COMPRESSIBILITY CHARACTERISTICS OF MUNICIPAL SOLID WASTE IN MEETHOTAMULLA WASTE FILL SITE

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Degree of Master of Engineering

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DECLARATION

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Prof. S.A.S. Kulathilaka

ABSTRACT

Municipal solid waste (MSW) is defined as solid waste generated from community, commercial and agricultural operations and it includes wastes from households, offices, stores, industries and other non-manufacturing activities. Management of municipal solid waste is a major problem all over the world. Recently, Municipal Solid Waste Management became a growing concern in Sri Lanka with the catastrophic landfill failures occurred at Meethotamulla. The need to ensure the stability of existing landfills which are mostly uncontrolled through appropriate engineering designs is a major task at present.

MSW forms the largest portion of the landfill and its strength and stiffness (compressibility) characteristics controls all aspects of landfill designs. In this research compressibility characteristics of MSW at different stages of decomposition were evaluated under both saturated and unsaturated conditions.

Considering the highly heterogeneous state of MSW, larger samples were tested using a Rowe Cell of diameter 150mm with loading, unloading and reloading increments. Characteristics such as; Coefficient of volume compressibility, coefficient of consolidation, coefficient of secondary consolidation, compression index, recompression index were determined to assess the applicability of conventional Terzaghi consolidation theory in modelling the MSW behavior. Results were compared with the behavior of residual soil and organic soils. The test results revealed that MSW experienced high primary and secondary consolidation settlements. These could be significantly reduced by preloading. The coefficient of consolidation values were quite high.

Keywords: Municipal solid waste (MSW), Consolidation characteristics, Meethotamulla, Rowe cell

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CHAPTER 1 INTRODUCTION

1.1 Background

According to the Technical Guidelines on Solid Waste Management in Sri Lanka, Municipal Solid Waste (MSW) describes as the discarded materials, substances or objects which originate (or refuse) from domestic, business and industrial sources, including household wastes which are typically disposed in municipal type landfills, but not including industrial hazardous or special wastes. Municipal solid waste management becomes one of the critical issue in all over the world. Open dumping is the currently adopted predominant method in Sri Lanka due to low cost and less processing involved. The daily solid waste generation in Sri Lanka is about 7500MT.

Percentage of solid waste generation in provincial level and per capita daily generation of MSW in Local Authorities are presented in Table 1-1 and per capita generation of MSW is presented in Table 1-2.

Table 1-1: Provincial waste generation in Sri Lanka (Source: Central Environmental Authority, Sri Lanka)

Province	**Solid waste generation (%)**
Western Province	58.5
Eastern Province	8.5
Central Province	8
58.Southern Province	7
North Western Province	6
Northern Province	3.3
Sabaragamuwa Province	3.2
Uva Province	3.
North Central province	2.5

Table 1-2: Per capita daily generation of MSW in Sri Lanka (Source: Central Environmental Authority, Sri Lanka)

Type of local authority	Per capita daily generation (kg/day)
Colombo Municipal Council	0.80
Municipal Councils	0.75
Urban Councils	0.60
Pradeshiya Sabha	0.40

As stated in Table 1-1 and Table 1-2, Western province generated highest amount of waste in Sri Lanka and per capita daily generation of waste is highest in Colombo Municipal Council. Recently, Municipal solid waste management became a growing concern in Sri Lanka with the catastrophic landfill failures occurred at Meeethotamulla (Figure 1-1). According to the situation report issued by the Disaster Management Center regarding "Meethotamulla Municipal Solid Waste Dump Disaster", 32 bodies have been recovered from the failure site and 60 houses have been fully damaged , 27 houses partially damaged.

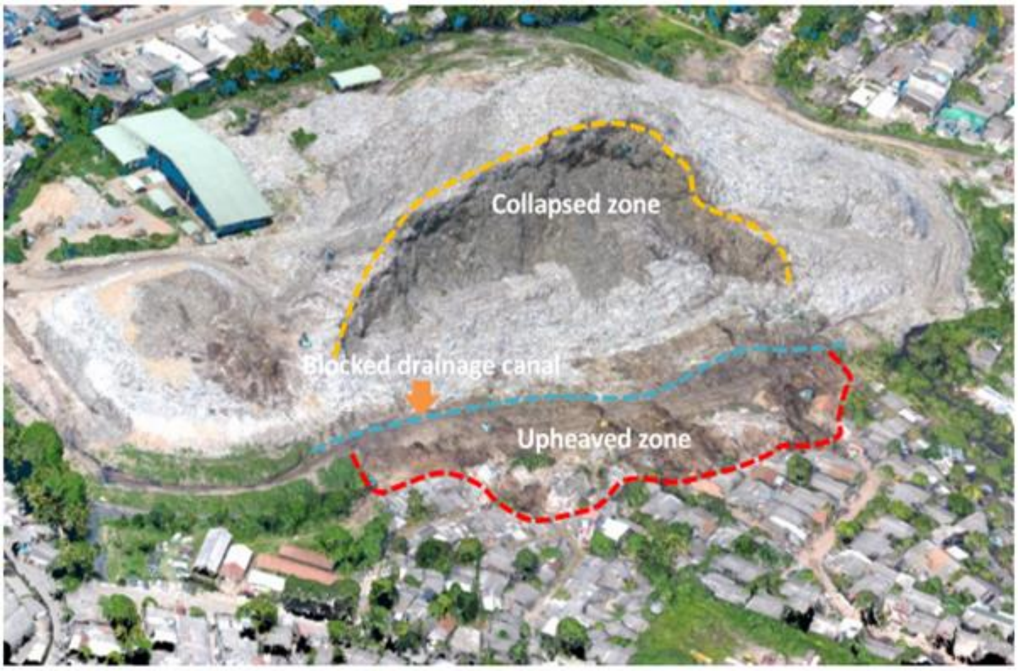

Figure 1-1: Aerial image of failure at Meethotamulla waste dump site

Geotechnical risk such as stability and settlement issues in landfills are mainly influenced by engineering behavior of the MSW. Hence, a reliable methods is required to evaluate the stiffness properties and shear strength which are necessary for stability and deformation analysis of the landfill during their operation and also in closure plans. Therefore, it is necessary to make a proper stability and deformation analysis of waste landfill in Sri Lanka to minimize the future risk of failure and plan optimal usage of landfill sites.

1.2 Problem Statement

In the past, many researchers have conducted studies to identify the factors influencing the shear strength and stiffness of MSW. Relevant studies for landfills in Sri Lanka are very limited. Further, it is widely reported that the MSW is highly heterogeneous and its engineering properties may vary from landfill to another and also with the age of landfill. Hence, site-specific assessment of engineering properties is required to determine the realistic parameters for assessments. Determination of stiffness properties of solid waste is useful for assessing the deformation of waste dumps and the effect on structures built on landfill with post-closure plans. The parameters of compressibility and consolidation characteristics are required to model the post closure long-term settlements of MSW sites. Due to extreme heterogeneity and anisotropy of MSW, determination of parameters is much more difficult compared to that of soils. Hence, with many limitations the conventional theories of soil mechanics related to compressibility are to be tested with MSW.

1.3 Scope and Objectives of the Thesis

Based on the identified knowledge gaps and shortcomings in the published literature related to mechanical properties of municipal solid waste and as part of post disaster assessment at Meethotamulla waste dump, the following specific objectives were established for this research study;

- Studying the consolidation behavior of MSW by conducting laboratory test
- Determining compressibility characteristics of MSW using different consolidation theories
- Study the influence due to density and waste composition on the compressibility characteristics

1.4 Outline of Thesis

Chapter 02 presents a review of literature on settlement behavior and methods of determining settlement of MSW and compressibility characteristics of MSW. Further, this chapter presents the different types of consolidation test performed for MSW and outcomes of past studies. Finally, available method to determine waste composition are discussed.

Chapter 03 demonstrates the experimental programme including specimen preparation, test methods and testing procedure. Also, this section presents the result of basic properties of waste. Then, determination of waste composition of the specimen used for the laboratory test is presented.

Chapter 04 covers the results of experimental programme, detailed discussion on the determination of compressibility indices and comparison of results with published literature.

Chapter 05 concludes the finding of the research study and made recommendation for further research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

When designing interim and final closure covers for landfills, the compressibility characteristics of waste plays major role. The properties related to compressibility of waste shows significant variation due to different sample types (unit weight, age, shredded, pre-treated and unsorted), inconsistent sample composition, lack of universally accepted methodology for laboratory testing procedures and analysis of test data. Hence, a proper understanding and knowledge of MSW properties is required for reliably evaluating and predicting its mechanical behavior.

This Chapter presents a review of current findings related to compressibility characteristics of MSW and experimental methods used to determine associated parameters. Further, different concepts used for interpretation of test results are also cited in this chapter.

2.2 Settlement in MSW landfills

Generally, landfill settlement is a combination of short-term load-related settlement and long-term settlement under constant load due to biodegradation phenomena. Short term settlement occurs rapidly (i.e. during the filling process) and significant amount of long-term settlement remains for a longer period. Prevailing compression models can exhibit load-related settlement and but not suitable for the displacement due to biodegradation. Magnitude of settlement and duration have direct impact on the design aspects, operational activities, termination of landfills and usage after closure of landfills. Settlement due to biodegradation predicts the pre-closure fill height. If the actual settlement exceeds the predicted settlement, the integrity of capping layer and leachate and gas management systems may be compromised. According to Bjarngard and Edges (1990) amount of total settlement which can be occurred in MSW landfill is about 25% - 50% of original fill height. As a result of considerable amount of settlement continuing for many years, constrains may occur to future development as well as vertical expansion of landfill sites. Therefore, knowledge and capacity to analyze settlement of waste dump is necessary during the design stage.

2.2.1 Mechanisms of Settlement

Sowers (1973) and Yen and Scanlon (1975) studied about several mechanisms of settlement in landfills (Table 2-1). Mechanisms identified by Yen and Scanlon (1975) is related to long term settlement and it closely corresponded to mechanism suggested by Sowers (1973).

Table 2-1: Mechanisms of settlement in MSW landfills

Mechanisms identified by Sowers (1973)	**Mechanisms identified by Yen and Scanlon (1975)**
▪ Mechanical: distortion, bending and crushing ▪ Erosion, sifting of fines. ▪ Physicochemical: corrosion, oxidation and combustion ▪ Biochemical decay: fermentation and decay, aerobic and anaerobic ▪ Interaction, between the four other mechanisms	▪ Movement of fines into large voids ▪ Strength loss due to chemical and biological reactions ▪ Material loss due to biodegradation and methane production ▪ Creep processes ▪ Consolidation processes

It is obvious that some listed mechanisms contributing to settlement in MSW landfills do not occur in engineering or inert soils. Conventional settlement mechanisms includes only consolidation and creep processes and the occurrence of consolidation settlement in MSW has some doubts due to following aspects; (Bjarngard & Edgers, 1990) & (Wall & Zeiss, 1995)

- Waste is less than fully saturated, especially at the time of placement
- Even if saturated, has a permeability that is too high to allow any persistent build up of excess pore water pressure

The occurrence of settlement mechanisms and temporal classification during the life of a waste dump site is interpreted by McDougall J (2008) using published settlement mechanisms by several authors (Figure 2-1).

