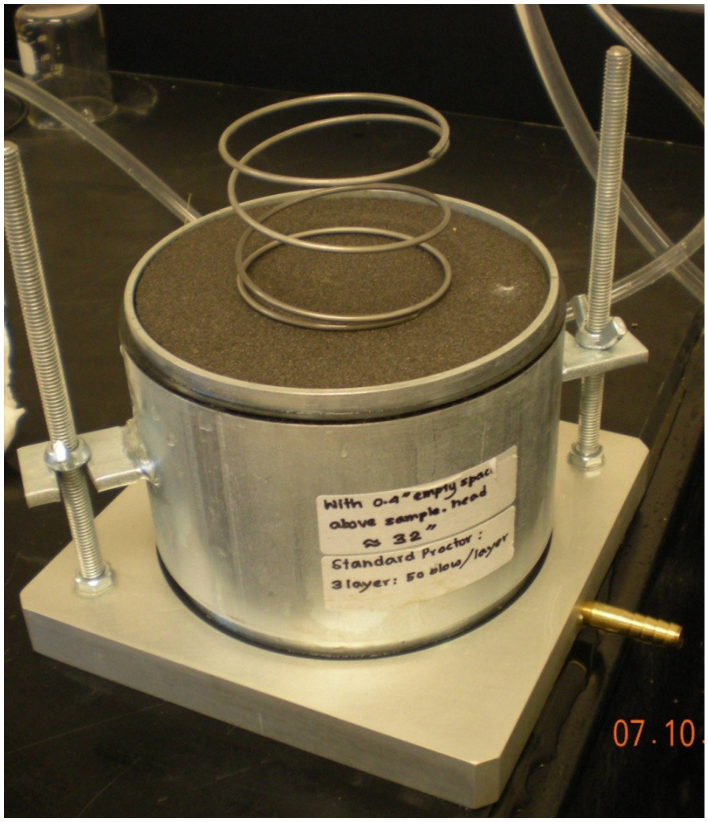

Figure 3.10 Permeability Setup (Partial)

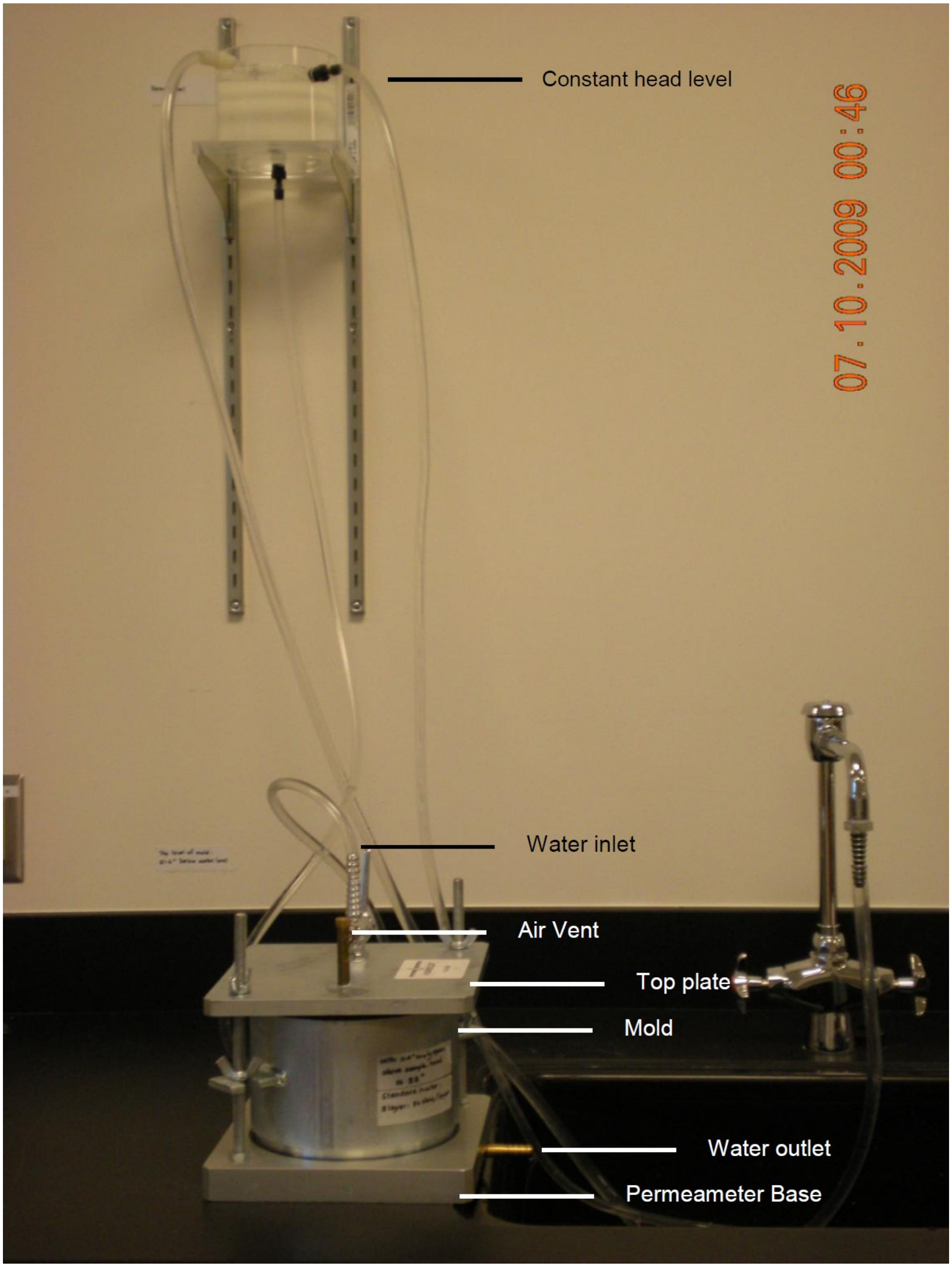

Figure 3.11 Entire Permeability Setup

The water was allowed to flow though the waste such that a constant head is maintained. For the current study, the head was maintained at 32 inches. The porous stones were soaked in water prior to the test and the whole set up was allowed to stand for at least 4 hours so that the waste is perfectly saturated and no air is entrapped. Then volume of water collected for a certain period of time was measured and permeability was calculated using Equation 3.4. For computation of accurate volume, the weight of the collected water was measured and then converted to volume using unit weight of water.

$$k = \frac{QL}{hAt} \tag{3.4}$$

Where, k = permeability (cm/s), Q = total flow collected in time t (cm^3), L = height of sample (cm), h = hydraulic head above sample (cm), A = cross-sectional area of sample (cm^2), t = time of collection for flow (sec).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

To achieve the objectives of the current study, municipal solid waste samples have been collected from the City of Denton Landfill, and have been tested in the laboratory following the procedures described in Chapter 3. The purpose of this chapter is to report the results found through laboratory tests.

4.2 Results

The test results for physical composition, degradable percentage, unit weight, moisture content and permeability for both sets of samples are presented in the following subsections. Set 1 represent the sample collected in May 2009, i.e., bag designations 1-a, 1-b, 1-c, 2-a, 2-b, 2-c, 3-a, 3-b, 3-c and 3-d. Set 2 comprises of the samples collected in August 2009. These are 4-a, 4-b, 4-c, 5-a, 5-b, 5-c, 6-a, 6-b, 6-c and 7-large.

4.2.1 Physical Composition

The physical composition of all 20 bags have been determined by manual sorting of MSW at natural moisture content and the results are tabulated in Table 4.1 and Table 4.2 Composition of each bag are based on at least 30 lbs of Solid waste.

The degradable and non-degradable percentage of each bag sample has also been calculated. The results are presented in Table 4.3 and Table 4.4.

Table 4.1 Physical Composition of Municipal Solid Waste (Set 1)

	Sample No.	Bag Designation	Physical Composition (% by weight)									
			Paper	Plastic	Food Waste	Textile & Leather	Wood & yard Waste	Metals	Glass	Styrofoam & Sponge	Construction Debris	Others (Soil & Fines)
Sample Set 1 (May 2009)	1	Bag 1-a	46.44	15.34	9.02	8.10	11.05	6.66	3.38		0.00	discarded
	2	Bag 1-b	55.36	30.29	2.26	1.09	0.65	8.21	0.59	1.55	0.00	discarded
	3	Bag 1-c	49.93	17.44	6.14	5.13	13.73	2.62	2.82	2.19	0.00	discarded
	4	Bag 2-a	54.38	24.10	2.77	5.82	5.22	5.93	0.32	1.45	0.00	discarded
	5	Bag 2-b	46.24	25.11	1.06	2.66	10.38	5.23	0.21	1.17	0.00	7.94
	6	Bag 2-c	40.81	17.83	2.09	2.51	14.00	4.30	0.53	2.60	0.00	15.33
	7	Bag 3-a	34.59	13.42	1.87	2.32	17.58	4.47	0.42	1.29	0.00	24.03
	8	Bag 3-b	44.77	17.23	3.01	1.63	5.53	6.12	0.51	0.66	0.00	20.55
	9	Bag 3-c	40.23	20.11	4.77	2.38	7.13	7.59	0.74	2.04	0.00	15.01
	10	Bag 3-d	47.78	11.75	1.32	11.30	2.22	7.77	1.61	0.93	0.00	15.32
		Average	46.05	19.26	3.43	4.29	8.75	5.89	0.86	1.54	0.00	16.36
		Standard Deviation	6.40	5.73	2.51	3.29	5.50	1.77	0.84	0.63	0.00	5.50
		Maximum	55.36	30.29	9.02	11.30	17.58	8.21	2.82	2.60	0.00	24.03
		Minimum	34.59	11.75	1.06	1.09	0.65	2.62	0.21	0.66	0.00	7.94

Table 4.2 Physical Composition of Municipal Solid Waste (Set 2)

	Sample No.	Bag Designation	Physical Composition (% by weight)									
			Paper	Plastic	Food Waste	Textile & Leather	Wood & yard Waste	Metals	Glass	Styrofoam & Sponge	Construction Debris	Others (Soil & Fines)
Sample Set 2 (August 2009)	1	Bag 4-a	54.52	8.99	1.82	1.06	9.32	0.12	1.27	0.61	0.15	22.14
	2	Bag 4-b	39.44	15.17	2.16	0.14	5.75	1.91	1.30	0.53	6.13	27.48
	3	Bag 4-c	20.28	23.64	1.76	3.66	5.81	7.52	0.93	0.67	4.53	31.21
	4	Bag 5-a	40.59	11.79	1.23	0.52	8.17	4.01	0.63	1.38	9.00	22.69
	5	Bag 5-b	25.07	11.40	3.15	1.43	6.23	7.47	1.21	2.74	9.47	31.84
	6	Bag 5-c	26.68	10.18	2.22	1.88	16.32	8.74	0.37	0.75	13.65	19.22
	7	Bag 6-a	38.80	19.38	3.39	2.44	13.30	4.05	1.33	0.83	1.71	14.76
	8	Bag 6-b	45.99	19.79	2.62	8.06	5.74	3.28	3.20	0.27	0.05	11.00
	9	Bag 6-c	25.65	19.91	5.51	16.34	6.23	4.62	0.51	0.97	3.09	17.18
	10	Bag 7-large	47.75	20.14	2.42	2.96	9.95	6.66	1.72	0.97	0.00	7.44
		Average	36.48	16.04	2.63	3.85	8.68	4.84	1.25	0.97	4.78	20.50
		Standard Deviation	11.45	5.15	1.20	4.93	3.64	2.73	0.81	0.69	4.71	8.21
		Maximum	54.52	23.64	5.51	16.34	16.32	8.74	3.20	2.74	13.65	31.84
		Minimum	20.28	8.99	1.23	0.14	5.74	0.12	0.37	0.27	0.00	7.44
Average for All 20 Bag Samples			41.27	17.65	3.03	4.07	8.72	5.36	1.18	1.24	4.78	18.95

