DECOMPOSITION AND SETTLEMENT BEHAVIOUR OF MUNICIPAL SOLID WASTE

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DECOMPOSITION AND SETTLEMENT BEHAVIOUR OF MUNICIPAL SOLID WASTE

by

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LIST OF SYMBOLS

Symbol	Description	Unit
$c^{'}$	Stress	kPa
ϕ	Angle	Degree
$\Delta\sigma'_v$	Vertical effective stress	kPa
$\Delta\varepsilon_v$	Vertical strain	-
D	Constrain modulus	KN/m^3
δ_p	Primary compression of MSW	m
H_i	Thickness of sub layer	m
D_i	Constrain modulus of sub layer	KN/m^3
c_c	Primary compression index	-
c'_c	Modified compression index	-
Δe	Change in void ratio	-
σ_1	Final vertical effective stress	kPa
ΔH	Change in thickness of waste layer	m
H_0	Original thickness of waste layer	m
e_0	Initial void ratio	-
σ_0	Initial vertical effective stress	kPa
c_α	Secondary compression index	-
t	Time at which settlement due to secondary compression	s
t_p	Time for completion of primary compression	s
c'_α	Modified secondary compression index	-
t_1	Starting time of secondary settlement	s
t_2	Ending time of secondary settlement	s
$c_{\alpha(EL)}$	Coefficient of secondary compression due to external loads	-

$c_{\alpha(SW)}$	Coefficients of secondary compression due to self weight	-
ΔH	Total settlement (Sowers Method)	m
ΔH_p	Primary (short term) settlement	m
ΔH_s	Secondary or long term settlement	m
p_0	Initial overburden pressure	kPa
Δp	Incremental pressure	kPa
m	Settlement rate (Logarithmic function)	(1/day)
c	Strain rate parameters (Logarithmic function)	(1/day)
d	Strain rate parameters (Logarithmic function)	(1/day)
ρ	Settlement rate at unit time ((power creep function)	mm/s
w_d	Dry gravimetric moisture content	%
w_w	Weight of water	g
w_s	Dry weight of solid waste	g
n	Porosity of solid waste	-
e	Void ratio of solid waste	-
V_v	Volume of voids	m^3
V_s	Volume of solids	m^3
V_a	Volume of air	m^3
V_w	Volume of water	m^3
ε	Strain	-
G_s	Specific gravity	-
A	The plan area of the sample	m^2
γ_w	Unit weight of water	-
W_s	Mass of MSW	kg
c_v	Coefficient of Consolidation	m^2/s
T_{50}	Time factor 50% of consolidation	-
D_{50}	Deformation at 50% consolidation	m
t_{50}	Time to reach 50% consolidation	s

k	Coefficient of permeability	m/s
m_v	Coefficient of volume changes	m^2/kN
H_f	Final thickness	m
p	Positive empirical constant (power creep function)	-
q	Positive empirical constant (power creep function)	-
r	Correlation coefficient	-
S	Settlement	m
S_f	Final settlement	m
S_{ult}	Ultimate settlement	%

LIST OF ABBREVIATIONS

APHA	American Public Health Association
AWWA	American Water Works Association
BOD	Biochemical Oxygen Demand
CAP	Consumer Association of Penang
CH_3COOH	Acetic acid
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
FAU	Formazin Attenuation Unit
FTU	Formazin Turbidity Unit
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
K_2PtCl_5	Potassium chloroplatinate
MSW	Municipal Solid Waste
N_2	Nitrogen
NH_3-N	Ammonia nitrogen
NTU	Nephelometric Turbidity Unit
SM	Standard method
WPCF	Water Pollution Control Facility

PERILAKU PEREPUTAN DAN ENAPAN SISA PEPEJAL PERBANDARAN

ABSTRAK

Pemahaman terhadap perilaku enapan dan pereputan sisa pepejal perbandaran adalah sangat penting dalam mengurus sebuah tapak pelupsan sampah yang baik. Oleh sebab itu, kajian ini dijalankan untuk meningkatkan pemahaman terhadap enapan dan pereputan sisa pepejal perbandaran melalui permerhatian terhadap perilaku sisa secara individu di dalam makmal. Kajian ini dijalankan terhadap perilaku individu sisa kerana berdasarkan fakta menunjukan pada kebiasaannya sisa berada di dalam keadaan bercampur-aduk dan amat kompleks sekiranya dianalisa serentak. Lapan jenis sisa telah digunakan iaitu kangkung, nasi, ikan, daging, campuran kangkung dan ikan, campuran nasi dan ikan, campuran nasi dan kangkung, dan campuran sisa perbandaran. Sisa-sisa ini dimasukan ke dalam lysimeter selama 60 hari dan dikenakan tiga tekanan yang berbeza iaitu 1.936kPa, 3.872kPa, dan 5.808kPa. Keputusan ujian kemudianya digunakan untuk menganggar enapan sisa selama 1000 hari menggunakan tiga fungsi iaitu fungsi logaritma, fungsi kuasa menyusup, dan fungsi hyperbolik. Larut lesapan yang dikumpul pula diuji pada kadar pH, warna, kekeruhan, BOD, COD dan kandungan nitrogen ammonia. Setiap jenis sisa didapati mempunyai ciri-ciri perilaku enapan dan pereputan yang unik dan tersendiri. Keputusan kajian menunjukan enapan berlaku secara pantas pada peringkat awal bagi sebahagian besar sisa dengan kadar enapan yang mencecah sehingga 50mm/hari dan kemudianya menurun pada kadar 1mm/hari di penhujung eksperimen. Beban didapati salah satu faktor preputan dan enapan sisa tetapi tidak begitu signifikan berbanding jenis-jenis sisa dan tempoh enapan. Dalam menganggar enapan untuk jangka masa yang panjang, fungsi hiperbolik