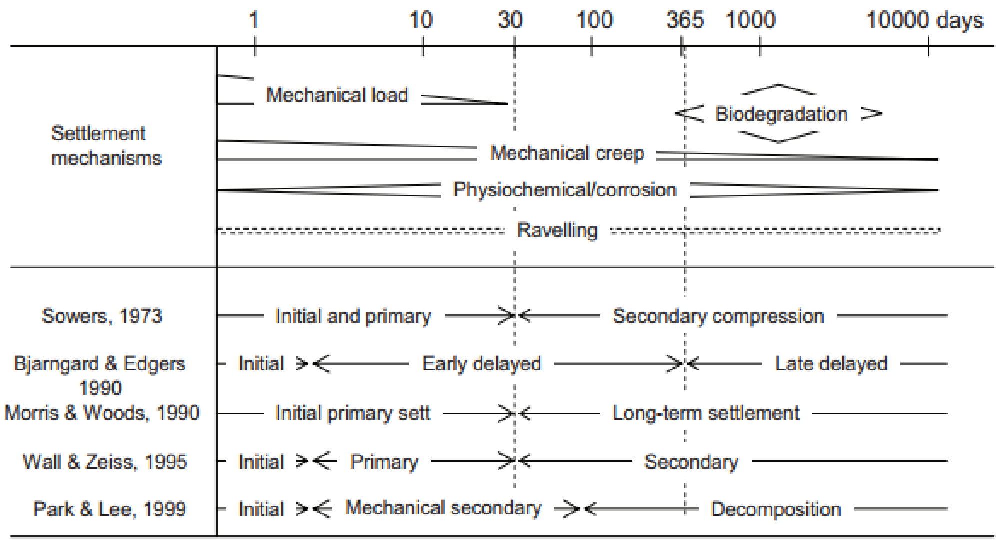

Figure 2-1: Occurrence of settlement mechanisms adopted by several researchers (McDougall J, 2008)

Settlement due to self-weight or surcharge is considered to be completed within about a month after filling. Creep settlement is considered as occurring in a gradually decreasing rate throughout the life time of the landfill site and settlement due to biodegradation is regarded as occurring after about one year. McDougall J (2008) mentioned that the Physio-chemical/corrosion effects are probably the least well understood mechanisms.

The bottom part of Figure 2-1 illustrates the temporal classification of the settlement as proposed by several researchers. As mentioned by Wall and Zeiss (1995), Morris and Woods (1990) and Sowers (1973), load related compression which are commonly referred as *Initial* and *Primary* settlement are thought to occurs over the first month, and compression related to biodegradation and creep which are collectively named as *Long-term phase and Secondary* are expected to occur after one month and it can last for more than 30 years. Terminologies used by Park and Lee (1997) and Bjarngard and Edgers (1990) are different and they have predicted different time frames. However, their concept regarding settlement mechanisms and interpretation comply with others judgement.

Further, Bjarngard & Edgers (1990) have studied aspects related to settlement mechanism of waste and stated that the total settlement is a combination of primary settlement (δp) and secondary settlement (δs). (Equation 2-1)

$$(\boldsymbol{\delta}) = (\boldsymbol{\delta_P}) + (\boldsymbol{\delta_s}) \quad \textbf{Equation 2-1}$$

2.2.2 Primary Settlement

Physical compression of particles such as bending, particle re-orientation, crushing, distortion and consolidation is considered as primary settlement. It can be stated as a short term as it will happen shortly after a load is applied, in a period of a few days to a few weeks (Dixon, N.; Russell, D.; Jones, V., 2005).

2.2.3 Secondary Settlement

Dixon and Jones (2005) stated that the secondary compression of waste contains all the effects of creep, chemical degradation and biological degradation. Creep effects contain time dependent particle distortion and reorientation. They noted that Bio-degradation is the most significant component of secondary settlement in waste dumps. There are several method to determine the secondary settlement, whereas in reality the degradation process is affected by a range of factors which change within a landfill and with time, such as the moisture content, temperature, and level of stress.

Bjarngard and Edgers (1990) examined a large field data set and identified that settlement occurs at a relatively slow rate in initial stage and have higher rate at secondary stage related to decomposition (Figure 2-2).

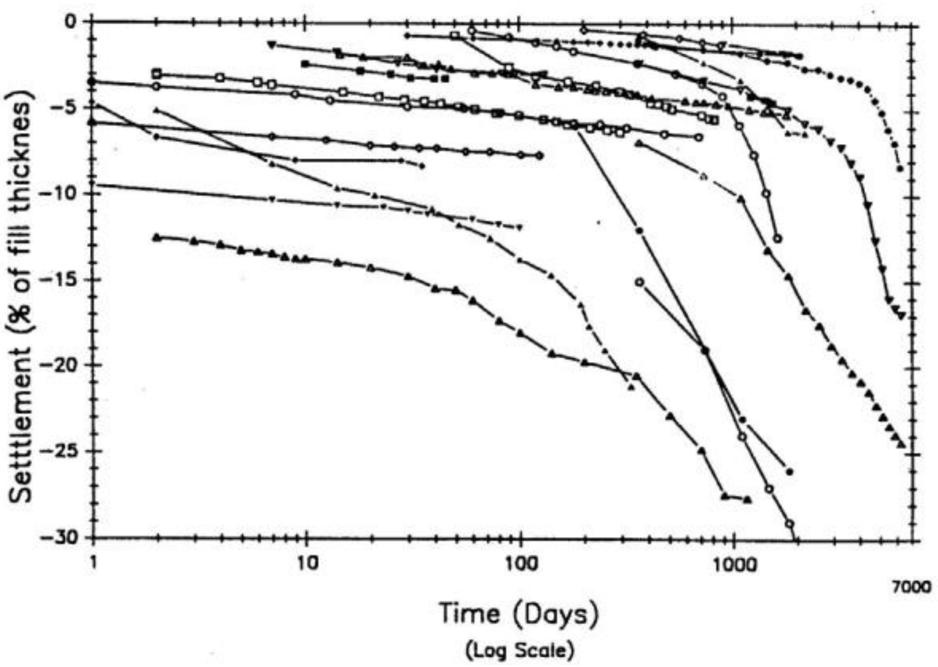

Figure 2-2: Landfill settlement vs log time from field case histories (Bjarngard and Edgers, 1990)

2.2.4 Total Compression

Dixon and Jones (2005) stated that to calculate the total settlement of waste, the following factors need to be considered;

- Settlement of waste due to self-weight (primary settlement)
- Settlement caused by the weight of each subsequent layer (primary settlement)
- Settlement caused by secondary compression, considering that C_α is likely to decrease with age
- Settlement of the mineral basal liner caused by primary and secondary compression
- Settlement of any compressible sub-grade

Due to the heterogeneous nature of waste material components and different rates of decomposition, differential settlement often happens. Differential settlement issue is more complicated because filling process usually carried out on top of older waste deposits at different times. Differential settlement is important because it can endanger the stability of the final cover and the integrity of the geosynthetic layer and compacted clay barrier.

2.2.5 Factors influencing landfill settlement

McDougall J (2008) summarized the external and internal factors affecting the primary and secondary settlement mechanisms of MSW (Figure 2-3).

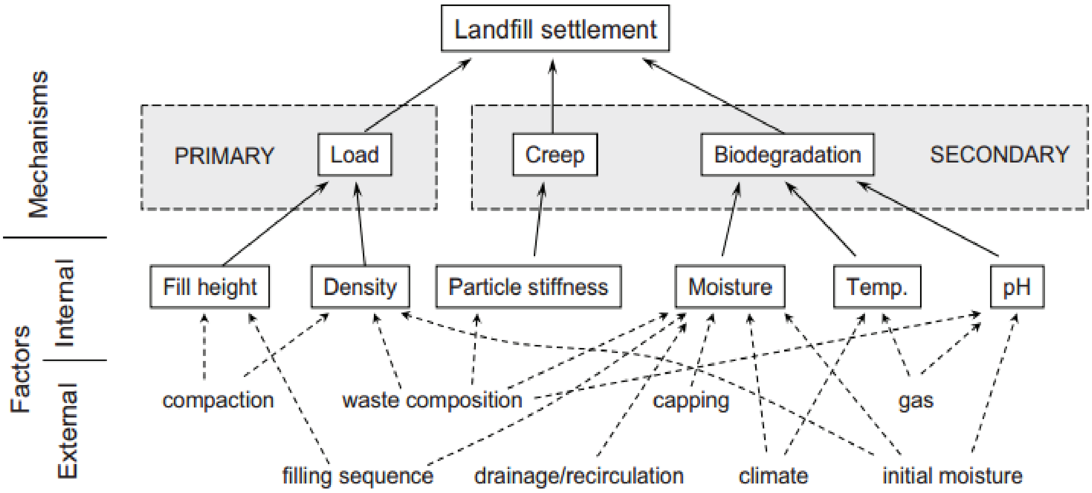

Figure 2-3: Factors influencing the landfill settlement (McDougall J, 2008)

As shown in Figure 2-3 influence factors are divided in to two categories.

I. Factors related to the condition or basic properties of the waste, i.e. internal to the landfill
II. External factors influence due to site operations and activities or initial conditions which have impact on internal conditions

Here, factors like leachate, moisture, and gas composition which are influencing factors for biodegradation are not incorporated. Further, Landva et al. (1984) concluded that assessment of settlement due to decomposition is difficult due to complex phenomena involved.

2.3 Settlement Estimation Methods for MSW landfills

2.3.1 Rheological Model

Based on Gibson and Lo's (1961) rheological model, Edil et al. (1990) suggested a method for estimating total settlement (ΔH) (Equation 2-2).

$$\boldsymbol{\Delta H = H(\Delta P)[a + b\left\{1 - \exp\left(-{}^{\lambda}/_{b}\right) t\right\}]} \qquad \text{Equation 2-2}$$

Where;

H = initial height of waste

ΔP = change in pressure

a = primary compression parameter

b = secondary compression parameter

λ/b = rate of secondary compression

t = time since load application

2.3.2 Sowers method

The total settlement (ΔH) is combination of primary settlement (ΔH_p) and secondary settlement (ΔH_s). Sowers (1973) presented the Equation 2-3 and Equation 2-4 for estimating settlement. These are in line with Primary and Secondary Consolidation defined for soils.

$$\Delta H_p = HC_{ce} log \frac{P_0 + \Delta P}{P_o}$$ **Equation 2-3**

$$\Delta H_s = H_1 C_{\propto} log \frac{t_2}{t_1}$$ **Equation 2-4**

Where;

H = initial thickness of waste

H_1 = thickness of waste at the beginning of the secondary settlement

C_c = compression index

C_{ce} = C_c/ (1+e_0)

e_0 = void ratio

C_α = secondary compression index

P_0 = initial overburden pressure

Δp = incremental pressure

t_1 = starting time for secondary compression

t_2 = ending time for secondary compression

C_α values for different ages of waste were reported by Oweis and Khera (1998). Table 2-2 presents the values chosen from their summary.

Table 2-2: Secondary compression parameters for MSW material (After Oweis and Khera 1998)

Material	**C_α**
Ten years old landfill	0.02
Fifteen years old landfill	0.24
Fifteen to twenty years old landfill	0.02
Old landfill	0.04
Old landfill with high soil content	0.001 to 0.005

Since the rate of degradation is varied with time, it is indeed that C_α is deviated with the age of waste material. Further, Sharma et al (2007) summarized the C_{ce} and C_α values collected from previously published data (Table 2-3).