Table 4.3 Degradable Composition of MSW (Set 1)

	Sample No.	Bag Designation	Physical Composition (By Degradability)	
			Degradable Percentage	Non-Degradable Percentage
Sample Set 1 (May 2009)	1	Bag 1-a	74.62	25.38
	2	Bag 1-b	59.36	40.64
	3	Bag 1-c	74.93	25.07
	4	Bag 2-a	68.20	31.80
	5	Bag 2-b	60.34	39.66
	6	Bag 2-c	59.41	40.59
	7	Bag 3-a	56.37	43.63
	8	Bag 3-b	54.93	45.07
	9	Bag 3-c	54.51	45.49
	10	Bag 3-d	62.62	37.38
		Average	62.53	37.47
		Standard Deviation	7.58	7.58
		Maximum	74.93	45.49
		Minimum	54.51	25.07

Table 4.4 Degradable Composition of MSW (Set 2)

	Sample No.	Bag Designation	Physical Composition (By Degradability)	
			Degradable Percentage	Non-Degradable Percentage
Sample Set 2 (August 2009)	1	Bag 4-a	66.72	33.28
	2	Bag 4-b	47.49	52.51
	3	Bag 4-c	31.51	68.49
	4	Bag 5-a	50.50	49.50
	5	Bag 5-b	35.88	64.12
	6	Bag 5-c	47.10	52.90
	7	Bag 6-a	57.94	42.06
	8	Bag 6-b	62.41	37.59
	9	Bag 6-c	53.72	46.28
	10	Bag 7-large	63.07	36.93
		Average	51.63	48.37
		Standard Deviation	11.60	11.60
		Maximum	66.72	68.49
		Minimum	31.51	33.28
Average for All 20 Bag Samples			57.08	42.92

4.2.2 Compacted Unit Weight

All the samples from both sample sets were tested for unit weight. The unit weights determined in this study are all for samples compacted by standard proctor compaction effort. The results obtained are presented in Table 4.5 and Table 4.6.

Table 4.5 Compacted Unit Weight of MSW (Set 1)

	Sample No.	Bag Designation	Compacted Unit Weight		
			pcf	kg/m3	KN/m3
Sample Set 1 (May 2009)	1	Bag 1-a	38.55	617.51	6.06
	2	Bag 1-b	37.50	600.69	5.89
	3	Bag 1-c	28.70	459.73	4.51
	4	Bag 2-a	33.90	543.03	5.33
	5	Bag 2-b	28.90	462.93	4.54
	6	Bag 2-c	27.60	442.11	4.34
	7	Bag 3-a	38.20	611.91	6.00
	8	Bag 3-b	38.25	612.71	6.01
	9	Bag 3-c	29.50	472.54	4.64
	10	Bag 3-d	37.65	603.10	5.92
		Average	33.88	542.63	5.32
		Standard Deviation	4.68	74.97	0.74
		Maximum	38.55	617.51	6.06
		Minimum	27.60	442.11	4.34

Table 4.6 Compacted Unit Weight of MSW (Set 2)

	Sample No.	Bag Designation	Compacted Unit Weight		
			pcf	kg/m3	KN/m3
Sample Set 2 (August 2009)	1	Bag 4-a	45.60	730.44	7.17
	2	Bag 4-b	50.55	809.73	7.94
	3	Bag 4-c	48.40	775.29	7.61
	4	Bag 5-a	31.90	510.99	5.01
	5	Bag 5-b	45.40	727.24	7.13
	6	Bag 5-c	33.90	543.03	5.33
	7	Bag 6-a	34.75	556.64	5.46
	8	Bag 6-b	26.40	422.89	4.15
	9	Bag 6-c	29.40	470.94	4.62
	10	Bag 7-large	31.95	511.79	5.02
		Average	37.83	605.90	5.94
		Standard Deviation	8.74	140.01	1.37
		Maximum	50.55	809.73	7.94
		Minimum	26.40	422.89	4.15
Average for All 20 Bag Samples			35.85	574.26	5.63

4.2.3 Moisture Content

At least two moisture content tests were conducted for MSW samples from each bag. The average values of the results are reported as the moisture content of that bag. The moisture content results are given in Tables 4.7 and Table 4.8.

4.2.4 Permeability

In this study, the permeability values of the bag samples were measured using constant head permeability test. The test specimens were prepared approximately at the same density. The results obtained are tabulated in Table 4.9 and Table 4.10. Also the actual densities at which the tests were conducted are mentioned.

Table 4.7 Moisture Content of MSW (Set 1)

	Sample No.	Bag Designation	Moisture Content (%)							
			Before sorting (uncompacted)		After sorting (uncompacted)		After sorting (compacted)		Average	
			Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis
Sample Set 1 (May 2009)	1	Bag 1-a	-	-	36.30	57.00	-	-	36.30	57.00
	2	Bag 1-b	40.60	68.34	35.80	55.76	-	-	38.20	62.05
	3	Bag 1-c	-	-	32.64	48.46	41.71	71.56	37.18	60.01
	4	Bag 2-a	42.79	74.79	39.53	65.37	-	-	41.16	70.08
	5	Bag 2-b	38.75	63.26	-	-	41.67	71.43	40.21	67.35
	6	Bag 2-c	42.98	75.37	-	-	42.21	73.04	42.60	74.21
	7	Bag 3-a	39.29	64.71	-	-	45.03	81.90	42.16	73.31
	8	Bag 3-b	-	-	32.74	48.68	35.25	54.44	34.00	51.56
	9	Bag 3-c	-	-	33.91	51.32	38.07	61.48	35.99	56.40
	10	Bag 3-d	-	-	48.10	92.69	47.94	92.09	48.02	92.39
		Average	40.88	69.29	37.00	59.90	41.70	72.28	39.58	66.43
		Standard Deviation	1.95	5.60	5.45	15.60	4.18	12.39	4.12	11.86
		Maximum	42.98	75.37	48.10	92.69	47.94	92.09	48.02	92.39
		Minimum	38.75	63.26	32.64	48.46	35.25	54.44	34.00	51.56

Table 4.8 Moisture Content of MSW (Set 2)

	Sample No.	Bag Designation	Moisture Content (%)							
			Before sorting (uncompacted)		After sorting (uncompacted)		After sorting (compacted)		Average	
			Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis	Wet Weight Basis	Dry Weight Basis
Sample Set 2 (May 2009)	1	Bag 4-a	43.76	77.81	39.08	64.15	44.55	80.36	42.46	74.11
	2	Bag 4-b	34.67	53.07	-	-	38.16	61.70	36.42	57.39
	3	Bag 4-c	37.34	59.60	-	-	44.97	81.73	41.16	70.67
	4	Bag 5-a	38.74	63.23	-	-	30.03	42.92	34.39	53.08
	5	Bag 5-b	24.60	32.62	-	-	35.98	56.21	30.29	44.42
	6	Bag 5-c	30.53	43.94	-	-	31.66	46.32	31.10	45.13
	7	Bag 6-a	35.79	55.73	-	-	34.05	51.64	34.92	53.69
	8	Bag 6-b	30.43	43.75	-	-	34.53	52.73	32.48	48.24
	9	Bag 6-c	36.75	58.11	-	-	31.57	46.13	34.16	52.12
	10	Bag 7-large	33.11	49.50	-	-	38.46	62.50	35.79	56.00
		Average	34.57	53.74	39.08	64.15	36.40	58.22	35.31	55.48
		Standard Deviation	5.28	12.41			5.19	13.63	3.95	9.91
		Maximum	43.76	77.81	39.08	64.15	44.97	81.73	42.46	74.11
		Minimum	24.60	32.62	39.08	64.15	30.03	42.92	30.29	44.42
Average for All 20 Bag Samples			36.68	58.92	37.26	60.43	38.58	64.01	37.45	60.96

Table 4.9 Permeability of MSW (Set 1)

	Sample No.	Bag Designation	Permeability		
			Permeability (cm/s)	At Density (pcf)	At Density (KN/m3)
Sample Set 1 (May 2009)	1	Bag 1-a	2.529E-03	33.83	5.32
	2	Bag 1-b	6.171E-03	33.90	5.33
	3	Bag 1-c	4.990E-03	31.20	4.90
	4	Bag 2-a	3.894E-03	34.35	5.40
	5	Bag 2-b	2.998E-03	33.15	5.21
	6	Bag 2-c	3.439E-03	33.95	5.33
	7	Bag 3-a	5.853E-03	33.83	5.32
	8	Bag 3-b	4.722E-03	33.83	5.32
	9	Bag 3-c	8.980E-03	-	-
	10	Bag 3-d	2.625E-03	33.87	5.32
		Average	4.620E-03	33.54	5.27
		Standard Deviation	2.000E-03	0.93	0.15
		Maximum	8.980E-03	34.35	5.40
		Minimum	2.529E-03	31.20	4.90

Table 4.10 Permeability of MSW (Set 2)

	Sample No.	Bag Designation	Permeability		
			Permeability (cm/s)	At Density (pcf)	At Density (KN/m3)
Sample Set 2 (August 2009)	1	Bag 4-a	3.123E-03	33.90	5.33
	2	Bag 4-b	3.287E-03	33.90	5.33
	3	Bag 4-c	1.887E-03	33.68	5.29
	4	Bag 5-a	1.967E-03	33.90	5.33
	5	Bag 5-b	1.649E-03	33.90	5.33
	6	Bag 5-c	1.201E-03	33.90	5.33
	7	Bag 6-a	2.625E-03	33.75	5.30
	8	Bag 6-b	3.622E-03	33.83	5.32
	9	Bag 6-c	1.244E-03	33.83	5.32
	10	Bag 7-large	2.858E-03	33.90	5.33
		Average	2.346E-03	33.85	5.32
		Standard Deviation	8.706E-04	0.08	0.01
		Maximum	3.62E-03	33.90	5.33
		Minimum	1.20E-03	33.68	5.29
Average for All 20 Bag Samples			3.483E-03	33.70	5.30

4.3 Analysis and Discussions

After the test results have been obtained, the average value for each of the physical and hydraulic characteristics have been determined. The average was determined both individually for sample sets 1 and 2 and also combined. The individual mean was determined to get an idea about whether there was any seasonal effect on the properties. The standard deviation from the mean was also computed to assess the level of variability.