menghasilkan anggaran terbaik berbanding dengan fungsi kuasa menyusup, dan fungsi logaritma. Keputusan ujian kualiti larut lesapan pula mendapati larut lesapan adalah jenis larut lesapan asli. Nasi didapati menghasilkan air sisa yang lebih berasid berbanding kangkung dengan purata pH sekitar 4. Larut lesapan yang dihasilkan oleh ikan didapati mengandungi nilai BOD yang tinggi pada sekitar 35000mg/l tetapi kandungan nitrogen ammonia yang rendah pada purata 3000mg/l. Walaubagaimanapun, larut lesapan yang dihasilkan oleh ikan adalah mengandungi COD yang tinggi sehinnga 25000mg/l. Semua sisa yang diuji menghasilkan kekeruhan larut lesapan yang sama pada purata 55000 FAU.

DECOMPOSITION AND SETTLEMENT BEHAVIOUR OF MUNICIPAL SOLID WASTE

ABSTRACT

Understanding the behavior of municipal solid waste settlement and decomposition is critical in managing a good landfill system. This study was conducted in order to develop understanding on MSW as it undergoes settlement and decomposition process through observation of individual waste behaviour in laboratory. The examination into the behaviour of individual waste was carried out due to the fact that real wastes are very heterogeneous and complex if it was to be analyzed at once. Eight types of waste namely Spinach, Rice, Fish, Meat, Spinach and Fish, Rice and Fish, Rice and Spinach, and Municipal mix were experimented. These wastes were fed into lysimeters for 60 days and subjected to 3 different stresses of 1.936 kPa, 3.872 kPa, and 5.808 kPa. The results were then used to predict waste settlement up to 1000 days using prediction functions namely logarithmic function, power creep function, and hyperbolic function. Collected leachate was tested for their pH, color, turbidity, BOD, COD, and nitrogen ammonia content. The results showed that each type of wastes had its own unique and individual decomposition and settlement behaviour. Rapid settlements occurred at the early stages for most types of waste with settlement rates up to 50mm/day before reduced to 1mm/day towards the end of the experiment. The applied stress was an insignificant factor unlike the type of waste and time in causing waste decomposition and settlement. In predicting the long term settlement, hyperbolic function produced the best prediction compared to power creep and logarithmic functions. Leachate produced by the test indicated that it was mainly raw leachate.

Rice produced leachate that was more acidic than that of spinach with an average pH of 4.0. Leachate from fish was high in BOD content around 35000mg/l, but relatively low in nitrogen ammonia content which was in average 3000mg/l. However, leachate from fish produced high COD contents that were up to 25000mg/l. All types of waste produced leachate of similar turbidity with an average value of 55000 FAU.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Open dumping at landfill is the most common method of municipal solid waste (MSW) disposal in developing countries. Landfill is an engineered waste disposal site facility that will continue to be chosen due to its simplicity and relatively cheap operation even when new methods of waste disposal are being introduced such as incineration and recycling. In Malaysia, MSW has been disposed off in landfill although some facilities have been not been properly presented and were simply open dump. A landfill is a very complex system in which various interactive processes work simultaneously.

The mass of waste in a landfill comprises of three main phases: solid, liquid, and gas. The solid phase includes waste and their respective cover, while liquid phase is made of the the infiltrating rainwater and leachate produced by MSW. Gas is produced as a result of microbial decomposition of waste material with its general composition consists of methane (CH_4), 50-60% by volume and carbon dioxide (CO_2), 40-50% by volume (Tchobanoglous et al., 1993; Durmusoglu et al., 2005).

As the amount of waste increases with rapid and continuing growth of economy and population, landfills become insufficient. .Such tremendous increase is primarily due to rapid urbanization, increase in population, improved living standards and change in consumption patterns (Adhikari, 2010). In peninsular Malaysia, the amount of waste produced has gone up from 16,200 tonnes per day in 2001 to 19,100 tonnes in 2005. Kathirvale et al. (2004) put it that percapita production of waste was 0.8kg for between 1994 to 1999. The national average for waste generations in 2003 was 4.5kg percapita per day (Sakawi, 2011).The amount for peninsular Malaysia is expected to reach 30,000 tonnes per day in 2020 (Manaf et al., 2009). The 9th Malaysia Plan has estimated that about 45% of the waste is made up of food waste, 24% plastics, 7% paper, 6% metal and glass, and others made up the rest (Mohamed, 2009).

Understanding the characteristics of settlement of municipal solid waste and the accompanying concepts of consolidation is critical in designing a good landfill system, maintaining various landfill facilities, and optimizing the extra landfill spaces for further filling (Swati and Joseph, 2008). Uncontrolled settlement may affect the integrity of landfill covers, liners, gas and liquid collection structures and drainages. Accurate prediction of landfill settlement is a challenge due to the large number of variables involved in the process. Estimation of settlement for MSW landfill is also critical for successful site operation and maintenance as well as for future development (Durmusoglu et al., 2005; Park Hyun et al., 2007; Elagroudy et al., 2008).

A landfill is always associated with generation of leachate. This liquid can cause considerable pollution once in contact with surrounding soil, ground, and surface water thus a problematic substance to deal with. Landfill leachate is one of the sources of highly contaminated and heterogeneous wastewater. Leachate often contains high concentrations of biodegradable and non biodegradable organic matters as well as inorganic ions (Ozkaya et al., 2006).