Table 2-3: Summary of C_{ce} and C_α values from literature (collected by Sharma 2007)

Reference	Primary C_{ce}	Secondary C_α
Sowers (1973)[a] (for e_0 =3)	0.1 – 0.41	0.02 – 0.07
Zoino (1974)[a]	0.15 – 0.33	0.013 – 0.03
Converse (1975)[a]	0.25 – 0.3	0.07
Rao et al. (1984)[a]	0.16 – 0.235	0.012 – 0.046
Oweis and Khera (1986)[a]	0.08 – 0.217	-
Landva et al. (1984)[a]	0.2 – 0.5	0.0005 – 0.029
Bjarngard and Edgers (1990)[a]	-	0.004 – 0.04
Wall and Zeiss (1995)[a]	0.21 – 0.25	0.033 – 0.056
Gabr and Valero (1995)[a]	0.2 – 0.23	0.015 – 0.023
Boutwell and Fiore (1995)[a]	0.09 – 0.19	0.006 – 0.012
Stulgis et al. (1995)[a]	0.16	0.02
Green and Jamenjad (1997)[a]	-	0.01 – 0.08
Landva et al. (2000)[a]	0.17 – 0.24	0.01 – 0.016
Zaminskie et al. (1994)	0.01 – 0.04	0.001 – 0.006
El-Fadel and Al-Rashed (1998)[b]	-	0.1 – 0.32 with leachate recirculation
Earth Tech(2001)[b]	-	0.18 – 0.26 with leachate recirculation 0.014 – 0.063 for fresh waste
Park et al. (2002)	-	0.087 - 0.34 for waste undergoing active decomposition
Marques et al. (2003) (field monitoring)	0.073 – 0.132	0.015 – 0.03 for creep
Hossain et al. (2003) (laboratory testing)	0.16 – 0.37	0.19 waste undergoing active decomposition
Anderson et al. (2004) (field monitoring)	0.17 – 0.23	0.024 – 0.030
Calculated by Sharma (2000)	-	$C_{\alpha(EL)}$[C]: 0.02 $C_{\alpha(SW)}$[d]: 0.19 – 0.28
Yolo Country case history	-	$C_{\alpha(SW)}$: 0.04 for fresh waste $C_{\alpha(SW)}$: 0.16 for waste in bioreactor
Lewis et al. (2004) (field monitoring, for external load)	-	$C_{\alpha(EL)}$: 0.014 for waste treated with DDC[C] $C_{\alpha(EL)}$: 0.045 for waste treated with surcharge

[a]Data originally presented by Landva et al. (2000)

[b]Data originally presented by Hossain et al. (2003)

[c]EL = external load

[d]SW = self – weight

[e]DDC = Deep Dynamic Compaction

2.3.3 Power creep Model

Further, Edil et al. (1990) suggested a model for Total Settlement (Equation 2-5).

$$\Delta H = H\Delta pm({}^{t}/_{t_r})^{n}$$ **Equation 2-5**

Where;

ΔH = total settlement

H = initial height of waste

Δp = change in pressure

m = reference compressibility

n = compression rate

t_r = reference time introduced into equation to make time dimensionless

t = time since load application

2.3.4 Hyperbolic function Model

Ling et al. (1998) used the hyperbolic function to estimate long term settlement (Equation 2-6).

$$S = \frac{t}{{}^{1}/_{P_0} + {}^{t}/_{S_{ult}}}$$ **Equation 2-6**

Where;

t = time interval of interest

S = settlement occurring in time interval, t

P_0 = rate of settlement at the beginning of the time interval

S_{ult} = ultimate settlement

2.4 Laboratory testing

Quantifying the engineering properties of municipal solid waste bodies is a challenging task due to the diversity of materials. It is also more desirable to perform experimental testing on materials in their undisturbed conditions, but that is not always possible because undisturbed samples cannot be taken, hence laboratory tests must be carried out on disturbed materials re-compacted inside the test apparatus. Moreover, the variation in constitution between samples can be excessive so changing the ratio of waste component to investigate the effects is difficult but also necessary to evaluate the influence of future changes in the composition of waste composition. Another significant parameter is the change in the engineering properties of wastes over time due to the degradation. At the present time, there are no approved standard sampling and testing procedures for determining the mechanical properties of waste materials and there are no clear instructions for choosing appropriate values of the engineering parameters to be used in designs and assessing the behavior of waste.

In practice, most commonly used laboratory test for determination of compressibility characteristics of MSW is the one-dimensional test with oedometer apparatus (Gabr &Valero 1995; Vilar &Carvalho 2004; Reddy et al. 2008)

Athanasopoulos G.A. (2008) mentioned that Laboratory compression / consolidation testing for MSW should adhere to the general guidelines of ASTM D-2435 with following conditions;

1. The maximum limit specified for size of particle can be changed based on the thickness of sample (e.g. the maximum particle size can be up to ½ of sample thickness, or less depending on compressibility).
2. The sample should be compacted to achieve the field density of sample.
3. The fluid expelled from the sample should be measured.
4. Gas emission and temperature variation should be monitored in reactor tests. At the end of very long term test /reactor test, level of degradation should be measured using appropriate techniques.
5. The minimum specimen size should be 300 mm.
6. Full description of any mechanical waste processing should be provided.

Test results are usually presented according to the compressibility parameters; primary compression index C_c and secondary compression index C_α. According to Fassett et al. (1994) parameters C_c and C_α depend on the values adopted for e_0. But the determination of the void ratio of municipal solid waste is quite complex. Therefore, some researchers (Vilar & Carvalho 2004; Hossain & Gabr 2005; Gabr & Valero 1995) assumed that the initial value of the void ratio e_0, in order to calculate values C_c and C_α. Therefore, the modified index of primary C_c' and the modified index of secondary compression C_α' are more often used, because they are expressed by axial deformation.

2.4.1 Rowe Cell

In order to overcome the shortcomings of Conventional Oedometer test when conducting test on low-permeability soils and non-uniform deposits, Rowe Cell was developed by Professor P. W. Rowe of Manchester University (Head, 1994). Hydraulic loading system with flexible diaphragm is used for loading the sample instead of mechanical lever system. Main features of Rowe cell apparatus is shown in Figure 2-4.

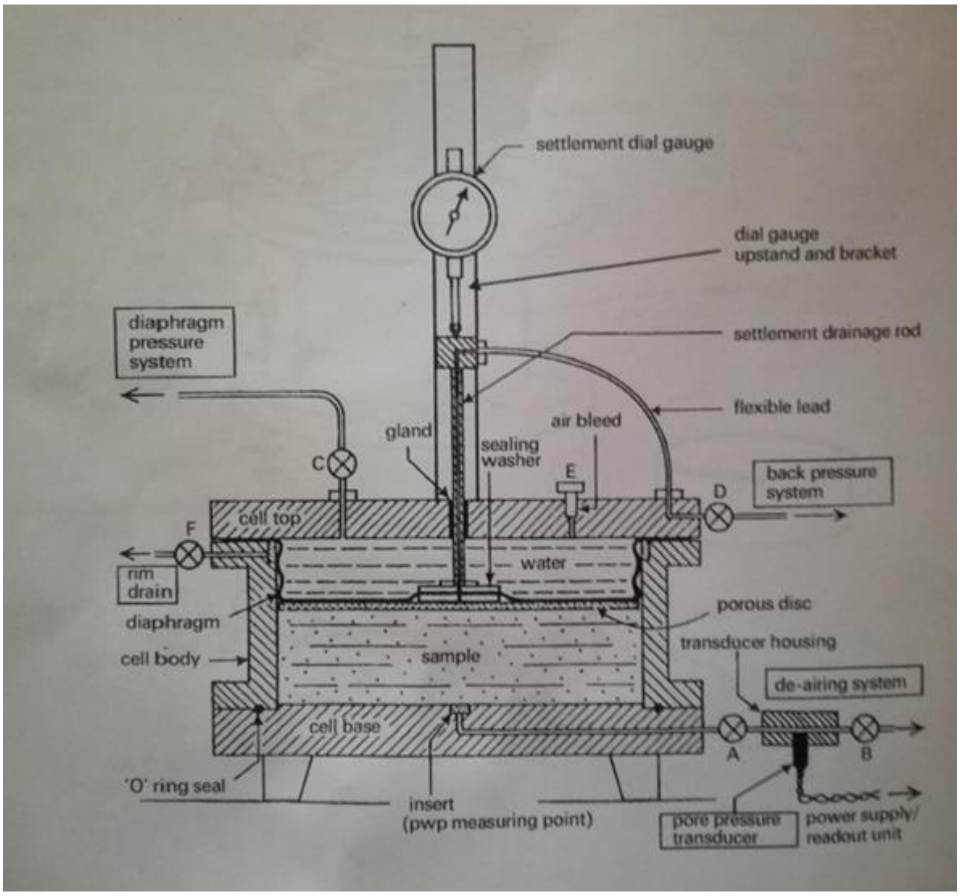

Figure 2-4: Main Features of the Rowe Cell Apparatus (Source: Rowe Cell Manual)

Sample size is one of the most important parameters to get the represented results from the experiments. Different sizes of Rowe Cell apparatus having nominal cell diameter of 3 inch, 6 inch and 10 inch are available and it allows for large deformations. Most important features of the Rowe Cell are ability of controlling drainage and ability of measuring pore water pressure. Several drainage conditions (vertical or horizontal) can be performed and back pressure can be applied to the sample.

Rowe Cell was developed with the pore water pressure measuring devices. Hence, the starting point of secondary consolidation can be clearly identified with the pore pressure measurements. The point where the pore pressure dissipates and remain constant is the starting point of secondary consolidation. There are some further advantages of the Rowe Cell,

- Using hydraulic loading system instead of mechanical lever system. Therefore, vibration effect for the experiment will be reduce.
- Pressure can be applied up to 1000kPa easily for larger samples.
- Drainage system of the experiment can be controlled. Therefore, several different drainage conditions can be used for the experiments.
- With the undrained condition pore water pressure of the sample can be taken to required level and immediate settlement of the sample can be measured at the same time.
- Pore water pressure measurement can be obtained directly throughout the experiment. From that end of the primary consolidation and beginning of the secondary consolidation can be identified.
- The sample can be saturated by applying increments of back pressure.
- The amount of the water expelled from the sample can be measured.
- Loading can be done either by applying uniform pressure over the surface or through a rigid plate.
- Fine control of the loading system.
- Large samples provide more reliable results compare to Conventional Oedometer.

Recommended sample heights and sample volume as per the Manual of Rowe Cell are shown in Table 2-4.

Table 2-4: Relevant dimensions of cell and sample

Nominal Cell Diameter (inches)	Sample Diameter (mm)	Sample area (mm^2)	Recommended sample height* (mm)	Sample volume (cm^3)
3	75.7	4500	30	135
6	151.4	18000	50	900
10	252.3	50000	90	4500

* Deduct thickness of rigid loading plate when used

2.4.1.1 Categories of Sample

Different categories of sample can be tested using Rowe cell. Following are the categories mentioned by Head (1997);

- Undisturbed samples which obtained from box sample or a sampling tube.
- Compacted sample - prepared in the cell body by static or dynamic compaction.
- Remoulded sample, pre-consolidated in the cell from a slurry.
- Samples that have been remoulded and compacted in large box/ cell and extruded a sample which suits to cell body as an undisturbed sample.

2.4.1.2 Type of tests performed using Rowe cell

Consolidation test using incremental loading stage can be carried out in any of the above-mentioned sample types under four different conditions of drainage (i.e. Vertical single drainage, vertical double drainage, horizontal outward drainage and horizontal inward drainage) and each may be subject to two types of loading (free strain or equal strain) (Head, 1994). The corresponding drainage and loading conditions are defined as follows;

- **Vertical single drainage**

Vertical drainage to the top surface of the sample only with pore pressure measured at the center of the base.

- **Vertical double drainage**

Vertical drainage to both top and bottom surfaces of the sample simultaneously without measurement of pore pressure.