4.3.1 Physical Composition

From visual inspection and also from the results, it was evident that “paper” (approximately 40%) is the main constituent of solid waste. Though by volume, plastic was as much as or sometimes even more than paper. But due to being lightweight and also due to having less water holding capacity than paper, the weight percentage was much smaller, about 17%. Food waste, though a very important ingredient of solid waste, was found to be of very small amount, on average only 3%. Another main component was the “others” group making about 19% of the total weight. This group contains mostly soil and other finer materials too fine to be hand-sorted. ‘Broken pieces of wood’ is another major ingredient found, and it makes about 9% by weight. Another observation was that, although “Styrofoam & sponge” was only about 1%by weight, as these are very lightweight materials, and the volume was much higher. The average composition of MSW for May, 2009 and August, 2009 are given in Figures 4.1 and 4.2 respectively. The physical composition of each bag sample from both sample sets are illustrated in Figure 4.3.

The results found from the last six bags of Sample set 1 indicate that the degradable portion was 55% to 60% by weight. The first 4 bags were not considered as the “Others” were discarded for those bags which will lead to misleading degradable percentage. For the sample set 2, the degradable percentage was lower and was about 52% on average. It is clear that the degradable portion was comparatively less for the second set. This is due to the fact that, in the second sample set, there was a lot of construction debris which were not present in the first set. The degradable composition is illustrated in Figure 4.4.