Leachate is produced during waste decomposition when the waste moisture content exceeds its field capacity or the maximum moisture that can be retained in a porous medium without the downward percolation. Leachate should be carefully treated before releasing it to the environment to prevent any possible pollution especially to surface and ground water sources. Today, there are many technologies (biological, physical, and chemical) being used to treat leachate. Leachate treatment is often difficult because of high organic content, irregular production rates and composition, variations in biodegradability, and low phosphorus content. The biggest constraint for successful treatment of the leachate is the difficulty in identifying the major compositions of any specific amount of the liquid. Waste is very heterogeneous in nature thus producing complex leachate composition.

1.2 Problem Statement

Many cities in developing Asian countries including Malaysia face serious problems in managing their solid waste. The increase in population has resulted in increasing daily human activities and thus the large amount of waste. The rise in waste generation is not only a technical problem, but also political, legal, socio cultural, environmental, and economical. The relationship between the given factors has caused challenges in waste management.

In Malaysia the popular and most common method to dispose solid waste is by landfilling but the increasing amount of waste is making the lifespan of these landfills shorter. The rapid development and high economic growth have caused suitable replacement landfill site for future disposal has depleted. Therefore, the available landfills should be optimally used. The two major problems most landfills have are settlement and leachate. Landfill capacity can be increased if the rate of settlement of waste is made to take placed quickly especially at the early stage of waste dumping. Unfortunately, actual landfill settlement goes on over an extended long period of time.

Many studies on the settlement of waste have been carried out. These studies have involved laboratory investigations, experimental lysimeters, numerical and physical model as well as field investigations (Ling et al., 1998; Youcai et al., 2002; Hossain et al., 2003; McDougall et al., 2004; Durmusoglu et al., 2006; Park et al., 2007; Sharma and Anirban, 2007; Elagroundy et al., 2008; Swati and Joseph, 2008; Hettiarachchi et al., 2009). The literature search has revealed that, most data were acquired from the behavior of complex mixture of municipal solid waste as dumped at landfill but scarce data have been generated from tests on individual waste. Therefore, there is a need for a series of data regarding waste settlement from studies carried on individual waste. Certain parameters on leachate generated by individual waste decomposition will be helpful in understanding fundamental waste behavior.

1.3 Objectives

The overall objective of the research is to develop an understanding on MSW as it undergoes decomposition and settlement process in landfill through observation of individual waste behavior in laboratory. A series of experimental work has been carried out to provide data on waste settlement and consolidation characteristics without having the leachate recirculated from waste material. The specific objectives for this study are:

1. To verify decomposition and settlement process behavior involving individual and simply mixed waste.
2. To determine the effect of various factors on rates of waste decomposition and settlement.
3. To predict long term settlement using prediction models.
4. To determine the quantity and quality of leachate.

1.4 Scope of study

The scope of study of this research includes a few tasks:

1. Constructing the waste consolidation and settlement model in laboratory
2. Monitoring and collecting data of waste settlement and leachate production from lysimeters models.
3. Testing for rate of leachate production and compositions.
4. Using of soil mechanic equation to predict primary and secondary settlements waste materials.

5. Transferring further the knowledge from the area of soil mechanics into the area of ‘waste mechanics’ such as in describing the process of consolidation.

1.5 Limitations of study

There were some limitations and assumptions that been used in the research such as:

1. The temperature inside of lysimeters was equal to the outside of the lysimeters (23^{o}C to 33^{o}C).
2. The experimental period was 60 days.
3. Inner diameter of lysimeters was assumed same with the outer diameter.
4. The leachate produce do not influenced by rainwater.
5. Leachate solely discharged from lysimeter into the leachate bottle.

1.6 Significance of study

This study is intended to simulate real condition from landfill site using laboratory experiments. The wastes used in the study are more ideal than the real ones thus helped in the understanding of the processes of consolidation. The experiments may help the prediction of settlement in real landfill sites and the resulting knowledge will be beneficial in the work of designing a good landfill system. This study will also involve a complete description of consolidation process including the use of related equations.

1.6 Thesis outline

Chapter 1, as introduction, describes basic information of waste settlement in landfill sites and the effects of settlement on landfill capacity. It also describes the statistical data of generation of waste in Malaysia in 2001 and 2005 and the predicted amount for 2020. The general idea about the objectives, scope of study, and significance of the research are also highlighted.

Chapter 2 discusses the literature review. A number of journals have been referred to in describing the background of idea, theory, and facts related to the study. The referred journal articles are on municipal solid wastes (MSW), landfills, settlement and consolidation, prediction functions, leachate and lysimeters. This chapter also explores some related studies with similar topics.

Chapter 3 describes research approach and methodology. It dwells on testing procedures which have been carried out in order to elaborate waste settlement processes and basic leachate characteristics.

Chapter 4 presents the results from laboratory tests and numerical analyses. It describes waste settlement and consolidation behavior as observed from lysimeters experiments. It also includes discussion of each presented result.

Chapter 5 concludes the thesis and puts forth recommendation should a future work is carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Limited understanding of waste behavior has caused researchers and practitioners to rely on knowledge of the behavior of soils when estimating the mechanical behavior of a landfill. Although this has been helpful to some point, there is an increasing realization that behavior of waste should be considered separated from soil. An increasing numbers of researchers are investigating behavior of waste and its interaction with engineered containment systems. Continuation of research and measurement can lead to the development of laboratory and field test solely for the purpose of obtaining engineering properties of municipal solid waste. Evaluating the engineering properties and hence the behavior of MSW bodies is challenging due to the variety of materials present. At the same time, due to the lack of classification system and test standards it is difficult to interpret published results and often leads to a waste test not described in full and the test boundary conditions not stated.