- **Horizontal inward drainage**

Horizontal (radial) drainage to a pervious boundary at the perimeter with the top and bottom faces sealed and pore pressure measured at the center of the base.

- **Horizontal outward drainage**

Horizontal (radial) drainage to a drainage well at the central axis and pore pressure measured at a distance of 0.55R from the center (where R is the radius of the cell).

- **Free strain loading condition**

Flexible porous disk is placed on the sample. Hence, sample is loaded under the flexible loading condition (uniform pressure distribution) (Figure 2-5).

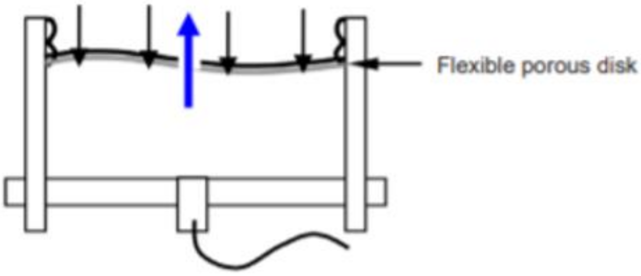

Figure 2-5: Graphical illustration of free strain loading condition (Head, 1994)

- **Equal strain loading condition**

Rigid porous disk which maintains a plane surface to the sample is placed on the sample (Figure 2-6).

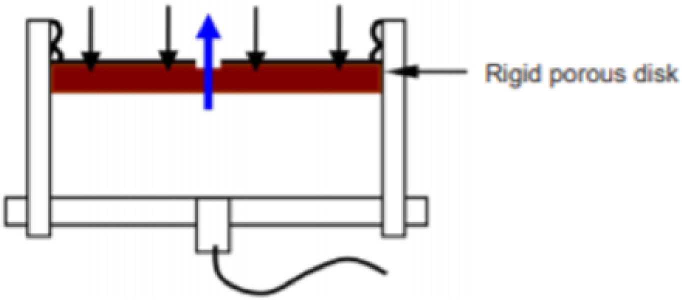

Figure 2-6: Graphical illustration of equal strain loading condition (Head, 1994)

Based on the drainage and loading conditions, eight different type of tests are defined as below;

a) Vertical single drainage and free strain
b) Vertical single drainage and equal strain
c) Vertical double drainage and free strain
d) Vertical double drainage and equal strain
e) Horizontal outward drainage and free strain
f) Horizontal outward drainage and equal strain
g) Horizontal inward drainage and free strain
h) Horizontal inward drainage and equal strain

2.5 Selection of Test Method

Head (1997) presented general guide for selection of the type of test based on conditions and requirements.

- For the determination of C_v, vertical single drainage with free strain method is normally preferred because the settlement measurement at the center of the sample is not restrained by the wall friction.
- Test with equal strain loading condition and vertical single drainage can be considered as the most related test to traditional oedometer tests. In this condition, settlement reading and volume change measurement taken from the drainage line can be directly correlated.
- Horizontal inward drainage with equal strain is usually carried out to simulate drainage wells.
- For the determination of C_h, horizontal outward drainage with free strain loading is usually preferred.
- Consolidation test with horizontal drainage drain nine times more rapidly outward to the periphery than inward towards a central drain.
- In order to maintain a uniform thickness of sample, equal strain loading condition is usually selected for permeability tests with either vertical or horizontal drainage.

2.6 Sampling techniques of MSW

Generally, waste samples for laboratory test have been extruded directly from fresh waste or from different depths within the landfill. Grisolia et al. (1995), Landva et al. (2000) and Dixon and Langer (2008) have conducted several studies using remoulded samples prepared by mixing different waste components.

2.6.1 Sampling Devices

In the absence of a fixed protocol for sampling, different researchers have incorporated several methods to obtain waste samples. Landva et al. (1984) and Landva and Clark (1990) have made attempts to obtain the waste specimens using a “Becker” type drill. In their studies, they faced many difficulties due to drive shoe is clogged with large waste particles and resulting drill hole location to be altered frequently.

Also, several researchers used split spoon samplers to obtain the waste sample. This method also had some difficulties due to bridging of the sampler opening by large waste particles, requiring re-driven of borehole in the same location or another appropriate location. Sampling using thin walled Shelby tubes has not been met with much success due to crushing the tube during driving. Generally, auger drilling is preferred to obtain waste samples from great depths. Auger drilling is used by Vilar and Carvalho (2004) and Landva and Clark (1990) to obtain the waste samples representing various degradation levels in different depth. Augers with diameter of 100mm to 400mm are used in their studies. As different sampling devices and methods are used by researchers to obtain the waste specimen for laboratory tests to determine the mechanical properties of waste samples, it occurs large variation in obtained values from the analysis. There are many difficulties in obtaining intact waste samples due to the inconsistency, presence of large fragments, etc. Hence, researchers used recompacted samples to overcome the deficiencies in sampling and sample preparation process. Further, it has been noted that large components of samples were often broken to avoid disturbance due to large fragments. In literature, information regarding the level of degradation, basic properties; moisture content, density of waste sample are not recorded in most of the studies (Landva & Clark, 1990).

2.6.2 Recompacted samples

Singh (2008) used recompacted samples for compressibility test and sample was compacted in four lift inside a steel sampler to achieve the targeted bulk unit weight. Particles that were too large to fit inside the sampler were either removed or, where possible, were broken by hand to make them fit inside the sampler. Recompacted samples were saturated and frozen to achieve the condition as in the intact samples (Singh, 2008) . The applicability of interpreted result using recompacted waste sample in landfill design need to be further investigated.

2.7 Compressibility Characteristics from published studies

- Kavazanjian et al. (1999) conducted several oedometer tests using oedometer ring having inner diameter of 460mm and height of 460mm. In all cases, there was a relatively rapid immediate compression response upon load application followed by a time-dependent delayed compression response. Figure 2-7 shows the obtained compression results.

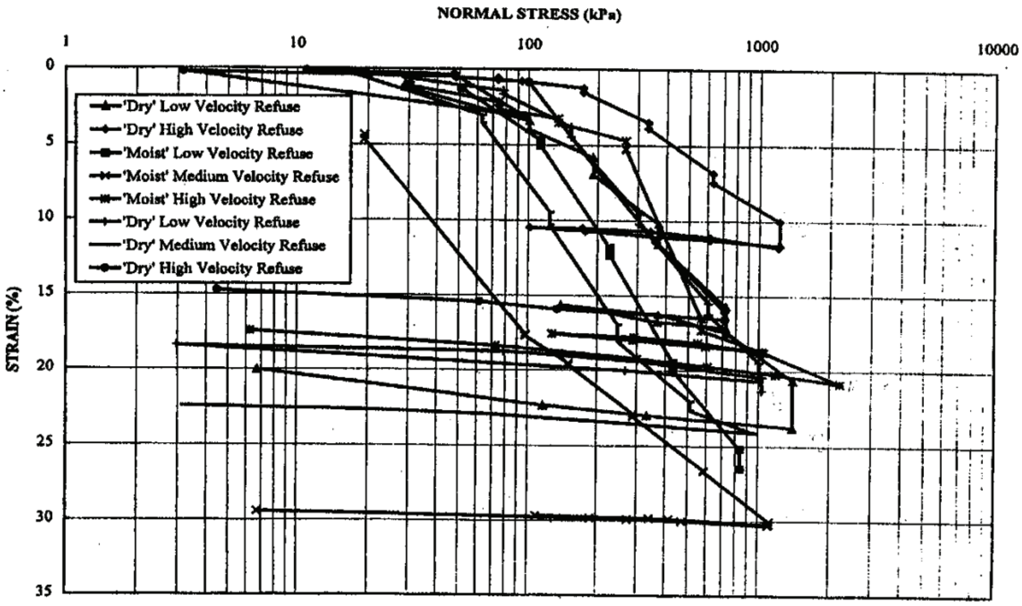

Figure 2-7: Large scale laboratory compression data from Kavasanjian et al. (1999)

- Obtained Compression index (Cc) is between 0.121 and 0.247 and recompression index (Cr) is between 0.003 and 0.017. Also, secondary compression index (Cα) have a range of 0.01 to 0.0000066. Further, they identified that the delayed response of the wettest specimen was a much more significant component of the total deformation than that of the moist and dry specimens. The transition from immediate to delayed compression was not well defined for the specimens with a high moisture content.

- Imre et al. (2014) conducted oedometer tests using box of 50cmx 50cm (thickness of sample = 7cm, depth of box = 40cm). Hydraulic loading system was used and test was performed under vertical single drainage through bottom of sample. Figure 2-8 compares the obtained compression curves for waste sample with behavior of a soft lacustrine Szeged clay. Curve 1, 2, 3 represented three different degradation levels (i.e. phase 1, phase 2, phase 3). The maximum volumetric strain for the waste samples is equal to 61% ,44%, 54%, for samples 1, 2 and 3 respectively. As the compressibility of waste decreases with the increase of degradation level, compressibility of waste does not have significant influence from the degradation level and it seems to be effected by the pre consolidation pressure.

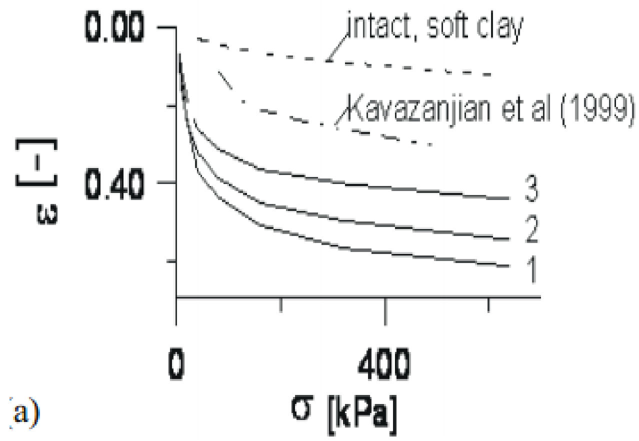

Figure 2-8: Compression curves for three samples with degradation phase of 1, 2, and 3 in semi-logarithmic plot (after Imre et al., 2014)

- Castelli et al. (2008) conducted confined compression test using a large scale one dimensional cell which is made of steel cylinder with diameter of 60cm and height of 80cm. The tests were performed on disturbed and unsaturated samples obtained from 5 years old MSW and fresh MSW. Vertical strain (ΔH/Hi) vs time plots obtained from the researcher are presented in Figure 2-9 and Figure 2-10. The result only represents the mechanical settlements.