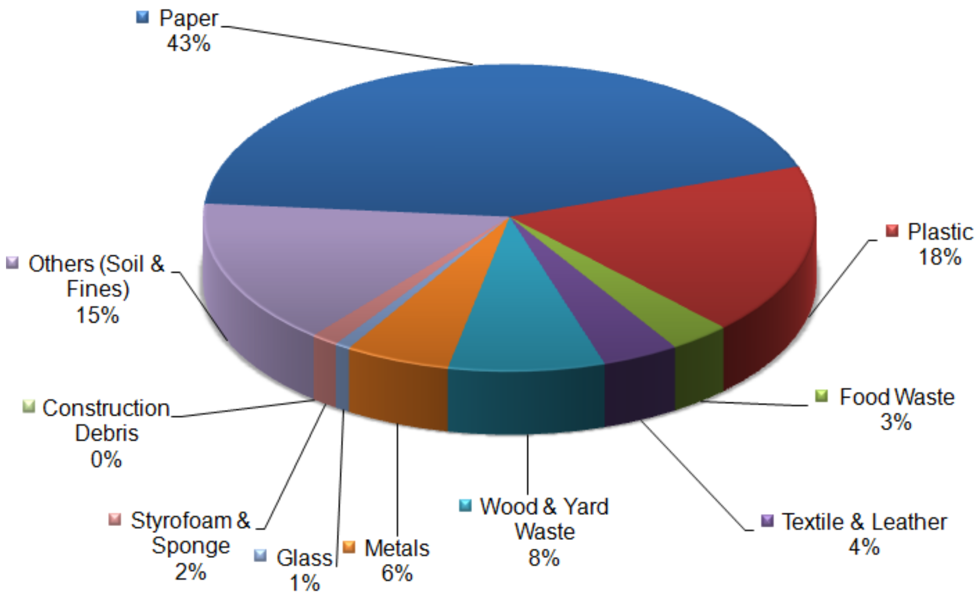

Figure 4.1 Average Physical Composition by Weight for Sample Set 1

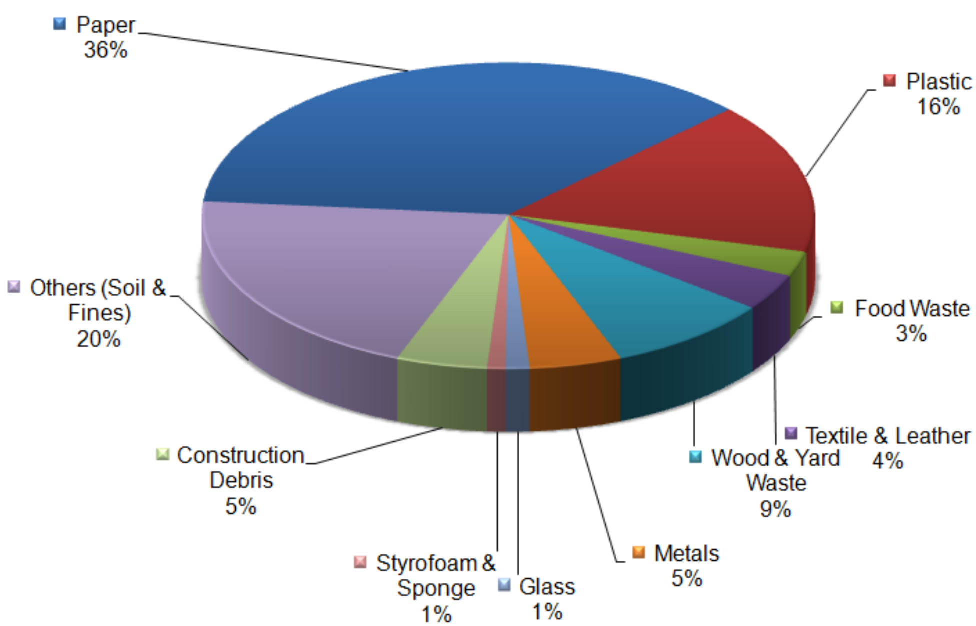

Figure 4.2 Average Physical Composition by Weight for Sample Set 2

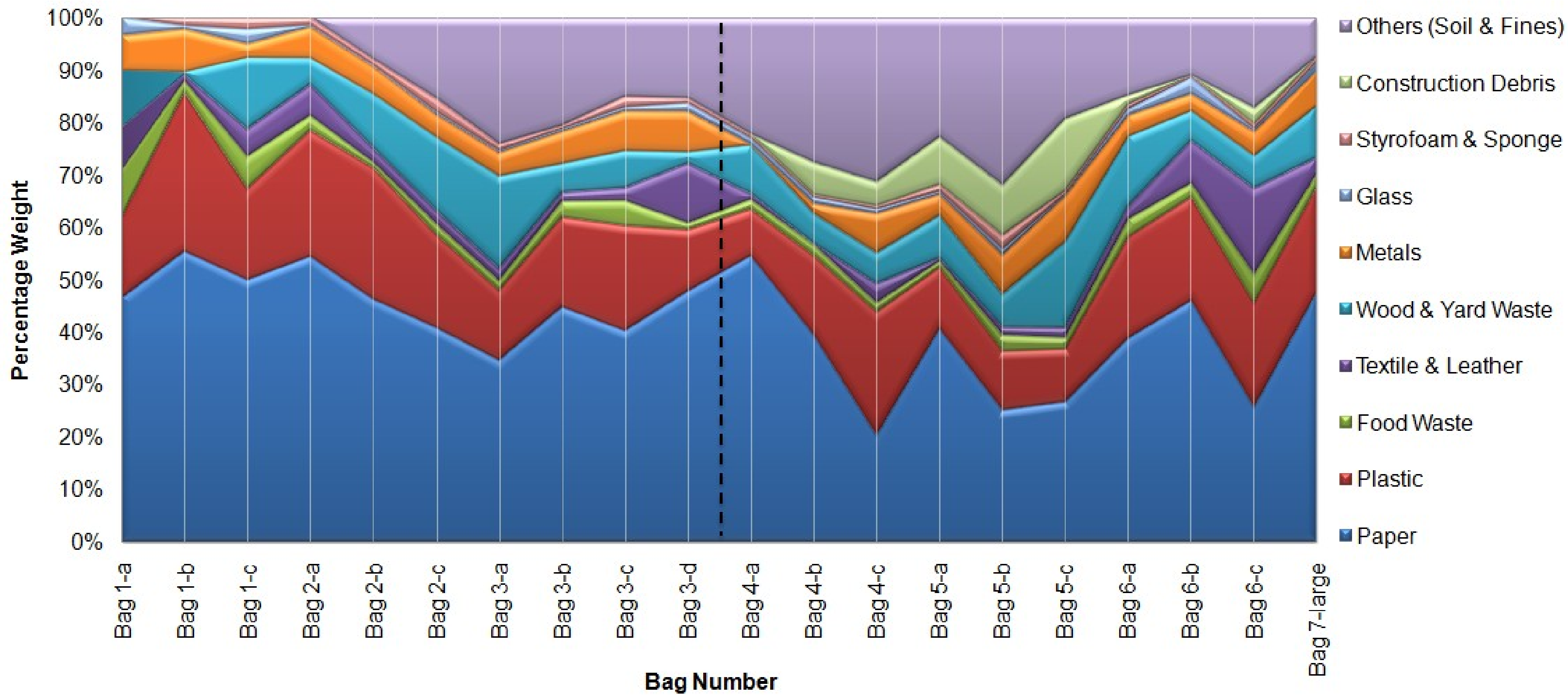

Figure 4.3 Physical Composition of All Bag Samples by Weight

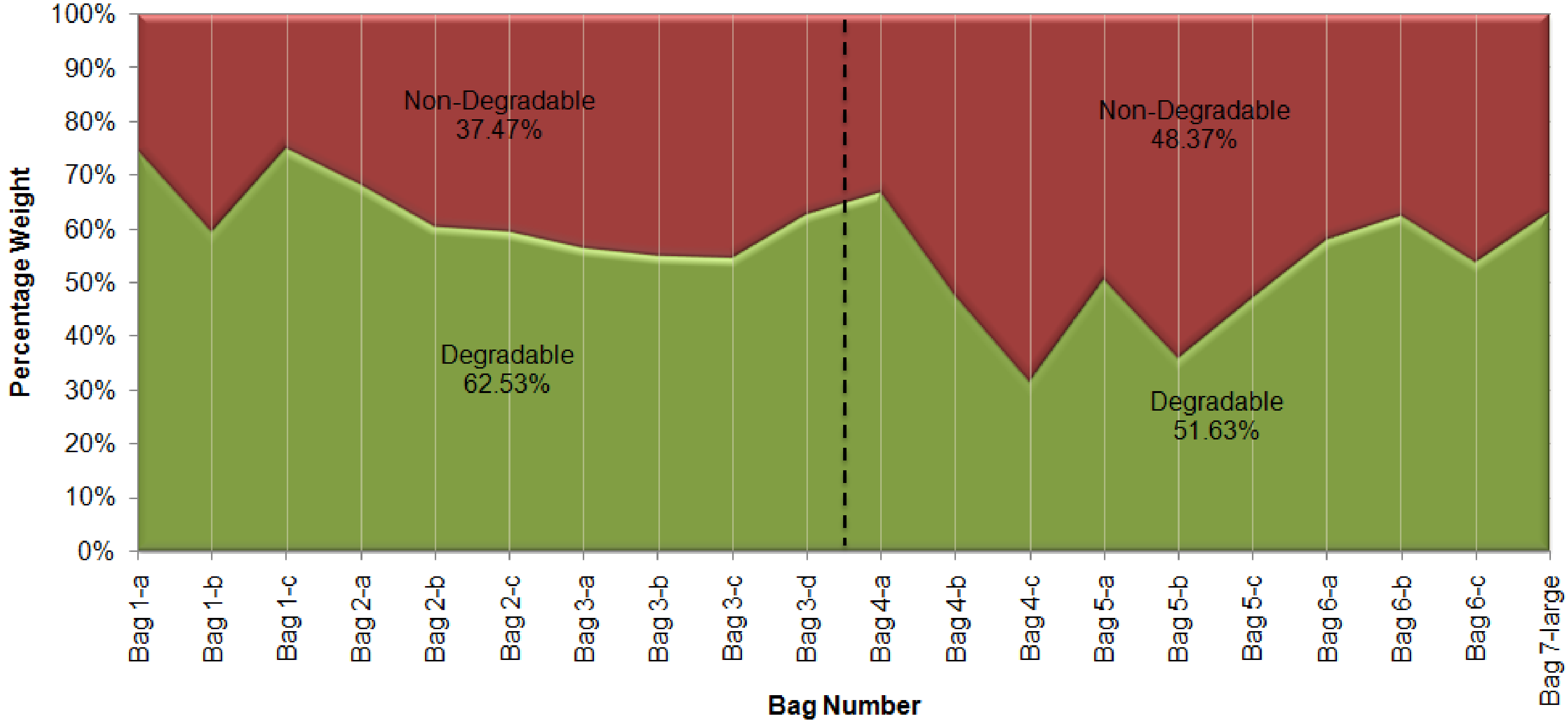

Figure 4.4 Degradable Percentages of All Bag Samples by Weight

4.3.1.1 Comparison to National Average

U. S. Environmental Protection Agency evaluates the average nationwide physical composition of solid waste on every two years. The MSW composition as available from their latest report of 2008 is summarized here in Table 4.11, which reports the waste of 2007. It will indicate how the composition found from current study compares to the national average. Also the composition of MSW of Texas for the year of 1993 (TNRCC 1995) is mentioned to assess the change in composition of MSW with time.

Table 4.11 Comparison of Physical Composition of MSW

Components	USA (USEPA 2008)	Texas (TNRCC 1995)	Present Study (2009)
	(%)	(%)	(%)
Paper	31.0	41.4	41.3
Plastics	12.0	8.3	17.7
Food scraps	12.7	10.2	3.0
Rubber, Leather & Textiles	7.9		4.1
Wood	6.6		8.7
Yard Trimmings	13.2	14.8	
Metal	8.4	7.2	5.4
Glass	4.9	4.8	1.2
Styrofoam & Sponges			1.2
Construction Debris			2.4
Household Hazardous Waste		0.6	
Others	3.3	12.7	15.2
Total	100.0	100.0	100.0
% Degradable	71.4	66.4	57.1
% Non-Degradable	28.6	33.6	42.9

Comparison of national average and present study indicates that, for the MSW of Denton, Texas, the amounts of both ‘Paper’ and ‘Plastic’ are more than those in the national average. The higher amount of paper is better for MSW if the landfill is operated as a bioreactor. Because in that case, paper being readily degradable and high in organic content, the chance of enhanced gas production rate will increase. On the other hand, paper being an absorbent material may necessitate increased amount of moisture addition and recirculation, as it can absorb moisture to itself making it unavailable to other components of the waste. But Plastic being more in amount will affect oppositely as plastic can be considered non-degradable. For plastic, there is little chance of gas production and consequent volume reduction. Again, although plastic may not absorb any water, but depending on size and shape may act as a barrier to the free movement of water within the solid waste mass. Another very important finding from the comparison is that the amount of food waste for MSW of Denton Landfill is very less as compared to both national average and that of Texas in 1993. As food waste is one of the main contributors to gas production, the reduction in the weight percentage may adversely affect the chances of gas production. The amount of 'Leather and Textile is slightly less in case of present study, but this is probably due to the fact that, rubber has also been included by EPA in this category, which in present study has been included in 'Plastic'. Wood accounts for about 8% and yard trimming about 13% in the national average, whereas for waste under study, the combination is only about 9%, which is considerably less. In fact, the amount of yard trimming in 'Wood & Yard Waste' category is very small and the category comprises mostly of wood. This indicates that the amount of wood is close for national average and MSW of City of Denton. Yard trimming is also putrescible and the lack may cause less landfill gas generation. The amount of 'Metal' and 'Glass' has also been found to be slightly less than EPA estimates. The category 'Others' contributes to a considerably larger portion in present study than EPA estimates. In current study, the 'Others' category contains mainly soil. But as EPA uses 'Materials Flow Methodology' instead of direct sorting, soils are not included there.

Again, the comparison of Texas (1993) data and present study shows that the percentage of 'Paper' in MSW has not changed over time. But the amount of 'Plastics' has almost doubled in 16 years. On the other hand, the percentage of Food Waste has drastically reduced in the municipal solid waste stream. The percentage of 'Glass' and 'Metals' has also decreased over time. The amount of 'Others' is a little higher in case of present study but the difference is not significant.

Computation of degradable percentage from the compositions shows that the percentage degradable is significantly less in MSW in question (57%) than the national average (71%) indicating lesser capacity of gas generation. Also the degradable percentage has decreased over time for Texas.

4.3.2 Compacted Unit Weight

For MSW of May 2009, the unit weight of the individual bag samples varied from 27.6 to 38.5 pcf. The average value was found to be 33.88 pcf with a standard deviation of 4.68 pcf. For the sample set of August 2009, the unit weight varied over a much broader range, from 26.4 to 50.55 pcf. Naturally the average value was also higher and stood at 37.83 pcf with a standard deviation of 8.74. This does not necessarily mean a seasonal variation, but can be easily explained. It was observed that the increase in percentage of "others" increases the unit weight, as these materials are heavy. The trend is shown in Figure 4.5.

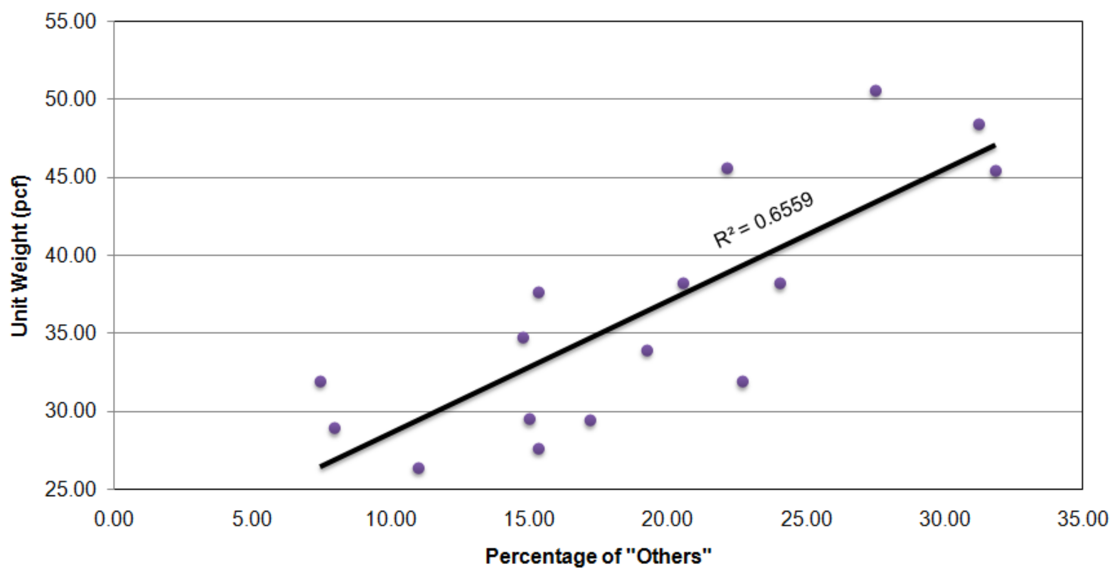

Figure 4.5 Trend of Change in Unit Weight with Percentage of "Others"

In case of first three bag samples of second set, this percentage was higher leading to higher unit weight for those bags, and consequently a higher mean value for the whole set. Besides, MSW being a highly heterogeneous material, the variation is not unexpected. Also, the range found complies with the unit weight values reported in literature. The compacted unit weight of MSW for all bag samples are illustrated in Figure 4.6. The overall average value for unit weight was found to be 35.85 pcf.