Previous experiments and studies on waste settlement and leachate characteristics have been reviewed and are summarized in this chapter. These are studies arranged in several sections and in order namely; (a) municipal solid waste; (b) landfill; (c) compressibility of MSW; d) waste settlement prediction (e) leachate characteristic and testing; and (f) lysimeter. The summary focuses on definition, theory, existing data and other related information.

2.2 Municipal Solid Waste (MSW)

Definition of MSW can be subjective where waste can be said as the garbage, refuse and unwanted solid material arising from human and animal activities that normally solid and described as useless or unwanted (Adhikari, 2010). Dixon and Jones (2005) defined that MSW is a mixture of wastes that are primarily of residential and commercial origin which is disposed of by or on behalf of a local authorities. Typically, MSW consists of food and garden wastes, paper products, plastics, rubber, textiles, woods, ashes, and soils (both waste products and material used as cover material). Some of the constituents are readily biodegradable, others are slowly biodegradable and some are not degradable. Food waste represent 32% of the waste composition in Malaysia is an important constituent of the solid waste that showed its unique degradation properties. The fraction of components and composition in MSW may vary one country to another country as the lifestyle, legislation, seasonal variation, pre-treatment and recycling rates are different (Dixon and Jones, 2005; Durmusoglu et al., 2006). Waste composition also reflects the economic situation of the country, the available income of its population and their consumer behaviour (Münnich et al., 2006). The waste compositions of various Asian countries are stated in Table 2.1. The variety of waste compositions also causes significant differences in the required waste engineering.

Statistically, generation rate of MSW in Malaysia varies between 0.88 and 1.44kg/day depending on the economic status of the area and this figured is expected to increase continuously as the number of population grows (Idris et al., 2004). The capital city, such as Kuala Lumpur generates 2500 tons of waste per day or 1.5 kg per capita per day, meanwhile smaller city such as Johor Bharu producing daily waste of 1300 tons per day. By the year 2020, the quantity of solid waste generated is expected to top 30 million tons (Manaf et al., 2009). Table 2.2 shows the predicted waste generation in Kuala Lumpur from year 2008 to 2024 taken after Saeed et al. (2009).

Table 2.1 MSW composition of Asian countries (after Idris et al. (2004)

Component (% by weight)	China 1998	India 1995	Indonesia 1993	South Korea 2001	Philippines 1999	Turkey 2000	Japan 2000
Organic matter	67.3	41.8	70.2	32.8	49	43	34
Papper and cardboard	8.8	5.7	10.9	23.8	19	7.8	33
Plastics	13.5	3.9	8.7	-	17	14.2	13
Glass	5.2	2.1	1.7	2.8	-	6.2	5
Metals	0.7	1.9	1.8	-	6	5.8	3
Others	4.5	44.6	6.2	40.6	9	23.1	12

Table 2.2 Predicted waste generations in Kuala Lumpur (after Saeed et al. (2009)

Year	Population of KL (millions)	MSW Generation (Kg/Cap./day)	MSW Generation (tons/day)	MSW Generation (tons/year)
2008	2.34	1.62	3798.88	1383642.0
2010	2.53	1.69	4274.86	1560323.9
2012	2.74	1.76	4810.49	1755828.9
2014	2.96	1.83	5413.23	1975828.9
2016	3.20	1.90	6/91.49	2223393.9
2018	3.46	1.98	6854.73	2501976.5
2020	3.75	2.06	7713.61	2815467.7
2022	4.05	2.14	8680.09	3168232.9
2024	4.38	2.23	9767.68	3565203.2

2.2.1 Engineering properties of Municipal Solid Waste

Knowledge of the engineering properties of waste materials is critical in the analysis and design of landfills for the municipal solid waste (MSW) to meet the long term performance especially due to landfill safety and operational cost. Unfortunately, MSW is very heterogonous in nature that makes it difficult to determine its properties. Lack of both standards for classification and test also increases the difficulty in determining MSW engineering properties. The geotechnical properties of MSW are prime importance for design and maintenance of any type of landfill (Reddy et al., 2009).

There are several important engineering properties in describing the MSW that have been intensively studied namely, unit weight (Landva and Clark, 1986; Kavazanjian et al., 2001; Gotterland et al., 2002), moisture content (Fasset et al., 1994; Kavazanjian et al., 2001), porosity (Koerner, 1990), hydraulic conductivity (Qian et al., 1994; Durmusoglu et al., 2006), field capacity (Tchobaglous et al., 1993), shear strength (Hossain et al., 2002; Qian et al., 2002), and compressibility (Dixon and Jones, 2005; Durmusoglu et al., 2006; Swati and Joseph, 2008; Elagroundy et al., 2008; Hettiarachchi et al., 2009). Table 2.3 summarizes the typical values of engineering properties of MSW as a produced by number of researchers.