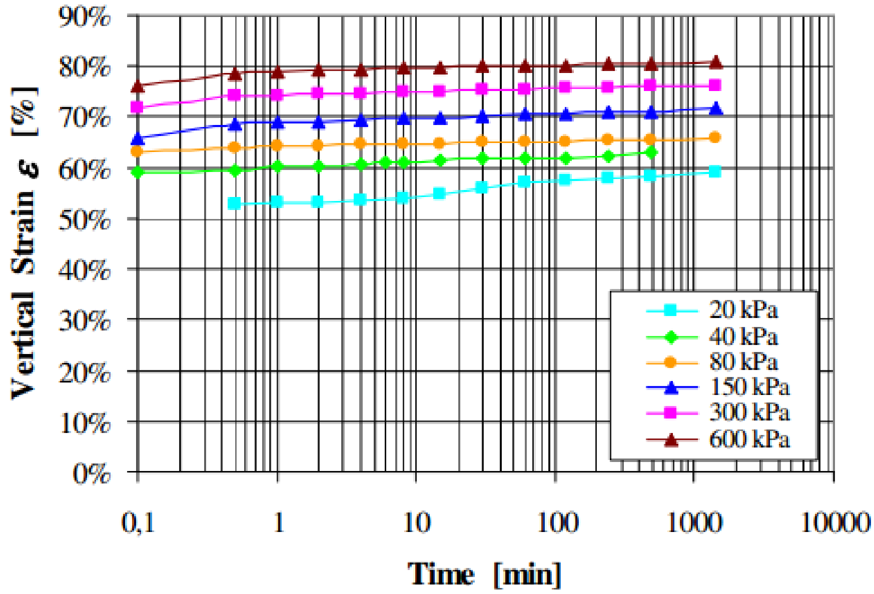

Figure 2-9: Time-vertical strain curves of fresh waste (after Castelli et al.,2008)

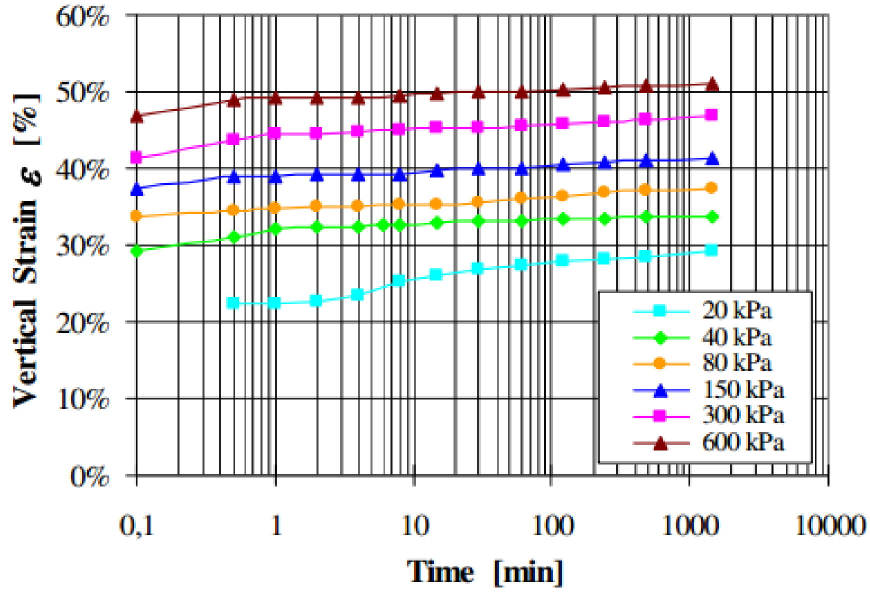

Figure 2-10: Time-vertical strain curves of 5 years old waste (after Castelli et al., 2008)

- Rakic et al. (2015) conducted consolidation test for old MSW obtained from two waste dump in Serbia. An Oedometer apparatus with diameter of 20cm ad height of 20cm was used and samples with height of 8cm were installed in it. Two series of four samples (A and B) were formed. The waste used for Series A and B were collected from the waste dump in Ada Huja (age over 40 years) and Novi Sad (age about 20 years) respectively. For both series, samples were formed with different unit weights and with natural moistures. Total duration of the test for samples of the series A was 74 days and for samples of the series B was 161 days. Authors emphasized that in the early period of time, most of the curves have a relatively slow trend, which significantly increases with time (Figure 2-11 and Figure 2-12).

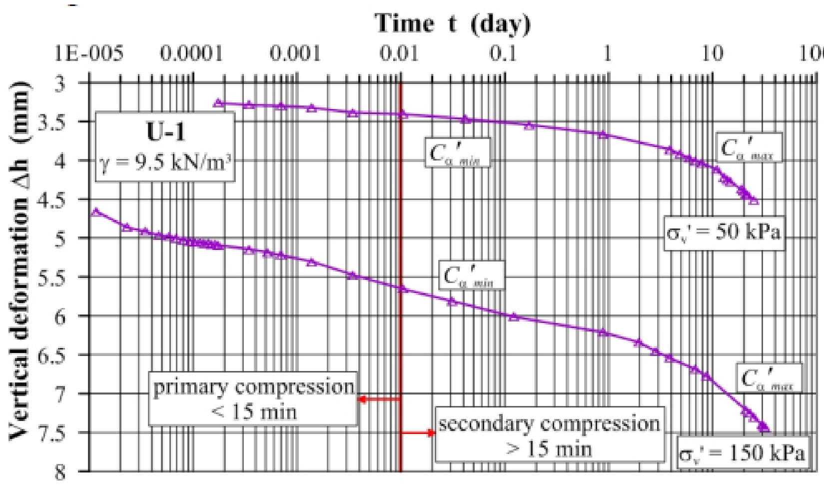

Figure 2-11: Compressibility diagram for loading level 50 and 150kPa - Sample Series A (after Rakic et al., 2015)

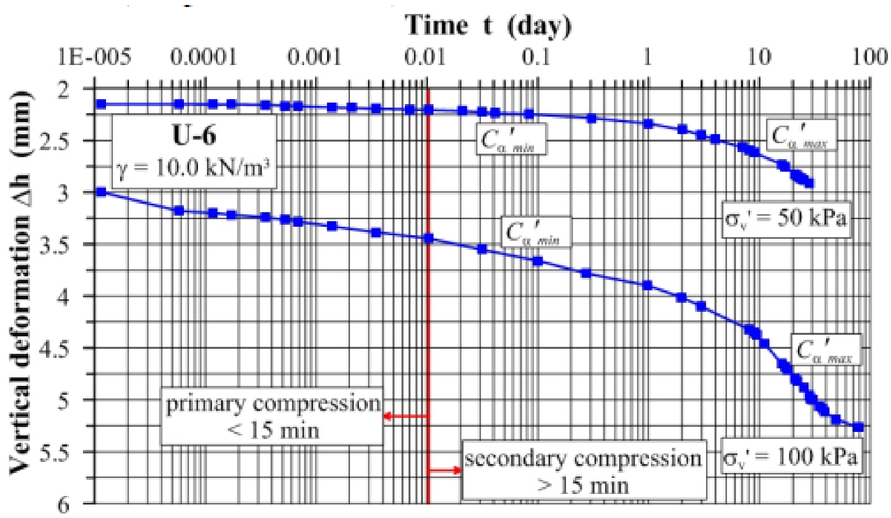

Figure 2-12: Compressibility diagram for loading level 50 and 150kPa - Sample Series B (after Rakic et al., 2015)

Further, Rakic et al. (2015) considered that the secondary compression starts after 15min. Further, Landva et al. (2000), Hossain & Gabr (2005) and Singh (2008) have made similar assumptions on both the duration of primary and the beginning of secondary compression.

Obtained values of modified primary and secondary compression index are presented in Figure 2-13 and Figure 2-14. Index and modified index of secondary compression were determined for all load steps, particularly for less steep and steeper parts of the curve. Considering the nature of deformations, its minimal values $C_{\alpha min}$ and ${C_\alpha}'_{min}$ were determined from the less steep part of the diagram, while from the steeper part of the diagram (which generally begins after 1 to 5 days), the maximal values $C_{\alpha max}$ and ${C_\alpha}'_{max}$ were determined.

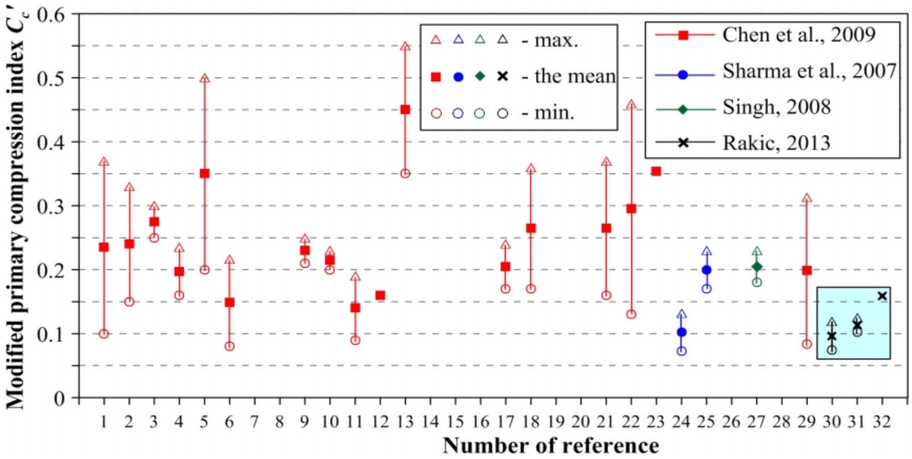

Figure 2-13: Comparison of Modified primary compression index (after Rakic et al., 2015)

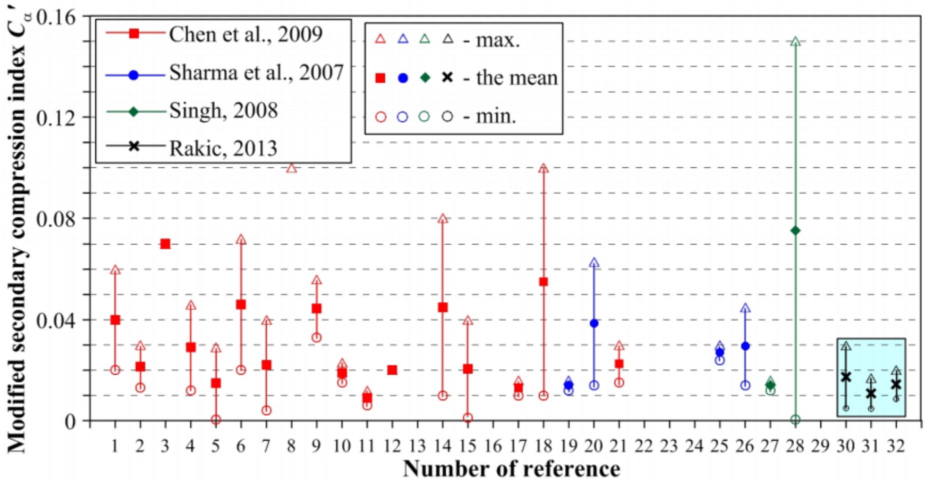

Figure 2-14: Comparison of Modified secondary compression index (after Rakic et al., 2015)

Rakic et al. (2015) concluded that the reasons for such pronounced result dispersion as follows:

- Method of sample preparation, i.e. Different initial values of void ratio and bulk density, but also the use of different normal stress values during the test.
- Using different methodologies during the test performance
- Duration of the test i.e. some researchers performed short-term tests and the loads lasted from several hours to several days during one stage
- Loading duration i.e. in some cases time per one load stage was several months and upto one year
- Using different apparatus rather than using conventional oedometer.

▪ Hossain et al. (2009) carried out laboratory tests for MSW and obtained compression index values varied between 0.16–0.37, and secondary compression coefficient ($C\alpha$) was between 0.02 and 0.07.

▪ Singh (2008) summarized the compressibility indices of MSW from published studies and the results are presented in Figure 2-15.