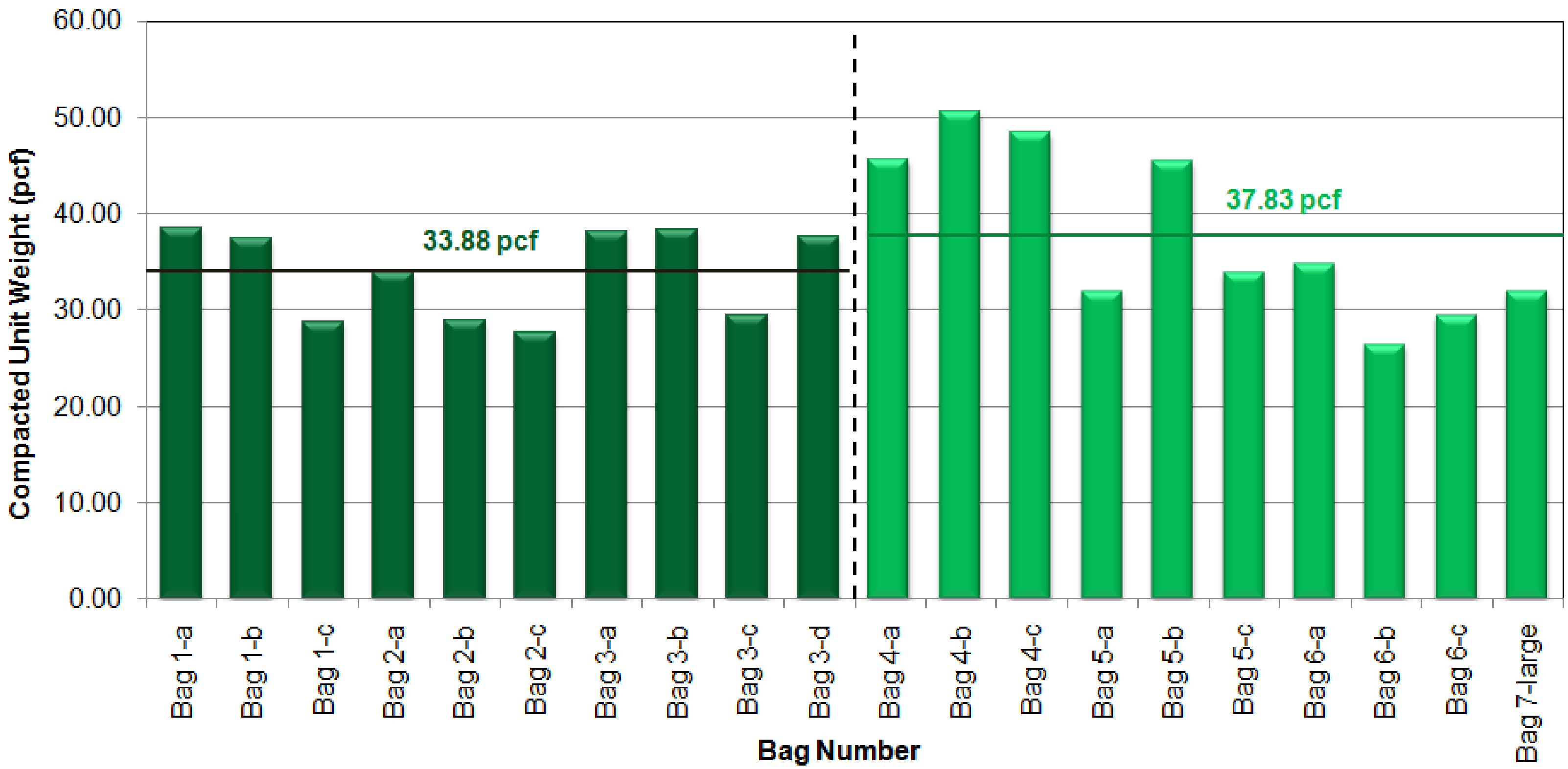

Figure 4.6 Compacted Unit Weight of All Bag Samples

4.3.2.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of unit weight of municipal solid waste. Some of the most important ones have been discussed in Chapter 2. The values suggested there are summarized in Table 4.12 and Figure 4.7.

Table 4.12 Summary of Unit Weights of MSW found in Literature

Source	Unit Weight		Conditions	Remarks
	lb/ft^3	KN/m^3		
Vesilind et al. (2002)	5.56 - 2.96	0.87 - 1.46	Trash Can (loose)	
	11.11	1.75	Trash Can (pushed)	
	22.22 - 25.93	3.49 - 4.07	Collection Truck	
	25.93-62.96	4.07-9.89	Landfilled (with cover soil)	
Gabr & Valero (1995)	47.09-52.18	7.4-8.2	14 to 30 years old waste	
Yousuf & Rahman (2007)	14.36	2.26	Wet Season	Dhaka City, Bangladesh
	14.98	2.35	Dry Season	
Reddy et.al. (2009)	37.46-38.71	5.89-6.08	Working face	Orchard Hills Landfill
Xiang-rong et. al. (2003)	50.91-106.91	8-16.8	Increases with depth	Tianziling Landfill, China
Landva & Clark (1990)	43.27-103.1	6.8-16.2		Canada
Hristovski et al. (2007)	8.77	1.38	Uncompacted	Residential waste of Veles, Macedonia
	13.92	2.19	Compacted	
Guermoud et al. (2009)	21.85-31.21	3.43-4.9		Developing countries
Elagroudy et al. (2008)	33.21	5.22	Initial Condition	Bioreactor Landfill
Chen et al. (2009)	31.82-95.46	5-15	Increases with depth	Qizhishan Landfill, China
Hettiarachchi et al. (2009)	31.21	4.9	Dry density	Bioreactor Landfill
	51.5-70.23	8.09-11.04	Wet density	
	70.23	11.04	25 year old waste at bottom of landfill	
Han et al. (2006)	40.45	6.36	At top, during landfilling	Sandtown Landfill, Delaware
	62.4	9.81	Average	

Table 4.12 - continued

Source	Unit Weight		Conditions	Remarks
	lb/ft^3	KN/m^3		
Maystre & Viret (1995)	4.99-7.49	0.78-1.18	Collection bag	Geneva, Switzerland
Sha'Ato et al. (2007)	17.92	2.82	household	Nigeria
	12.49	1.96	Non-household	
Hudson et al. (2004)	81.16	12.76	Raw domestic waste at 463 kPa effective stress	
	116.12	18.26	Aged domestic waste at 458 kPa effective stress	
Hazra & Goel (2009)	37.46	5.89		Kolkata, India
Hernandez-Berriel et al. (2008)	24.97	3.92		Mexico
Bleiker et. al. (1995)	42.76	6.72	At 21 kPa effective stress	
	83.97	13.19	At 441 kPa effective stress	
Oweis & khera (1986) (From Bleiker et. al. (1995))	70.04-80.28	11.01-12.62	Old waste	
	42.01	6.6	During active landfilling	
Sowers (1973) (From Bleiker et. al. (1995))	37.46	5.89		
Ham & Bookter (1982) (From Bleiker et. al. (1995))	28.59	4.49	At 1.2 m depth of refuse	
	30.65	4.82	At 1.4 m depth of refuse	
Lukas (1992) (From Bleiker et. al. (1995))	20.14	3.15	Poor compaction	
	40.08	6.3	Good compaction	
	60.12	9.45	Best compaction	
Gharabaghi et al. (2008)	56	8.8	open dump	Brazil
	93.55	14.7	Partially engineered	
Zekkos et al. (2005b) (From Zekkos et al. (2006))	19.09-127.28	3-20		

Table 4.12 - continued

Source	Unit Weight		Conditions	Remarks
	lb/ft^3	KN/m^3		
Kavazanjian (1995) (From Zekkos et al. (2006))	38.18	6	At surface	
	82.73	13	At 45 m depth	
Fassett (1993) (From Zekkos et al. (2006))	19.09	3	Poor compaction	
	108.19	17	Good compaction	
Dixon & Jones (2005)	19.09-57.28	3-9	Poor compaction	
	31.82-49.64	5-7.8	Moderate compaction	
	56-66.82	8.8-10.5	Good compaction	
	38.18-50.91	6-8		UK
	31.82-63.64	5-10		Belgium
	44.55	7		France
	38.18-44.55	6-7	Fresh	USA
	89.09-127.28	14-20	Degraded	
Oweis & Khera (1998)	17.82-29.91	2.8-4.7	Poor compaction	
	29.91-45.18	4.7-7.1	Moderate to good compaction	
	45.18-59.82	7.1-9.4	good to excellent compaction	
	35-66.82	5.5-10.5	Baled waste	
	40.73-66.82	6.4-10.5	Shredded and compacted	
	43.27-89.09	6.8-14		Canada
	42	6.6	Active landfill with leachate mound	
	29.27-40.09	4.6-6.3	Active landfill	Northeast US
Manassero et al. (1997)	19.09-89.09	3-14	possible range	
Fungaroli et al. (1979) (From Manassero et al. (1997))	7-25.46	1.1-4		
Koriates et al. (1983) (From Manassero et al. (1997))	54.73	8.6		

Table 4.12 - continued

Source	Unit Weight		Conditions	Remarks
	lb/ft^3	KN/m^3		
Manassero (1990) (From Manassero et al. (1997))	50.91-63.64	8-10		
Beaven & Powrie (1995) (From Manassero et al. (1997))	31.82-82.73	5-13		
Brandle (1994) (From Manassero et al. (1997))	57.28-108.19	9-17		
Present Study (2010)	26.4-50.55	4.15-7.94	Range for Fresh MSW	Denton, Texas
	35.85	5.63	Average	

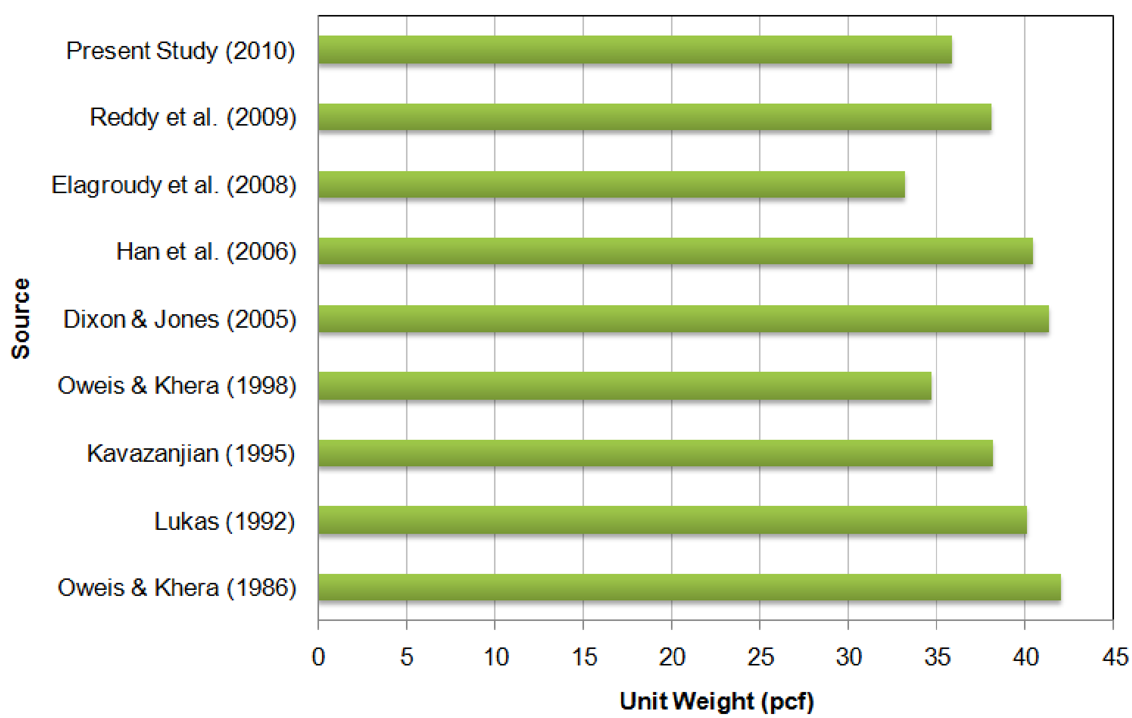

Figure 4.7 Unit Weight of Fresh MSW from Literature

The comparison from Table 4.12 shows that the results found from the present study closely complies with most of the previous studies conducted across US for fresh MSW from surface or active landfilling. The range suggested by Vesilind et al. (2002) is 26 to 63 pcf which is reasonably close to the range found here. The unit weight values for fresh MSW reported by Reddy et a. (2009) (37.5-38.7pcf), Elagroudy et al. (2008) (33.21 pcf), Hazra & Goel (2009) (37.46 pcf), Kavazanjian (1995) (38.2 pcf), Oweis & Khera (1998) (29.3-40.1 pcf) are very similar to the average value found. Also the average of 35.85 pcf is closest to the values reported for moderate compaction. This indicates that the fresh solid waste is medium dense. If the solid waste is too dense or over compacted, it helps to reduce volume in traditional dry-tomb landfill, but it can hamper the free movement of leachate though the waste mass of ELR landfills and may cause reduction in gas production.