Table 2.3. Typical MSW engineering properties values

Engineering Properties	Measured values	Measured conditions	References
Unit weight	6-7 kN/m^3 14-20 kN/m^3 4.7-9.4 kN/m^3 9-13.2 kN/m^3	Fresh MSW Old MSW Sanitary refuse: depending on compaction efforts Refuse landfill	Kavazanjian, 2001 Kavazanjian, 2001 Sowers, 1968 Landva and Clark, 1986
Moisture content	15%-60% 2%-8%	Organic material Inorganic material	Qian et al., 2002
Porosity	0.49-0.62	-	Zornberg at al., 1999
Hydraulic conductivity	$1.0x10^{-3}$-$4.0x10^{-3}$ $9.2x10^{-3}$-$1.1x10^{-3}$	Test pits Estimated based on field data	Landva and Clark, 1986 Qian et al., 2002
Field capacity	55%	-	McBean et al., 1995
Shear strength	$c' = 10kPa\ \phi = 23^o$ $c' = 19kPa\ \phi = 42^o$ $c' = 23kPa\ \phi = 24^o$	Suggested values by authors Old refuse Fresh, shredded refuse	Fasset et al., 1994 Landva and Clark, 1986 Landva and Clark, 1986

Note: Field capacity is the residual volumetric water content after a prolonged period of gravity drainage

2.3 Landfill

Open dumping at landfills less proper or dump sites is the most common method of MSW disposal in developing countries. Landfilling is still considered as the most cost effective method even though new ways of waste disposal being introduced such as incineration and recycling (Elagroundy et al., 2009). A landfill allows disposal of large quantities of MSW at an economical cost. The continuation of usage landfill mostly due to convenience even it shows some adverse environmental effect. Landfills are very complex system in which various interactive processes working simultaneously. The mass of waste in a landfill comprises three main phases: solid, liquid, and gas. The solid phase includes waste and their respective cover, meanwhile the liquid phase is the infiltrating rainwater and leachate produced by MSW. Gas phase is generated as a result of microbial decomposition of waste material with general composition contains of methane (CH_4) (50-60% by volume) and carbon dioxide (40-50%) (Tchobanoglous et al., 1993; Durmusoglu et al., 2005).

However, as the amount of waste is increasing with the rapid and continuing growth of economy and population, the land available for landfilling becomes scarce. Understanding the characteristics of municipal solid waste (MSW) is critical in designing good landfill system, maintaining various landfill engineering components and facilities and optimizing the extra space for further filling of MSW (Swati and Joseph, 2008). Uncontrolled landfill settlement may affect the integrity of landfill covers, liners, gas and liquid collections and drainages (Durmusoglu et al., 2005). Table 2.4 projected the total waste disposed at landfill site even when there are alternative methods being introduced.

In Malaysia, the disposal of solid waste is done almost solely through landfill method. In 1988, there were 230 official dumping sites in Malaysia and about 49 sites are landfill. By the year 2002, there are 161 disposal sites are actively operated in Peninsular Malaysia (Sakawi, 2011). During the Seventh Malaysia Plan (1995-2000), the Malaysian Federal Government spent RM20.9 billion to build 9 sanitary landfills and upgrade 27 existing landfills under the jurisdiction of 34 local authorities. Due to scarcity of land and high rate of waste generation, the Government had palled to use incinerators as alternatives in disposing the MSW. During the seventh Malaysia Plan, the government had spent around RM17 million to purchase 7 mini incinerators each with a capacity of disposal between 5tones/day out 20tones/day to be operated in Langkawi, Labuan, Tioman and Pangkor (CAP, 2001). The ultimate challenge in running landfills is to ensure the landfill is properly designing and maintaining various landfill system and component even after the closure.

Table 2.4. Projection of total waste disposed of at landfill site (Source Chong et al., 2005)

Year	Population	Total waste Generated (tonnes/year)	Disposal Method					Total Waste disposed in landfill (tones/year)
			*1	*2	*3	*4	*5	
2001	500,000	160,600	3.0	0.0	0.0	0.0	97.0	155,782
2002	512,500	164,615	4.0	0.0	0.0	0.0	96.0	158,030
2003	525,313	168,730	5.0	0.0	0.0	0.0	95.0	160,294
2004	538,445	172,949	6.0	0.0	0.0	0.0	94.0	162,572
2005	551,906	177,272	7.0	47.9	4.0	10.0	31.1	55,132
2006	565,704	181,704	8.0	47.4	4.0	10.0	30.6	55,601
2007	579,847	186,247	9.0	46.9	4.0	10.0	30.1	56,060
2008	594,343	190,903	10.0	46.4	4.0	10.0	29.6	56,507
2009	609,201	195,676	11.0	45.9	4.0	10.0	29.1	56,942
2010	624,431	200,567	12.0	45.4	4.0	10.0	28.6	57,362
2011	640,042	205,582	13.0	44.9	4.0	10.0	28.1	57,769
2012	656,043	210,721	14.0	44.4	4.0	10.0	27.6	58,159
2013	672,444	215,989	15.0	43.9	4.0	10.0	27.1	58,533
2014	689,256	221,389	16.0	43.4	4.0	10.0	26.6	58,889
2015	706,487	226,924	17.0	42.9	4.0	10.0	26.1	59,227
2016	724,149	232,597	18.0	42.4	4.0	10.0	25.6	59,545
2017	742,253	238,412	19.0	41.9	4.0	10.0	25.1	59,841
2018	760,809	244,372	20.0	41.4	4.0	10.0	24.6	60,116
2019	779,829	250,481	21.0	40.9	4.0	10.0	24.1	60,366
2020	799,325	256,743	22.0	40.7	8.0	10.0	19.3	49,551
Total		4,102,472	-	-	-	-	-	1,556,279

*1, recycling; 2, incineration; 3, composting; 4, inert landfill; 5, landfill

2.3.1 Principles of decomposition in landfill

Solid waste deposited in landfill decomposed by a combination of chemical, physical, and biological processes. The decomposition of waste material produces solid, liquid, and gaseous as the final product. The biological process is acting on the organic material in the waste as soon as the waste is placed into the landfill. Biological decompositions occur with naturally present bacteria. It is a complex process within landfill site which lead waste to decompose in the end of the process. Physical decomposition of solids waste is the results from breakdown or movement of the refuse components by physical degradation and by the rinsing and flushing action of water movements (McBean et al., 1995). Chemical processes resulting in refuse decomposition include the hydrolysis, dissolution/precipitation, absorption/desorption, and ion exchange of refuse components.