Reference	Primary		Secondary		Remarks
	C_{ce}	C_c	$C_{\alpha e}$	C_α	
Vilar and Carvalho (2004)	0.18-0.23	0.52-0.92	0.012-0.016	0.021-0.044	auger cuttings; 15 year old waste; test cell 365mm in diameter; γ = kN/m^3; loading duration 7-15 days but no consideration for degrad max. vertical stress =640 kPa
Hossain et al. (2003) (a) With accelerated degradation (b) Degradation inhibited		 0.16-0.37 0.16-0.25		 0.08-0.22 0.07-0.12	test cell 63.5mm in diameter; shredded waste(10mm x 20mm); loa duration 70 days; constant vertical stress 95 kPa;
Landva et al. (2000)	0.17-0.24		0.01-0.016		test cell 600 mm diameter; sample 5 year old+ additional artificial s degraded for 9 years; constituents > 150mm were shredded; vertic 46-260 kPa; loading duration 1-32 days
Gabr and valero (1995)		0.4-0.9		0.009-0.03	test cell 63mm diameter; particle size < 6.3mm; sample-auger cutt representative of 15-30 yaer old waste; initial void ratio 1.0-3.0; Nc vertical stress and test duration
Wall and Zeiss (1995) (a) With accelerated degradation (b) Degradation inhibited	 0.25 0.21		 0.033-0.056 0.037-0.049		test cell 570mm in diameter designed to perform as both lysimeter consoildometer; particle size reduced by shredding; loading durati 229 days at a constant average vertical stress of 10kpa.
Sowers (1973)		0.15-0.55 times e_o		0.03-0.09 times e_o	Compression indices related to initial void ratio

Figure 2-15: Compressibility indices of MSW from published studies (Singh, 2008)

2.8 Parameters to characterize a stiffness of Soil /MSW

In soils, settlement is mainly subdivided into elastic settlement and consolidation settlements. Elastic settlement occurs from shear strains which happens at constant volume with the application of load on soil. A linear elastic model is commonly applied for the computation of immediate settlement in nearly saturated or saturated cohesive soils. Consolidation settlement are time dependent and results from volume change due to dissipation of water from the voids of the soil skeleton. Similarly, MSW behave as soil with respect to settlement characteristics.

Magnitude of settlement that occurs in a given period and time taken for a given settlement to occur are always necessary for the constructions on compressible materials. These time-settlement computations are determined based on the Terzaghi's theory of consolidation. As the rate and magnitude of settlement are non-uniform, differential settlement can have significant influence on the integrity of structure developed on the waste dumps.

2.9 Analytical methods for determination of Compressibility indices

2.9.1 Coefficient of Volume Compressibility (m_v)

Coefficient of volume compressibility is a parameter used to estimate the settlement. m_v is defined as in Equation 2-7.

$$\boldsymbol{m_{v}} = \frac{\Delta h}{h\Delta\sigma} = \frac{\Delta e}{(1+e)\Delta\sigma} \qquad \textbf{Equation 2-7}$$

2.9.2 Compression Index (C_c) and Recompression (C_r)

The compression index (C_c) is equal to the slope of the linear portion of field compression versus log time plot, which is usually referred to as 'Virgin Compression Line' (VCL). Numerically, C_c is equal to the change in void ratio for one log cycle of pressure change as illustrated in Figure 2-16 (Head, 1994).

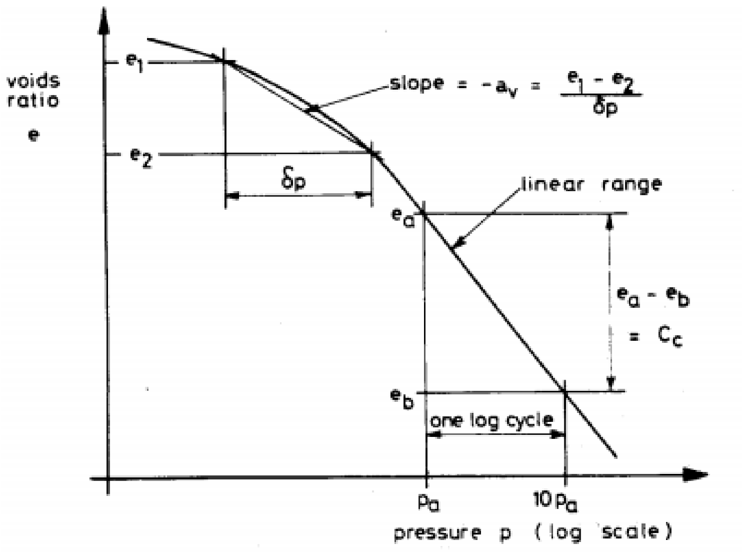

Figure 2-16: Schematic diagram for determination of compression index (Head, 1994)

The recompression index (C_r) is equal to the slope of the unloading curve of void radio versus log pressure (Head, 1994) . It is obtained in similar manner to the method used for determining C_c.

2.9.3 Coefficient of Secondary compression (C_α)

The Coefficient of Secondary compression (C_α) was determined from the slope of the straight-line portion of void ratio versus log time plot beyond the primary consolidation and graphical method is explained in Figure 2-17.

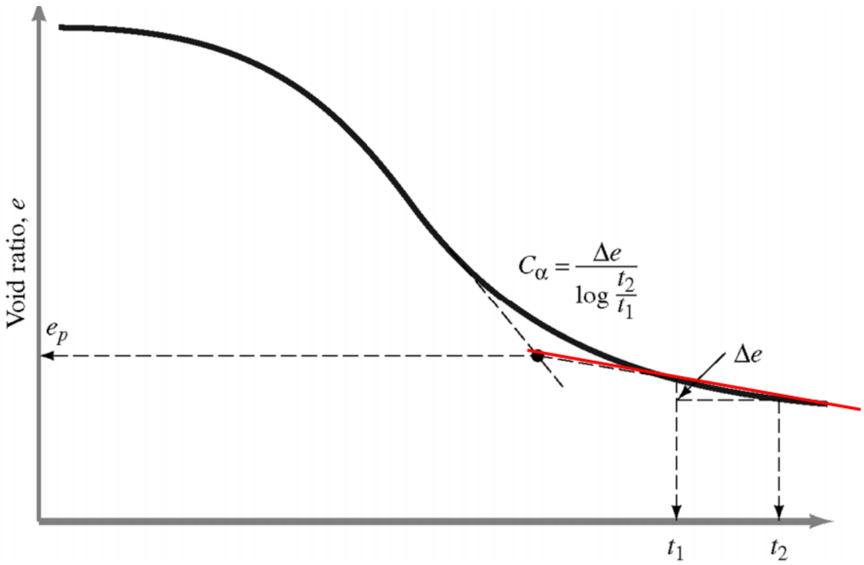

Figure 2-17: Schematic diagram for determination of C_α (Head, 1994)

The coefficient of secondary compression is given by Equation 2-8.

$$C_\alpha = \frac{\Delta e}{\log\left(\frac{t_2}{t_1}\right)}$$ **Equation 2-8**

2.9.4 Coefficient of Consolidation (C_v)

In consolidation test, initially specimen undergoes immediate settlement and thereafter primary and secondary compression phases are occurred respectively. In laboratory test, it is difficult to clearly identify the ends and beginning of each phases. Hence, identification of type of settlement that correspond to different degree of consolidation is complex. Further, compression behavior in actual field condition is slightly different from the behavior observed in laboratory test (Naveen, et al., 2018). Therefore, curve fitting methods were introduced to determine the coefficient of consolidation values using laboratory test results.

There are different analytical methods used to calculate the coefficient of consolidation. Some of them are;

1. Logarithm of time method } Curve fitting method
2. Square root of time method } Curve fitting method
3. Rectangular Hyperbola Fitting method
4. Velocity method

Square root time method and logarithm of time method became routinely used method for evaluation coefficient of consolidation and are recognized as standard methods with the publication of the book "Fundamentals of Soil Mechanics" authored by D.W. Taylor in 1948 (Shukla, et al., 2009).

2.9.4.1 **Logarithm of time method of Casagrande and Fadum (1940)**

In order to determine the coefficient of consolidation using logarithm of time method, compression reading at least for 24 hours is required. Hence, secondary compression of the material can be accounted by the settlement versus logarithm of time. Compression dial reading are plotted against log time for each increment of load. Generally, semi logarithmic plot of settlement vs time gives identifiable 3-branches curve; (1) an initial parabolic curved part (2) a midpart is relatively straight (3) a curved part for the end portion and shape is generally in the form of S shape.

Graphical construction as illustrated in Figure 2-18 shall be performed in order to obtain t_{50} (i.e. time required for 50% consolidation) and co efficient of consolidation can be determined using Equation 2-9 (Bowels, 1997).

$$C_v = \frac{0.197H^2}{t_{50}} \qquad \textbf{Equation 2-9}$$

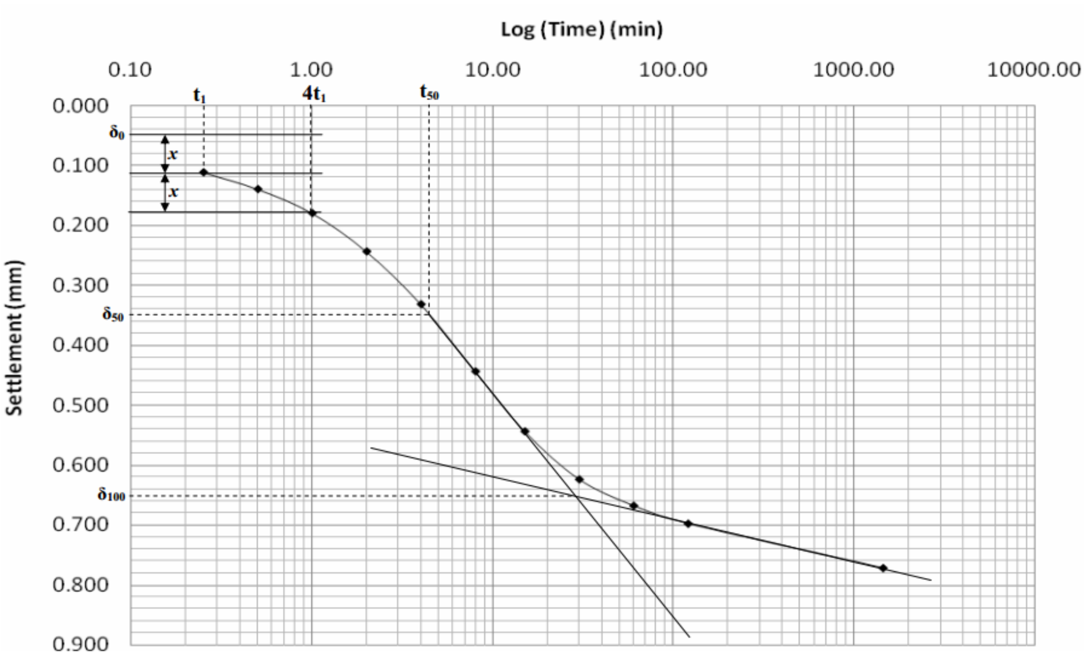

Figure 2-18: Graphical construction of Logarithm of time method

2.9.4.2 **Square root of time method per Taylor (1948)**

In order to determine the coefficient of consolidation using this method, compression reading should be recorded until reaching at least 90% of primary settlement for each load increment. Time taken to reach 90% consolidation is varied with type of sample, thickness of sample. Hence, dial gauge reading is taken in close intervals up to period of 1 hour after applying the load on specimen. The procedure for determination of C_v is illustrated in Figure 2-19 and coefficient of consolidation can be determined using Equation 2-10.