4.3.3 Moisture Content

For the samples from first set, the moisture content on wet basis varied from 34 to 48%. The same for the second sample set varied from 30.29 to 42.46%. The average value for the first set was found to be 39.58% with a standard deviation of 4.12% and that for second set was found to be 35.31% with a standard deviation of 3.95%. Although the overall moisture content for the samples from August was slightly lower than that from May, 2009, the average values are actually quite close, the overall average being 37.5% by wet basis. The wide range of variation was also noticeable while sorting. MSW samples from some bags were comparatively dry and some bag samples were really moist. As the MSW comes from different types of areas (residential, commercial, institutional, etc.) in Denton Landfill, and also as different bags were collected from different places on the working face, the variation is possible. A bar chart showing the moisture content of all bag samples is given in Figure 4.8.

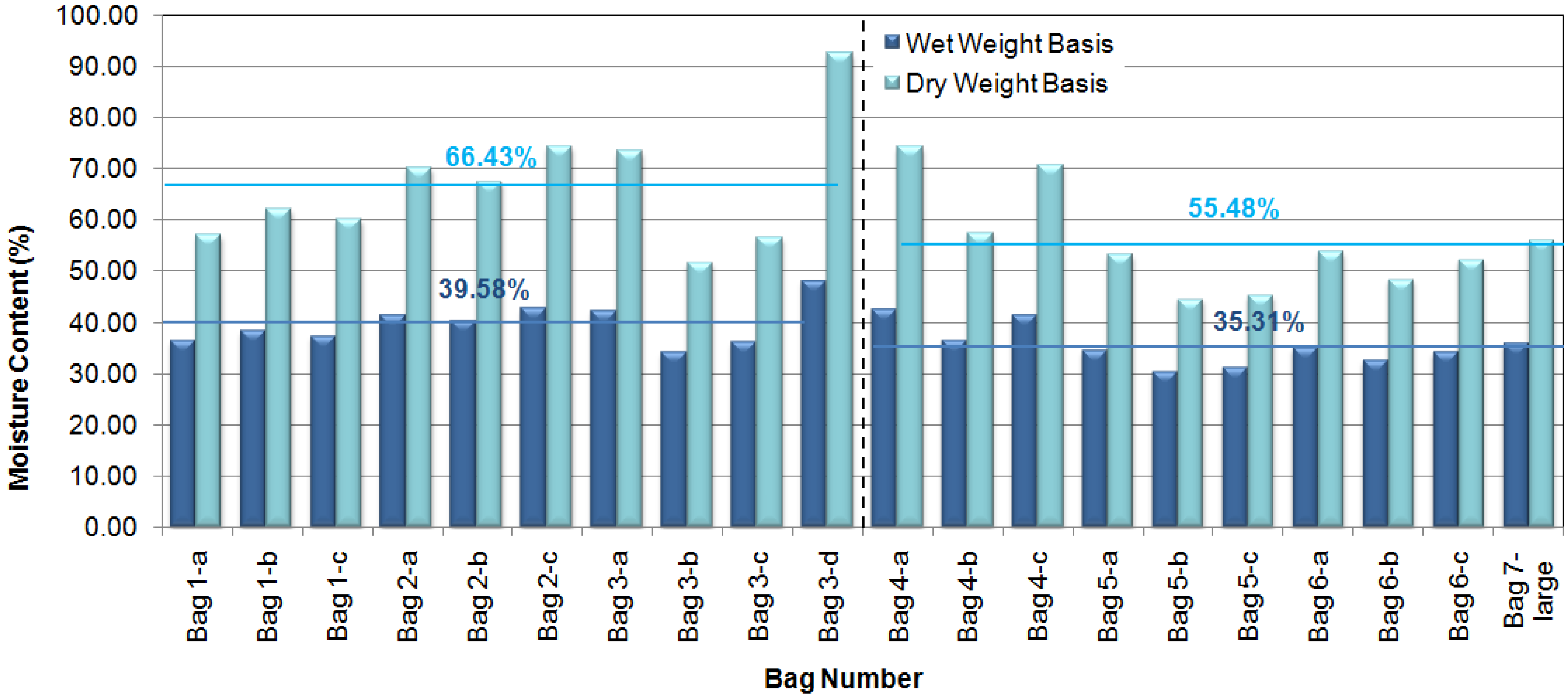

Figure 4.8 Moisture Content of MSW from All the Bag Samples

4.3.3.1 Comparison with Previous Studies

Numerous studies have been conducted in the past for determination of moisture content of municipal solid waste. Some of the most important ones have been discussed in Chapter 2. The values mentioned there are summarized in Table 4.13 and Figure 4.9.

Table 4.13 Summary of Moisture Content of MSW found in Literature

Source	Moisture Content (%)	Condition	Remarks
Vesilind et al. (2002)	20.0	Dry weather, w/w	
	40.0	Rainy weather, w/w	
Pichtel (2005)	15-40	w/w	USA
Gabr & Valero (1995)	30.0	At Surface	15 to 30 years old waste
	130.0	At greater depth	
Yousuf & Rahman (2007)	65-80	Fresh MSW	Dhaka, Bangladesh
Xiang-rong et al. (2003)	60-20	Decreases with depth	Tianziling Landfill, China
	30.0	Average	
Reddy (2009)	44.0	Working face, d/w	Orchard Hills
Landva & Clark (1990)	120.0	Maximum	Canada
Gomes et al. (2005)	61.0	Fresh Waste	Portugal
	117.0	3 years old waste	
Hogland et al. (2004)	30.0		
Sharholy et al. (2007)	25.9		Allahabad, India
Kumar et al. (2009)	17.7		India
Elagroudy et al. (2008)	67.0	Bioreactor	
Hettiarachchi et al. (2009)	5-30	Volumetric m/c of dry landfill	
	39.0	At bottom	
Zhen-shan et al. (2009)	61.2		Beijing
Han et al. (2006)	26.5	w/w	Sandtown, Delaware
Sha'Ato et al. (2007)	26.8	household w/w	Nigeria
	22.7	non-household w/w	
Hudson et al. (2004)	32.5	w/w	
Hazra & Goel (2009)	60.0		Kolkata, India
Sakai (1996)	46.0	w/w	Osaka, Japan
Bai & Sutano (2002)	30-60	w/w	Singapore
	46.8	average, w/w	
Abduli (1995)	52.7		Tehran

Table 4.13 - continued

Source	Moisture Content (%)	Condition	Remarks
Kumar et al. (2009)	23.0	Initial, Before recirculation	Bioreactor, Florida
	45.0	final, after recirculation	
Zekkos et al. (2006)	10-50	d/w	
Manassero et al. (1997)	15-40	typical	USA
	25.0	evapotranspiration >> precipitation	
	22.5	fresh uncompacted	
	55.0	1 to 5 years old	
Present Study (2010)	30-48	Range, w/w	Denton, Texas
	37.5	Average, w/w	

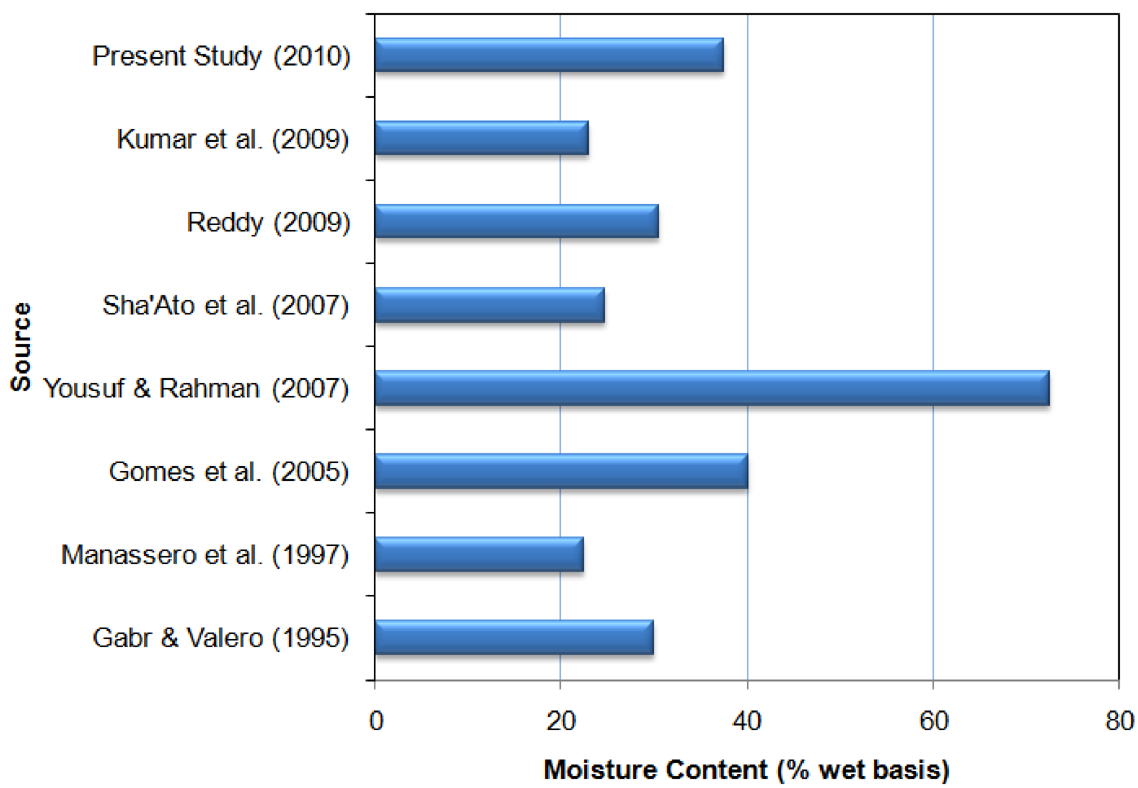

Figure 4.9 Moisture Content of Fresh MSW from Literature

The values for moisture content suggested by different researchers are widely varying. Pichtel (2005), Han et al. (2006), Manassero et al. (1997), Reddy et al. (2009) reported moisture content for fresh waste in USA. The values are mostly around 30% by wet weight basis. But, the moisture content of MSW found from current study is slightly higher (37.5%) than these published values. The higher moisture content as long as below the optimum moisture content can be helpful when the landfill is operated as a bioreactor. It can help reduce the amount of leachate recirculation required to attain the target moisture content. As in present case, the moisture is mostly trapped within the papers, and also as paper is the major degradable component of this MSW, it is expected to enhance gas production. Comparison of moisture content with other countries indicate that, for Asian countries, the moisture content is significantly higher (China (60%), India (60%), Bangladesh (65%), Japan (46%0, Singapore (47%), etc.) than the values found for USA and from current study.