2.3.2 Type of Municipal Solid Waste Decomposition

(a) Aerobic decomposition

Aerobic is a process that occurs with the presence of oxygen. Thus, aerobic decomposition occurs after the placement of waste whiles the oxygen still available. This type of decomposition may continue to occur below the surface of cover soils as well but, with limitation of oxygen buried within waste it make the aerobic process only responsible for a small portion of decomposition of waste. In the first stage of decomposition process, aerobic microorganisms degrade organic materials to carbon dioxide, water, partially degraded residual organics and heat. It more alkaline compared to anaerobic due to carbon dioxide stripping by air and leads to decrease in carbonic acids (Erses et al., 2008). Aerobic decomposition will be increased with the increased oxygen supply. A general relation for this decomposition is:

Degradable waste + oxygen $\longrightarrow$ CO_2 + H_2O + biomass + heat + partially degraded materials

For this decomposition cycle, leachate is not usually produced because the waste has not reached field capacity in this early stage.

(b) Acid phase anaerobic decomposition

As oxygen source depleted, the second stage of waste decomposition is involving facultative microorganisms. These microorganisms continue the decomposition process resulted high concentration of organics acids, ammonia, hydrogen, and carbon dioxide produced (Ejlertsson et al., 2003). The end product of this acid fermentation prevails decomposition process are high level of carbon dioxide, partially degraded organic and some heat. A general equation of this decomposition process is:

Degradable waste $\longrightarrow$ CO_2 + H_2O + organism growth + partially degraded organics

The decomposition process will be producing chemically aggressive leachate with high specific conductance which has pH range of 5.5 to 6.5 as the result of the production of carbon dioxide and large amounts of organic acids.

(c) Anaerobic decomposition

The depletion oxygen as the decomposition process continued will resulting the third decomposition process that involving the anaerobic methanogenic bacteria becomes dominant. These organisms work relatively slow but effective in long duration of time and produce carbon dioxide, methane, water and some heat. The methanogenic bacteria utilize the products of the anaerobic acid stage, for example hydrogen and acetic acid:

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad \text{and} \qquad CH_3COOH \rightarrow CH_4 + CO_2$$

Consumption of the organic acids raises the pH of the leachate to the range of 7 to 8. Consequently, the leachate becomes less aggressive chemically and possesses a lower total organic strength. Hydrogen is produced during the aerobic stage but is consumed during the anaerobic stage. The gases N_2 and H_2S may also be produced during anaerobic decomposition. Nitrogen is produced from the microbial process of denitrification in which the nitrate ion is reduced. The time required for the anaerobic stage to commence may be from six months to several years after placement. During the anearobic phase, leachate characteristically has a near neutral pH, low volatile fatty acids content, and total low total dissolved solids.

2.4 Compressibility and settlement of MSW

Understanding the characteristics of municipal solid waste (MSW) is critical in designing good landfill system, maintaining various landfill engineering components and facilities and to optimize the extra spaces for further filling of MSW (Swati and Joseph, 2008). Uncontrolled settlement may affect the integrity of landfill covers, liners, gas and liquid collections and drainages (Durmusoglu et al., 2005). Settlement of MSW is known to be characteristically irregular and depending on various variable such as waste composition, moisture content, initial compaction, depth, time of placement, self weight, overburden pressure, climate, landfill mode of operation. (Youcai et al., 2002; Swati and Joseph, 2008; and Hettiarachchi et al., 2009). MSW settlement can occur in a very long extended time with final settlement reaching up to 30% to 40% of the initial fill height (Ling et al., 1999). Large settlement is desirable during landfill filling stage as an increase in settlement would also increase landfill capacity; however a large undesirable settlement during post closure stage would affect the maintenance of the site and their installed facilities.

Sharma and Anirban (2004) described and classified the mechanism of waste settlement is very complex in nature and can be attributes to following main process;

(a) Physical and mechanical processes (mechanical distortion, crushing, and re-orientation of particles);

(b) Chemical process (combustion, corrosion, and oxidation);

(c) Dissolution process (dissolving soluble substances by percolating liquids and then forming leachate);

(d) Biological decomposition (decompose of organics matters, controlled by temperature, humidity and percentage of organics and nutrients in the waste).

However, Hettiarachchi et al. (2009) only divided MSW settlement into two broad mechanisms that can be used to describe the MSW settlement: mechanical compression and biodegradation-induced settlement.

In 2005, Dixon and Jones listed eight main factors that control the magnitude of settlement; the factors are (a) initial composition of waste (grading, particle shape, material properties of the components); (b) initial density and void ratio; (c) layer of thickness; (d) type, thickness and number of cover soils layer; (e) stress history (pre and post filling mechanical treatment); (f) leachate levels and fluctuations; (g) environmental controlled factors (moisture content, temperature, gas generation); and (h) compressibility of sub grade.

MSW settlements are involved in three main stages namely initial compression, primary compression and secondary compression. The initial compression takes placed almost immediately after waste placement due to rearrangement of MSW skeleton caused by self weight or other applied load (Hettiarachchi et al., 2009). Following the initial compression is primary compression that believed due to physical and mechanical mechanisms such as compression due to the dissipation of water and gas from the void spaces. Meanwhile Liu et al. (2006) divided settlement of MSW into five stages that been illustrated in Figure 2.1 below. Secondary compression occur mainly due physiochemical and biochemical decay under constant load applied onto MSW components. Due to the heterogeneous nature of MSW constituents and their varied rates of decomposition, differential settlement occurs and increases the complexity of the computations of the total settlement (Dixon and Jones, 2005).