$$C_v = \frac{0.848H^2}{t_{90}} \qquad \textbf{Equation 2-10}$$

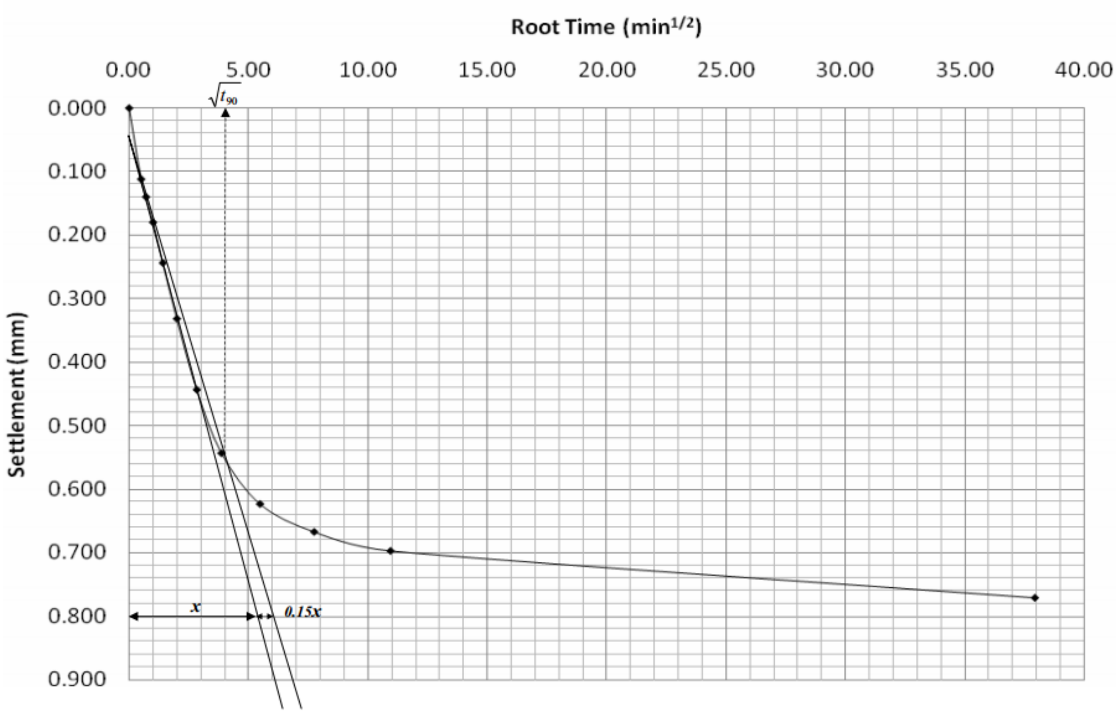

Figure 2-19: Graphical construction of square root time method

Both the Taylor's and Casagrande's method are most widely used in general practice with several limitations. Settlement reading corresponding to 0% and 100% consolidation at each loading increments can be determined using these curve fitting methods: Taylor's and Casagrande's method. However, these methods are not applicable in some cases due to variation encountered in the pattern/shape of time settlement curves.

The difficulties that are often encountered with Casagrande method are;

- In the Logarithm of time method, point corresponding to 100% consolidation is recognized as intersection of the tangential line through the inflection point in the curve representing primary settlement segment and straight line representing the secondary settlement. Hence, this method is applicable only for instances where typical S-shaped curves are obtained.
- The identification of the linear portion which represent the secondary compression is required in the Casagrande method. When the soil undergo large secondary settlement, it is difficult to clearly identify the secondary settlement from primary settlement.

- This method takes a substantially longer time for the secondary portion to be established clearly (Shukla, et al., 2009).

The Taylor's method suffers from the following disadvantages;

- In some case, an initial linear portion is not obtained.
- For some materials, rate of compression is slow in initial stage and rapid compression thereafter. In such situations, when extending initial linear portion backward, it may result a negative intercept on the compression axis and it causes problem in demarcating the point corresponding to 90% consolidation.
- There are instances where the soil exhibits rapid compression in initial stage of the test. Hence, obtaining dial gauge reading at close time intervals is difficult. Also, flattened compression curve can be seen after sudden large compression.

2.9.4.3 **Rectangular Hyperbola Fitting method**

Initially, Sridharan and Rao (1981), and Sridharan and Prakash (1985) conducted studies related to basic concept and methodology of curve fitting method. Further Sridharan et al. (1987) conducted detailed study regarding rectangular hyperbola method to determine the coefficient of consolidation. The rectangular hyperbola fitting method is developed based on the Terzaghi's theory of consolidation. In this method, plot developed with time (T) vs Degree of Consolidation (U) can be represented by a rectangular hyperbola in the range of 60%-90% degree of consolidation (Sridharan, et al., 1987). Subsequently, T/U plotted against T as shown in Figure 2-20. The typical T/U vs T curve initiated from the origin and curvature continue up to 60% degree of consolidation and became straight line beyond the point corresponded to 60% of U.

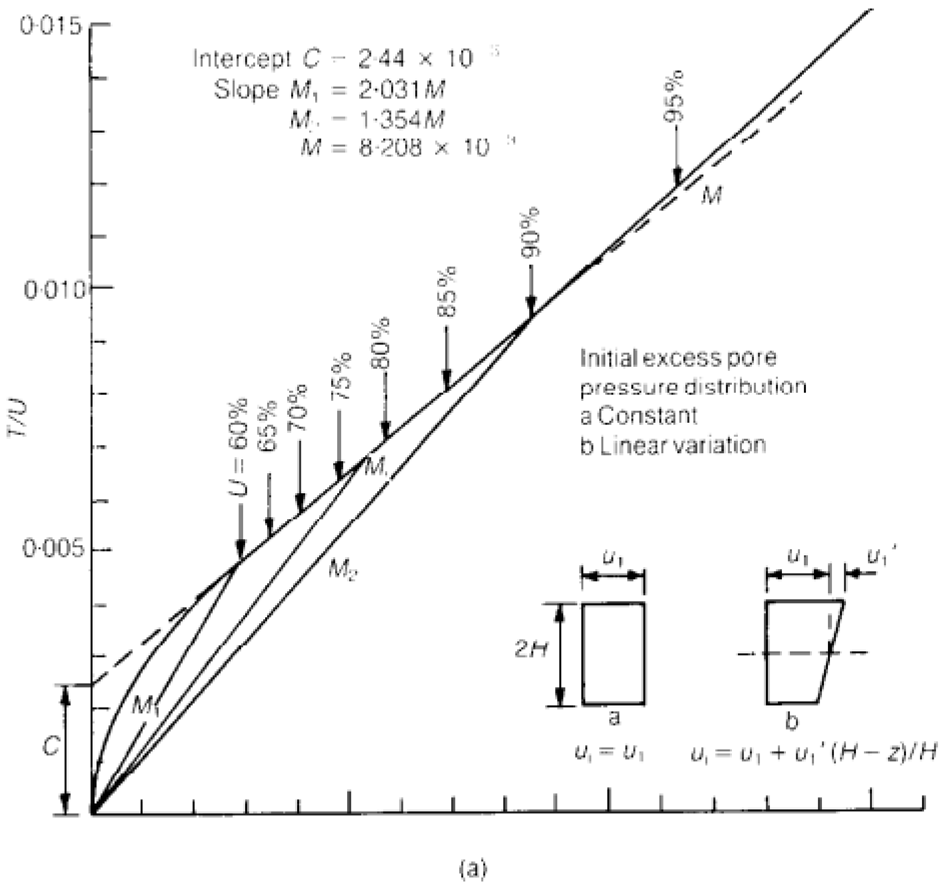

Figure 2-20: Theoretical plot of T/U vs T relationship from Terzaghi's consolidation equation (after Sridharan et al., 1987)

The method for determination of Cv using rectangular hyperbola method is as follows;

- Record the deformation values (δ) and respective time (t)
- Plot t/δ against t and find the initial straight line part of the graph
- Calculate the gradient (m) and intercept (c) of straight line part of curve

Using obtained m and c, C_v can be computed using Equation 2-11.

$$C_v = \frac{0.24mH^2}{c} \quad \textbf{Equation 2-11}$$

When the soil exhibits large secondary compression, several straight-line segments will be obtained in the t/δ vs t plot. In such situations, the first line which presence after the initial curve portion is selected for interpretation.

The rectangular hyperbola method can be mentioned as a simple method and have several advantages.

- It is applicable for any type of time settlement curves
- Recording compression reading at equal time intervals is not an essential requirement to obtain initial straight-line part of experimental plot (t/δ vs t).

However, small variation in fitting initial straight-line part causes a significant change in result, especially in the cases having lower intercept value.

2.9.4.4 **Velocity method**

Parkin (1978, 1981) developed another method called velocity method to determine the coefficient of consolidation by avoiding identified drawbacks of standard existing procedures. In this method, it does not involve any construction to identify the initial primary compression or secondary compression. Basically, theoretical compression curve (theoretical consolidation rate vs time) and experimental settlement curve (experimental settlement rate vs. time) are plotted to compare the geometry of curves by direct superposition. Both curves are developed in double logarithmic plot which facilitate the matching operation of theoretical and experimental curves (Parkin, 1978). As the analysis is carried out using rate of settlement instead of settlement due to load, there is no any influence on result due to initial and final conditions.

The theoretical Terzaghi's consolidation equation is given as a velocity plot in Figure 2-21. In this method, it is assumed that behavior of all experimental compression curves must be geometrically identical.

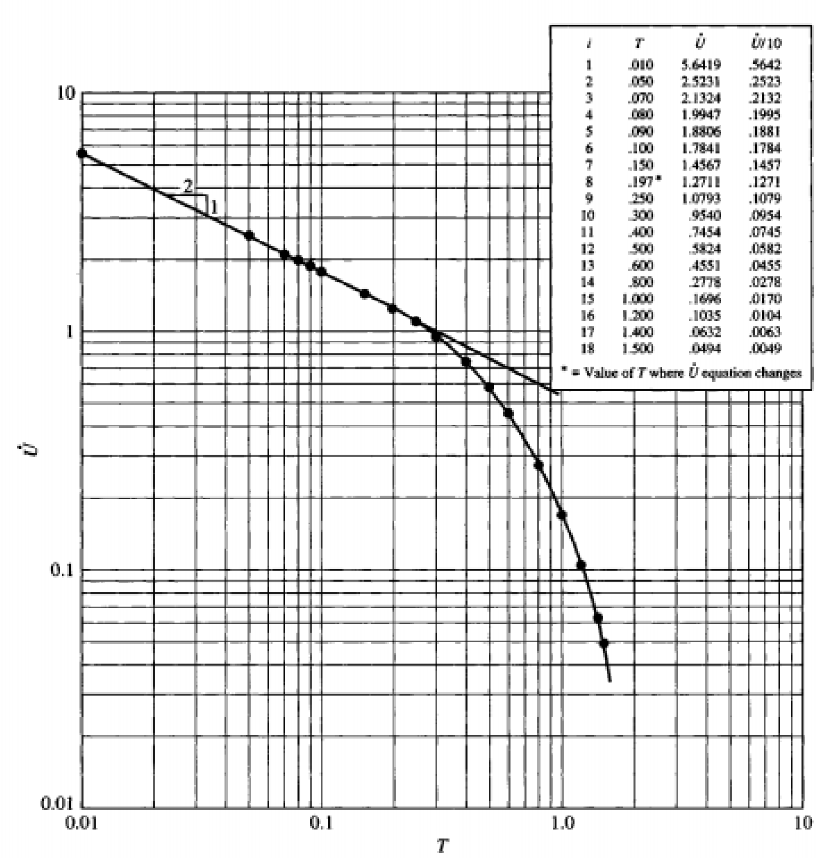

Figure 2-21: Theoretical plot for velocity method (After Parkin, 1978)

This theoretical curve has a slope of 2H:1V in the initial section, up to U≈ 50% and thereafter the slope increases continuously tending to infinity.