4.3.4 Permeability

As permeability of any material depends on pore space, it is expected to be dependent on density of the material. Based on this notion, all the permeability tests were run at approximately the same density of MSW. As the fixed density, 33.88 pcf was chosen based on the average value of unit weight for first set of samples. Although, the average unit weight of second set of samples was slightly higher, the same value was maintained to keep consistency. The permeability for the MSW of sample set 1 varied over a wide range from 2.5×10^{-3} cm/sec to 6.2×10^{-3} cm/sec. The same from second set was less variable ranging from 1.2×10^{-3} cm/sec to 3.6×10^{-3} cm/sec. The overall average value of permeability from all 20 samples was found to be 3.5×10^{-3} cm/sec. For municipal solid waste, the permeability range of 10^{-2} to 10^{-4} cm/sec is most commonly found in literature. The results found in this study closely comply with the previously published data. The values found in the current study are graphically represented in Figure 4.11.

4.3.4.1 Comparison with Previous Studies

Various studies conducted for determination of have been discussed in Chapter 2. The values proposed by different studies as mentioned there are summarized in Table 4.14 and Figure 4.10.

Table 4.14 Summary of Permeability of MSW found in Literature

Source	Permeability cm/sec	Condition	Remarks
Oweis & Khera (1990)	$7x10^{-4}$	dense, 71 pcf	
	$15x10^{-3}$	loose, 35.8 pcf	
Gabr & Valero (1995)	10^{-3} - 10^{-5}		15 to 30 years aged waste
Hossain et al. (2009)	10^{-2} - 10^{-4}		Decreases with decomposition
Durmusoglu et al. (2006)	$4.7x10^{-4}$ - $1x10^{-3}$		Large scale test, 10 years old waste
	$2.35x10^{-4}$ - $1.24x10^{-2}$		Small scale test, 10 years old waste
Bleiker et al. (1995)	$8.1x10^{-3}$	21 kPa effective stress	
	$4.8x10^{-3}$	441 kPa effective stress	
Chen & Chynoweth (1995)	$9.6x10^{-2}$	10 pcf	
	$7.3x10^{-4}$	20 pcf	
	$4.7x10^{-5}$	30 pcf	
Dixon & Jones (2005)	10^{-5}	At surface	
	10^{-8}	At 60 m depth	
Reddy et al. (2009)	10^{-3} - 10^{-2}	Working face	Orchard Hills Landfill
	10^{-6}	40.6 pcf	
Xiang-rong et al. (2003)	$4x10^{-3}$ - $2x10^{-4}$		Decreases with time, Tianziling Landfill, China
Landva & Clark (1990)	$1x10^{-3}$ - $4x10^{-2}$	Excavation Pit	Canada
Manassero et al. (1997)	10^{-3}	Good approximation	
Oweis & Khera (1998)	$7x10^{-4}$	71.3 pcf	Baled Refuse
	$5x10^{-3}$	49 pcf	
	$3.5x10^{-3}$	52.2 pcf	
	$15x10^{-3}$	35.6 pcf	
	10^{-2} - 10^{-4}		Shredded Refuse
Present Study (2010)	10^{-3}	Range	
	$1.2x10^{-3}$ - $9x10^{-3}$	33.9 pcf	

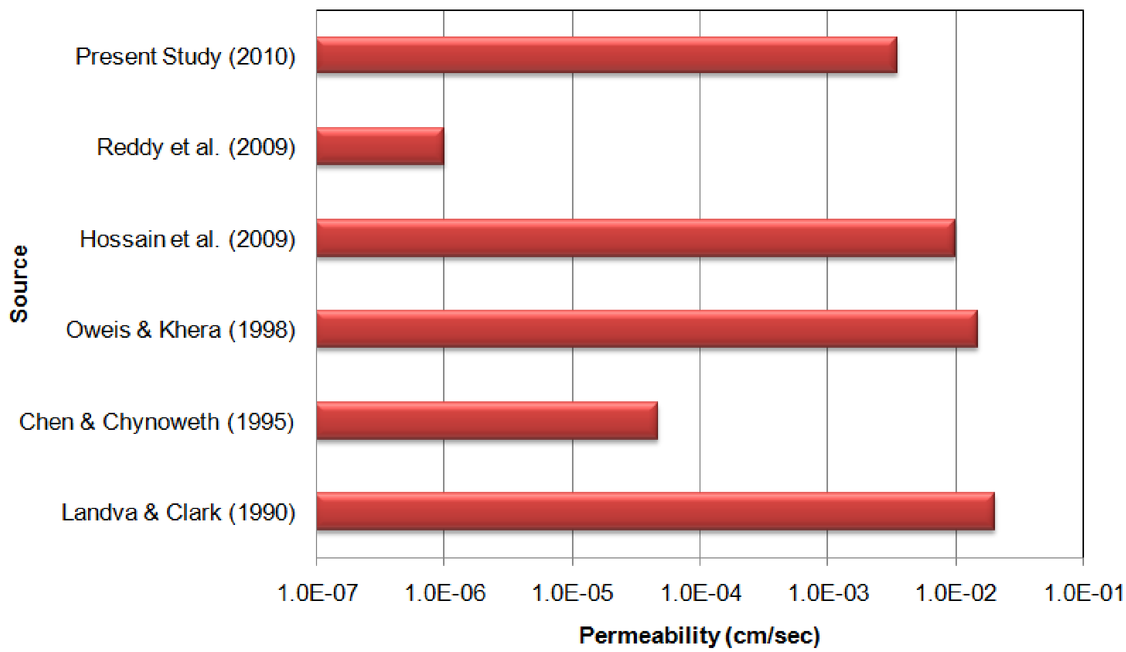

Figure 4.10 Permeability of Fresh Waste at 30 to 40 pcf Density from Literature

The values for permeability computed by laboratory testing were found to be in the region of 10^{-3} cm/sec for all twenty samples tested. From Table 4.14, it is clear that the finding from present study closely complies with most of the previous studies. This value is of high importance as it dictates the ease with which recirculated moisture might flow within the waste mass.

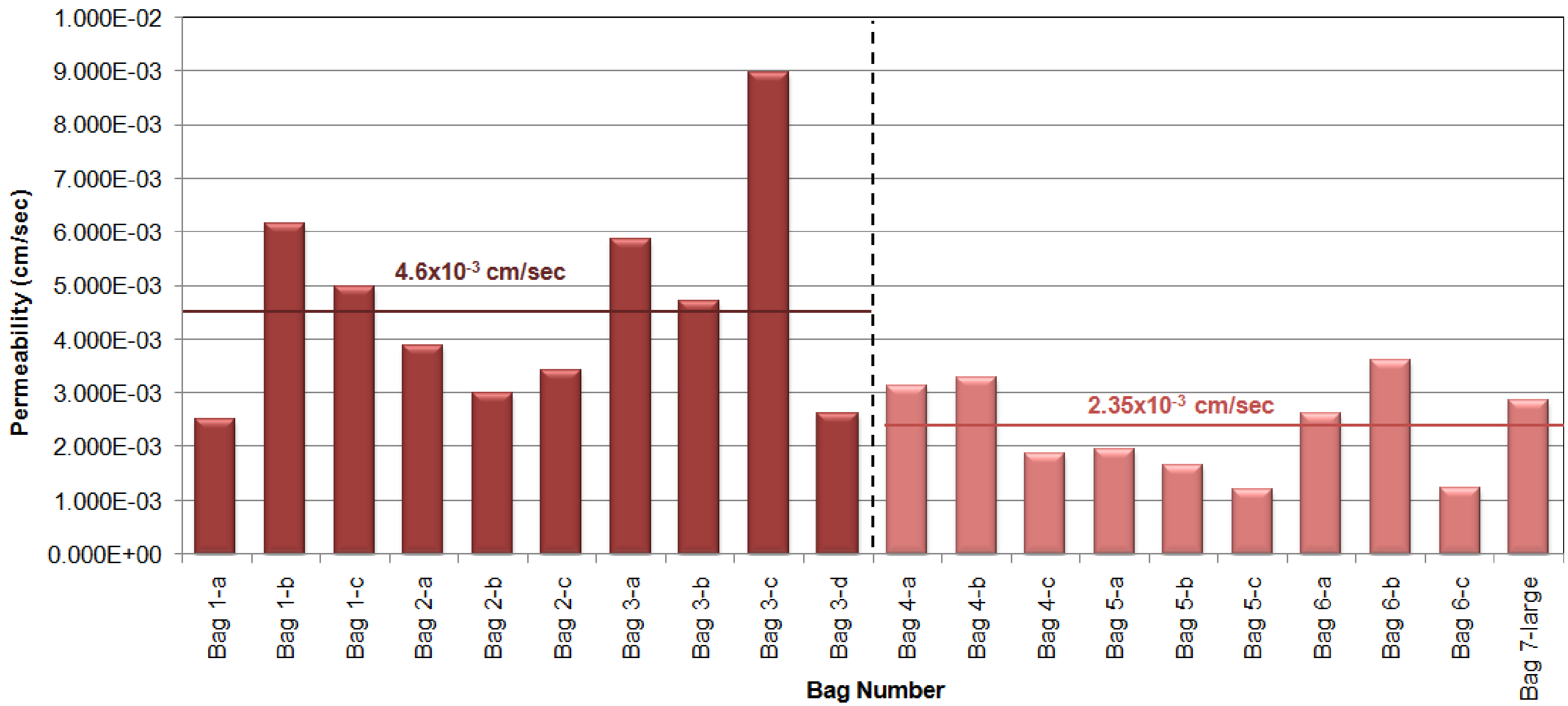

Figure 4.11 Permeability of MSW from All the Bag Samples

4.4 Determination of Number of Samples to be Sorted

Based on the approach of Sharma & McBean (2007), as mentioned in Chapter 2, initially 10 bags of sample were collected. During sorting the first set of samples, the change in 90% confidence interval range about mean with each additional sort was noted. For each waste category, these were plotted in a graph and can be found in Figure 4.12.