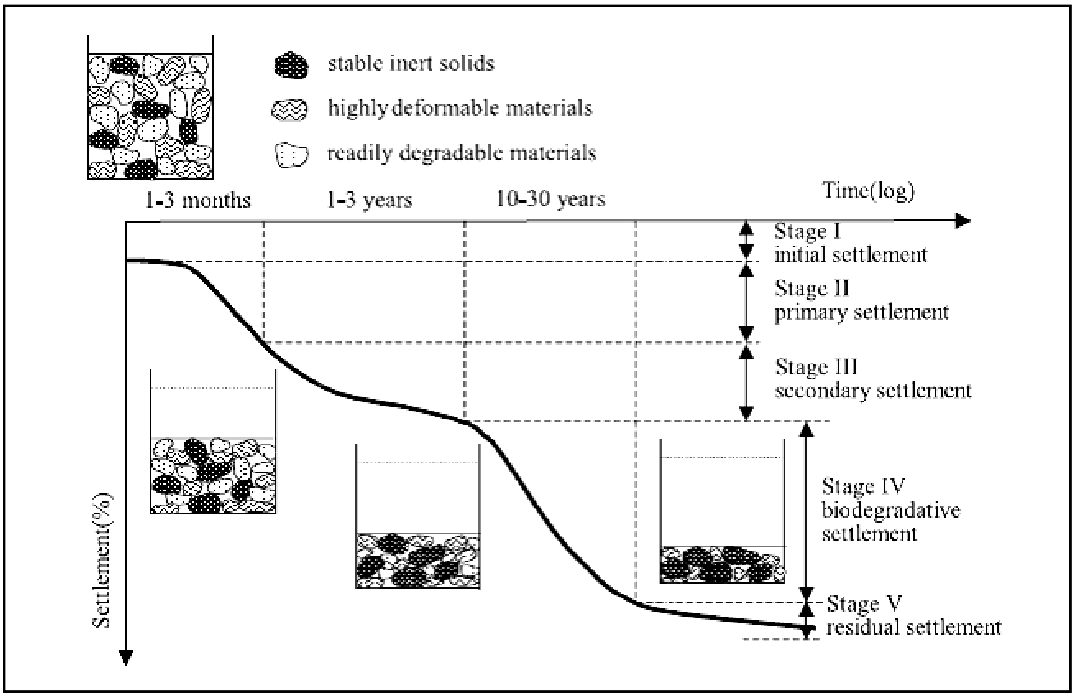

Figure 2.1 Stages of municipal solid waste settlement (Source: Liu et al., 2006)

2.4.1 Primary compression

Primary compression includes physical compression of particle (distortion, bending, crushing and particle orientation) and consolidation (significant for saturated waste bodies) (Dixon and Jones, 2005). Initial settlement of waste materials occurs as soon as load is applied onto waste. Therefore, primary compression will occur in a period of a few days to a few weeks and can be considered to be short term. Sharma and Anirban (2007) reported that primary settlement of MSW typically occurs within the first four months after loads placement and over by the time of landfill closed.

Dixon and Jones described MSW primary compression as a one-dimensional compression problem. An increment of vertical effective stress $\Delta\sigma'_v$, produces an increase in vertical strain $\Delta\varepsilon_v$. Stresses are assumed to be effective for fresh waste and strains are assumed to occur immediately after application of the stress. A constraint modulus D, can be defined as

$$D = \frac{\Delta\sigma'_v}{\Delta\varepsilon_v} \text{(units kN/m}^3 \text{ or MN/m}^2\text{)} \tag{2.1}$$

The primary compression of MSW can be computed as follow

$$\delta_p = \sum_{i=1}^{n} \frac{H_i \Delta\sigma'_v}{D_i} \tag{2.2}$$

Where $\Delta\sigma'_v$ the change is in vertical effective stress, H_i is the thickness of the sub-layer i of waste, D_i is the constrained modulus of layer i .The combination of primary compression index (c_c) and modified compression index (c'_c) is often used in describing parameters of primary settlement of MSW. These parameters is written as

$$c_c = \frac{\Delta e}{\log(\sigma_1/\sigma_2)} \tag{2.3}$$

And

$$c'_c = \frac{\Delta H}{H_0 \cdot (\sigma_1/\sigma_2)} = \frac{c_c}{1+e_0} \tag{2.4}$$

Where, Δe = change in void ratio; e_0 = initial void ratio; σ_0 = initial vertical effective stress; σ_1 = final vertical effective stress; H_0 = original thickness of waste layer; and ΔH = change in thickness of waste layer.

2.4.2 Secondary compression

The secondary compression of MSW material is mainly due to biodegradation of waste material and mechanical creep compression and normally represent following linear compression on a settlement versus log-time graph (Dixon and Jones, 2005).

$$\delta = c_\alpha H \log \frac{t}{t_p} \tag{2.5}$$

Where, t is the time at which settlement due to secondary compression is required $(t > t_p)$; t_p is the time for completion of primary compression. Qian et al. (2002) use the secondary compression index (c_α) and the modified secondary compression index (c'_α) to estimate the settlement that occurs while the waste is subjected to a constant load for long period of time.

The indexes are;

$$c_\alpha = \frac{\Delta e}{\log(t_2/t_1)} \tag{2.6}$$

And

$$c'_\alpha = \frac{\Delta H}{H_0 \cdot \log(t_1/t_2)} = \frac{c_\alpha}{1+e_0} \tag{2.7}$$

Where t_1 is starting time of secondary settlement; and t_2 is the ending time of secondary settlement.

The typical values for primary compression index (c_c) and secondary compression index (c_α) that have been reported by various researchers shown in Table 2.5.

Table 2.5. Typical values for primary compression (c_c) and secondary compression (c_α) (After Sharma and Anirban, 2007)

Reference	Primary (c_c)	Secondary (c_α)
Sowers (1973)	0.1-0.41	0.02-0.07
Zoino (1974)	0.15-0.33	0.013-0.03
Converse (1975)	0.25-0.3	0.07
Rao et al. (1977)	0.16-0.235	0.012-0.046
Oweis and Khera (1986)	0.08-0.217	-
Landva et al. (1984)	0.2-0.5	0.0005-0.029
Bjarngard and Edgers (1990)	-	0.004-0.04
Wall and Zeiss (1995)	0.21-0.25	0.033-0.056
Gabr and Valero (1995)	0.2-0.23	0.015-0.023
Boutwell and Fiore (1995)	0.09-0.19	0.006-0.012
Stulgis et al. (1995)	0.16	0.02
Green and Jamenjad (1997)	-	0.01-0.08
Landva et al. (2000)	0.17-0.24	0.01-0.016
Zaminskie et al. (1994)	0.01-0.04	0.01-0.006
El-Fade and Al-Rashed (1998)	-	0.1-0.32 (leachate recurculation)
Earth Tech (2001)	-	0.18-0.26(leachate recirculation)
Park et al. (2002)	-	0.014-0.063 (fresh waste) 0.087-0.34 (active decomposition)
Marques et al. (2003) (field monitoring)	0.073-0.132	-
Hossain et al. (2003) (laboratory testing)	0.16-0.37	0.015-0.03 for creep 0.19 (active decomposition)
Anderson et al. (2004) (field monitoring)	0.17-0.23	0.024-0.030
Calculated by authors;		
Sharma (2000)	-	$c_{\alpha(EL)}$:0.02
Yolo County Case history	-	$c_{\alpha(SW)}$:0.19-0.28
	-	$c_{\alpha(SW)}$:0.04 for fresh waste
	-	$c_{\alpha(SW)}$:0.16 for bioreactor waste

However, Sharma and Anirban (2007) divided secondary compression of MSW into two categories based on the type of loading applied:

1. Settlement under self weight: this type of settlement is caused by load imposed due to the weight of waste material on the underlying waste layers. The externally load does not have on a secondary settlement components due to its self weight; the overlying waste material itself also goes settlement. The time dependent secondary settlement (ΔH_s) can be expressed by the following equations:

$$\Delta H_s = \Delta H_{(sw)} = c_{\alpha(sw)} H_1 \log \frac{t_1}{t_2} \tag{2.8}$$

Where $\Delta H_{(sw)}$ is settlement at time t_2 after fill placement; t_1 time for primary settlement end; t_2 is time of interest, since the self weight was applied; H_1 is the thickness of refuse fill at the end of primary settlement; and $c_{\alpha(sw)}$ is the coefficients of secondary compression due to self weight with typical values in the range of 0.1 and 0.4.

2. Settlement under external loads: the time dependent secondary settlement occurs after primary settlement over very long period of time due to externally applied loads. This settlement can be expressed by equation (2.9);

$$\Delta H_s = \Delta H_{(EL)} = c_{\alpha(EL)} H_1 \log \frac{t_2}{t_1} \tag{2.9}$$

Where $\Delta H_{(EL)}$ is settlement at time t_2 after external load application; t_1 is time for secondary settlement; t_2 is the interest time since the external load application; H_1 is thickness of refuse fill at the end of the primary settlement; and $c_{\alpha(EL)}$ is the coefficient of secondary compression due to external loads. Typically in landfill, external loads are in forms of their soils cover and after the closure of the landfill the loads are in forms of final cover or structures built at the landfill site. NAVFAC (1983) concludes that for refuse that undergone decomposition for more than 10 years, secondary compression index ($c_{\alpha(EL)}$) are in the range of 0.02 to 0.07.

2.5 Municipal Solid Waste settlement estimation

Municipal Solid Waste (MSW) exhibit heterogeneous and anisotropic properties that are difficult to be characterize. MSW landfills suffer very large long term settlement caused by decomposition of waste material. Large settlement is desirable during landfill filling stage as an increase in settlement would also increase landfill capacity; however a large undesirable settlement during post closure stage would affect the maintenance of the site and their installed facilities. Accurate prediction of a landfill settlement is a challenge due to the large number of variables involved in the process (Hettiarachchi et al., 2007; Elagroundy et al., 2008). Meanwhile, the consolidation theory proposed by Terzaghi (1943) that has been successfully used in predicting soil settlement is less applicable in municipal solid waste, thus more suitable procedure need to be tried.

Researchers have come out with various prediction models to describe settlement behavior in Municipal Solid Wastes such as soil mechanic based model, empirical model, rheological model, settlement models incorporating biodegradation, and constitutive model (Babu et al., 2010). Ling et al. (1998) reported that the usage of empirical models such as logarithmic function model, the power creep law function, and hyperbolic function is more compatible over model that are based on conventional soil mechanics theory due some limitations especially on nature of waste materials. Based on the prediction made on three existing landfill, Ling et al. (1998) concluded that hyperbolic function produced better prediction compared to logarithmic and power creep law model. However, further validation of the model needs to be carried out especially against field measurement.