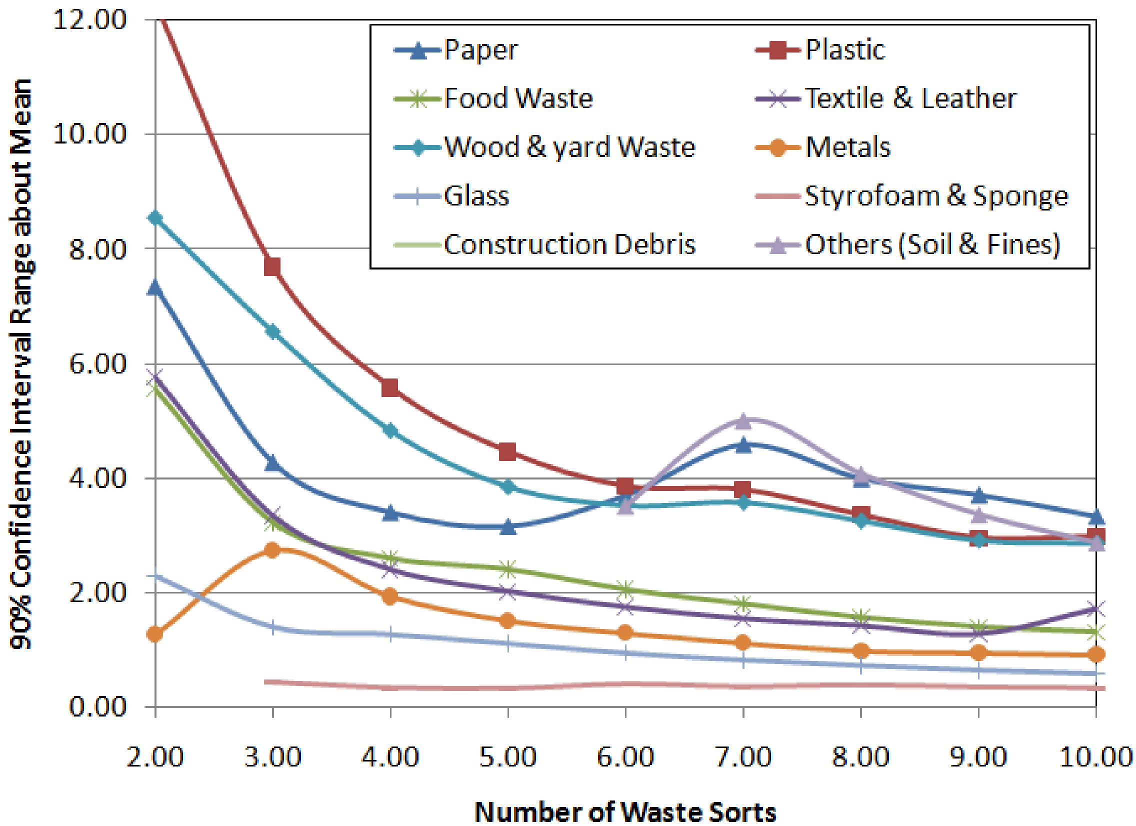

Figure 4.12 90% Confidence Interval about Mean vs. Number of Sorts for Sample Set 1

From the graph shown in Figure 4.12, it is clear that from the 6th sort, the rate of change in confidence interval decreases significantly, and after 9th sort it almost stabilizes. As minimum number of waste sort as recommended by Sharma & McBean (2007) is 10, selection of a sample size of ten bags is justified for the current study.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, municipal solid waste samples have been collected from the working face of City of Denton Landfill. The MSW samples have been collected twice, each time ten bags weighing thirty pounds each. The collected MSW samples were utilized to determine physical and hydraulic properties. These properties are: physical composition, compacted unit weight, moisture content and permeability. MSW is highly heterogeneous and region specific, the properties are expected to be different for different landfills. The properties determined from current study will help to have a better understanding of the solid waste coming to Denton Landfill. It will also help in determining best operational practices and leachate recirculation quantity during the lifetime of the landfill operation. Especially, the moisture content and permeability will help in operating the portion of the landfill that has currently been upgraded to enhanced leachate recirculation landfill.

5.1 Summary and Conclusions

The work completed for the present study can be summarized as follows.

1. Municipal Solid Waste samples have been collected from the City of Denton Landfill, TX two times: First time in May, 2009 and second time in August 2009. Each time 1 set of sample comprising of 10 bags weighing 30 lbs each has been collected.
2. Statistical analysis has been carried out with each additional sort to compute the reduction in 90% confidence interval about mean and it was found that, for this present case a sample size of 10 bags are expected to provide consistent results.
3. The composition of MSW has been determined by manual sorting for each bag individually. The overall average composition by weight of MSW has been found to

be: Paper (41.27%), Plastic (17.65%), Food Waste (3.03%), Textile & Leather (4.07), Wood & yard waste (8.72%), Metals (5.36%), Glass (1.18%), Styrofoam & sponge (1.24%), Construction debris (4.78%), and Others (18.95%).

4. The degradable and non-degradable percentage of the solid waste has been calculated based on the solid waste composition. On average, 57% of the solid waste is degradable and 43% is non-degradable.
5. The compacted unit weight has been determined for all the bags using standard proctor compaction. The average unit weights of first and second batch were found to be 33.88 pcf and 37.83 pcf respectively. The values are reasonably close. The average of all 20 samples was found to be 35.85 pcf (5.63 KN/m^3).
6. Moisture content has been determined for two specimens for each of 20 bag samples. The average moisture content for first sample set was 39.58% on wet weight basis. The same for the second set was 35.31%. The overall average moisture content was found to be 37.45% with a standard deviation of 4.5%.
7. The permeability was found to be consistent in range of 10^{-3} cm/sec for all 20 samples. The overall average permeability of the waste of Denton Landfill was $3.48x10^{-3}$ cm/sec at about 33.88 pcf of density.
8. No conclusive comment can be made on the seasonal variation from the computed results. The results of two sets are not off by a large amount. The differences are mainly due to heterogeneity of the material itself rather than time of the year.

5.2 Recommendations for Future Studies

To enhance the reliability of the results found and to make the current study even more effective, it is recommended that the work is further continued as mentioned in this section:

1. Municipal solid waste sample can be collected over two more seasons of the year (November and February) to make the results representative of the whole year.

2. The weight of collected MSW sample can be varied to monitor the effect of amount of sample collection on solid waste properties.
3. The study may be repeated every year for at least three years to develop a database. It will also help to recognize the trend of change in the MSW properties with time.
4. Sample can be collected directly from source or transfer stations in addition to that from landfill to study whether any impurities like soil get mixed with the solid waste.
5. Due to time constraint, other important properties such as grain size distribution, volatile organic content, compression indices, could not be determined in this study. Determination of these properties in the future would make the study more complete.

APPENDIX A

PHOTOGRAPHS OF SITE AND LABORATOTY WORKS

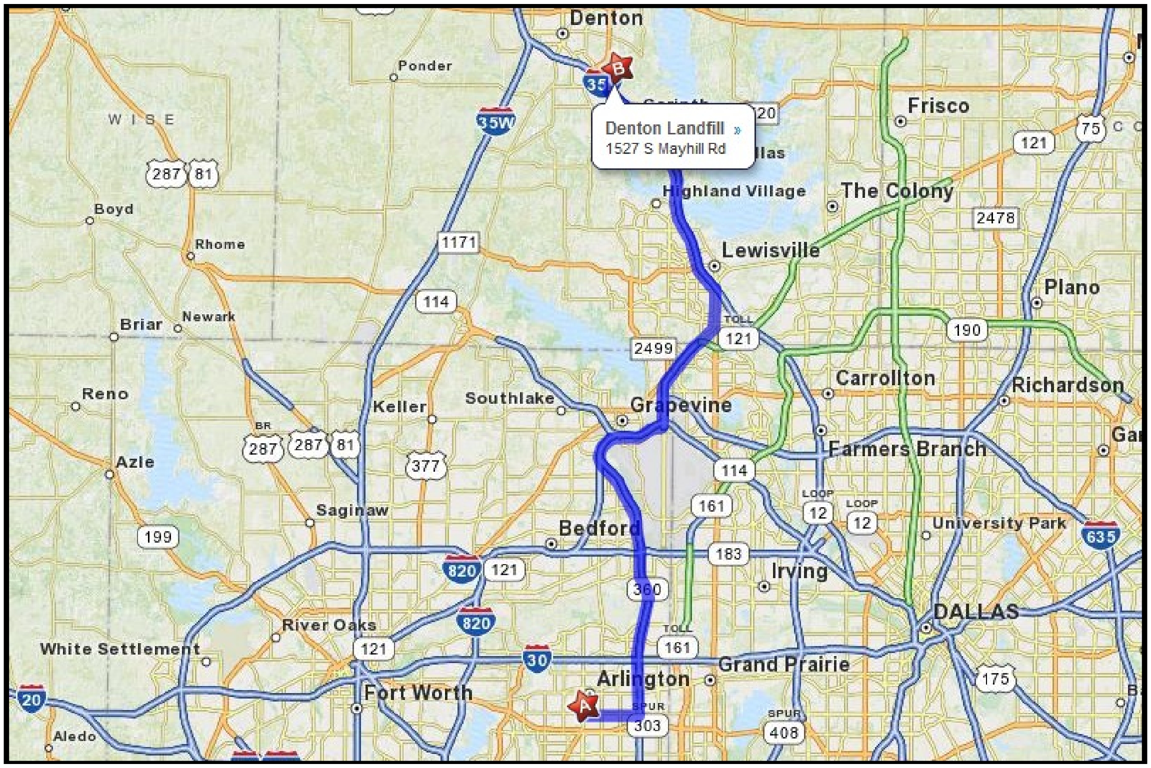

Figure A.1 Map to City of Denton Landfill, TX

Figure A.2 City of Denton Landfill, TX

Figure A.3 Sample Collection at Denton Landfill

Figure A.4 Sample Collection at Denton Landfill

Figure A.5 Sample Collection at Denton Landfill

Figure A.6 MSW Sample of Bag 3-b

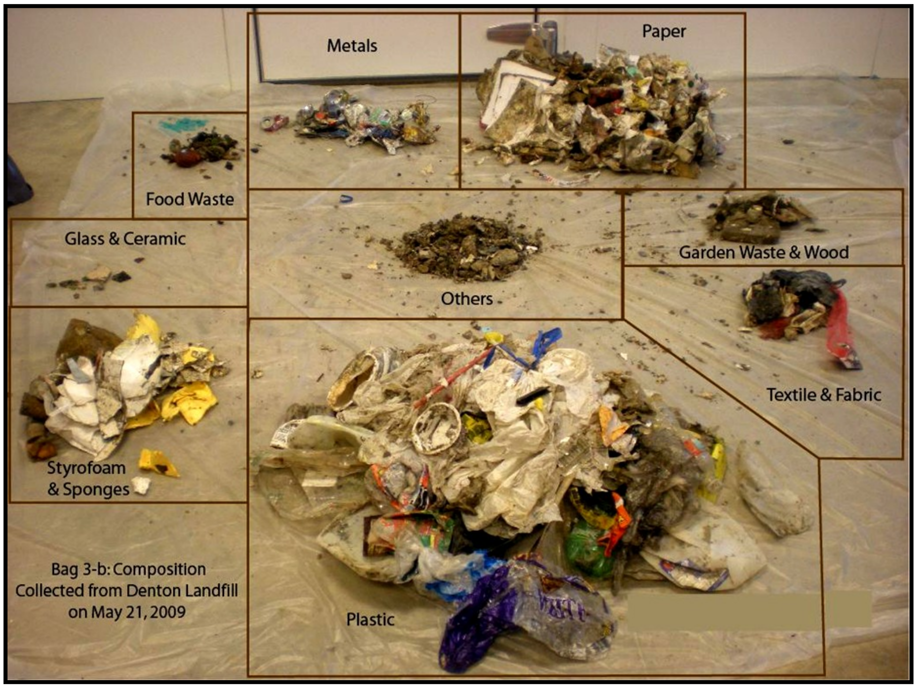

Figure A.7 Physical Composition of Bag 3-b

Figure A.8 Physical Composition of Bag 5-a

Figure A.9 Physical Composition of Bag 6-a

Figure A.10 Physical Composition of Bag 6-c

Figure A.11 Physical Composition of Bag 7-Large

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