The procedure for determination of C_v is as follows:

- Record the deformation values (δ) and respective time (t)
- Develop the log(δ/t) vs log (t) plot and obtain a best fit curve by aligning the section with gradient of 1:2 in theoretical curve with the experimental curve
- Obtain the time t on the experimental curve relating to T=1 on the theoretical curve

When T=1, U is equal to 93% in the theoretical curve. Hence obtained t value in this situation is denoted as t_{93}. C_v can be computed using Equation 2-12 for each load increment.

$$C_v = \frac{H^2}{t_{93}} \qquad \textbf{Equation 2-12}$$

When the experimental points lie scattered, it is not possible to obtain t corresponding to T=1 as point where the 2H:1V line deviates to a nonlinear portion cannot be clearly recognized. When material undergo large secondary settlement, experimental settlement rate was greater than the theoretical settlement rate and resulting difficulty in obtaining t_{93} (Parkin, 1978). If the previous load increment is maintained for a period during which a considerable amount of secondary consolidation occurs, the initial part of the velocity curve is slightly flatter than 2H:1V for the load increment under consideration. Further, Parkin and Lun (1984) identified that the type of soil affects the slope and difficulties occurred in overlaying process of experimental and theoretical curves.

Improved velocity method

Based on the consolidation rate concept proposed by Parkin (1978), Pandian et al. (1994) suggested an improved velocity method to address the shortcoming of velocity method. Patrick et al. (1985) illustrated that the generalized velocity curves included three straight line sections (a, c and d) and one transition curve (b) (Figure 2-22). The liner segment (a) represented variation of settlement rate related to initial primary consolidation (i.e. less than 50% consolidation). The linear segment (c) and linear segment (d) are representing the condition just before the end of primary settlement and just after the beginning of secondary settlement respectively. (Pandian, et al., 1994).

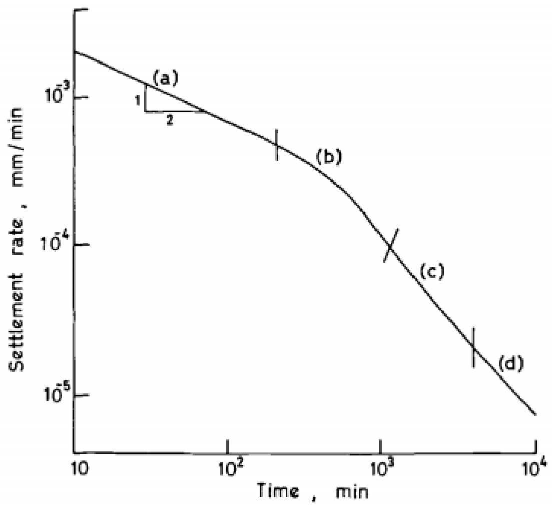

Figure 2-22: General characteristics of and experimental velocity curve (Patrick et al., 1985)

Accordingly, following procedure was proposed to determine the C_v;

- Record the deformation values (δ) and respective time (t)
- Compute the settlement rate dδ/dt between successive readings and the corresponding average time (t)
- Plot log(dδ/dt) against log (t)
- Find the three linear sections and transition curve
- Find the value of t corresponding to the intersection of linear portion (a) and (c)
- Find time t on the experimental velocity curve corresponding to T=1 on the theoretical velocity curve

C_v can be computed using Equation 2-13 for each load increment.

$$C_v = \frac{0.524d^2}{t} \qquad \textbf{Equation 2-13}$$

2.9.4.5 Comparison of different methods used to determine C_v of MSW

The shape and behavior of the experimental settlement curves are varied significantly with the type of waste and the initial segment of the curve can be more erratic. In such cases, it is not possible to obtain an accurate value for t_{50} (time corresponding to 50% consolidation) as the settlement readings corresponding to beginning of initial settlement and the settlement corresponding to 100% consolidation are incorrect. While, both primary and secondary settlements are incorporated in Casagrande's method and Taylor's method used only the primary settlements. Hence, the Taylor's method can be considered as more accurate method except cases which obtained non liner segment for secondary settlement (Naveen, et al., 2018).

Sridharan et al. (1978) analyzed several consolidation test results to obtained C_v using Casagrande's method, Taylor's method and Rectangular Hyperbola method (Figure 2-23 and Figure 2-24). It can be seen that the rectangular hyperbola method gives C_v values which fall in between those obtained from Casagrande's and Taylor's method. Hence, they concluded that the values of C_v obtained from Rectangular Hyperbola method can be taken as satisfactory and confirmed the validity of the method for determining coefficient of consolidation.

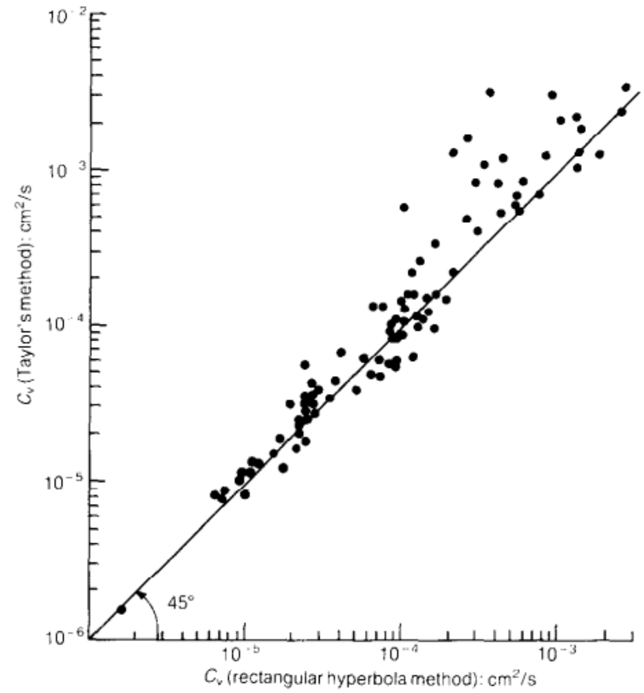

Figure 2-23: Comparison of value of C_v obtained from the Taylor and Rectangular Hyperbola method (Sridharan et al., 1978)

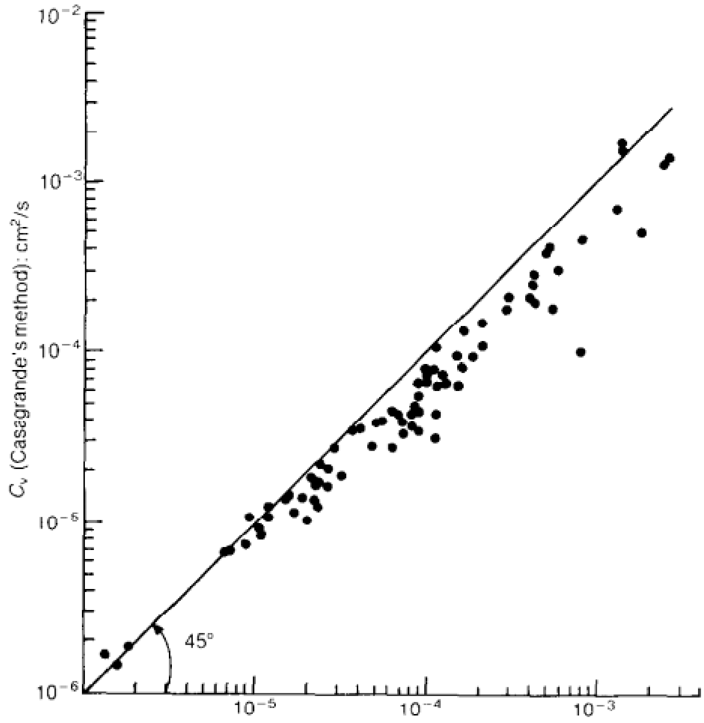

Figure 2-24: Comparison of value of C_v obtained from the Casagrande and Rectangular Hyperbola method (Sridharan et al., 1978)

Pandian et al. (1994) analysed experimental data obtained from standard Oedometer test conducted in the Soil Mechanics Laboratory of the Indian Institute of Science and compared improved velocity method with other analysis method used for determining Cv (Figure 2-25 to Figure 2-27).

As the experimental points lied on both side of the 45^0 line, Pandian et al. (1994) mentioned that there is fairly good agreement between the improved velocity method and other method.

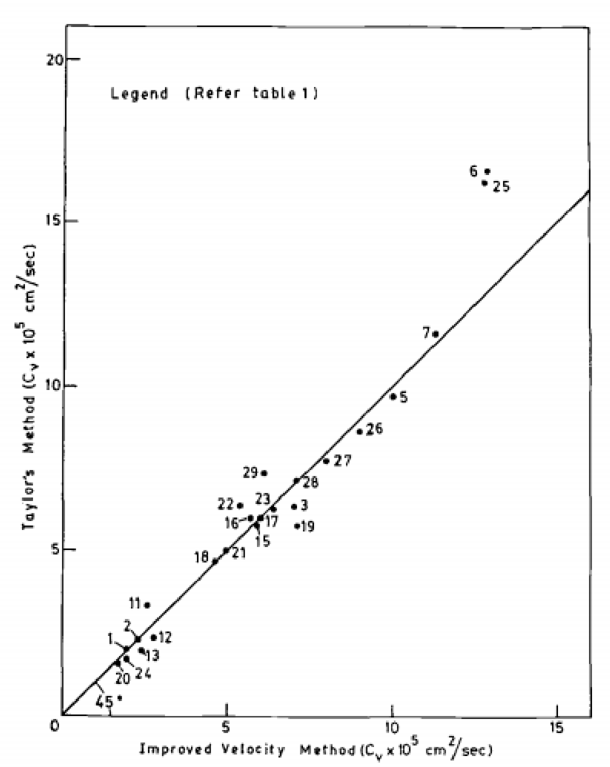

Figure 2-25: Comparison of value of C_v obtained from the Taylor and Improved velocity method (Pandian et al. ,1994)

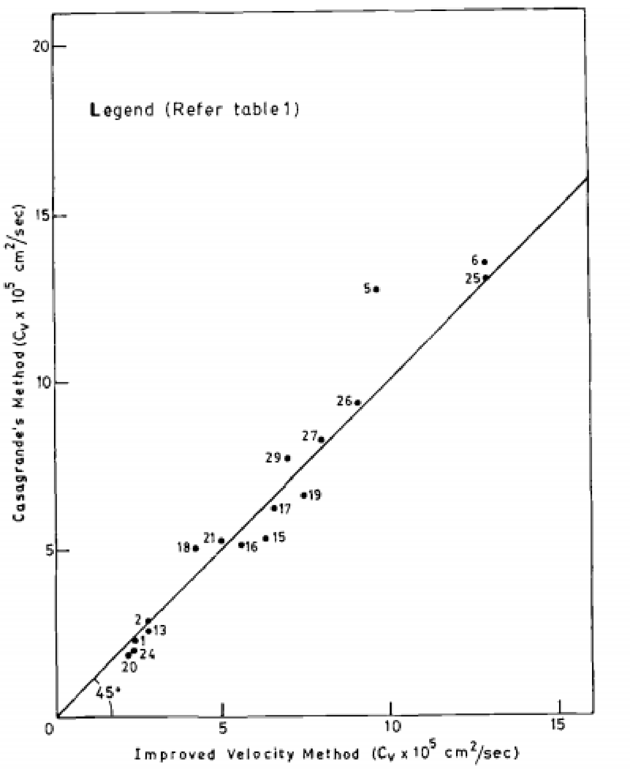

Figure 2-26 : Comparison of value of C_v obtained from the Casagrande and Improved velocity method (Pandian et al. ,1994)

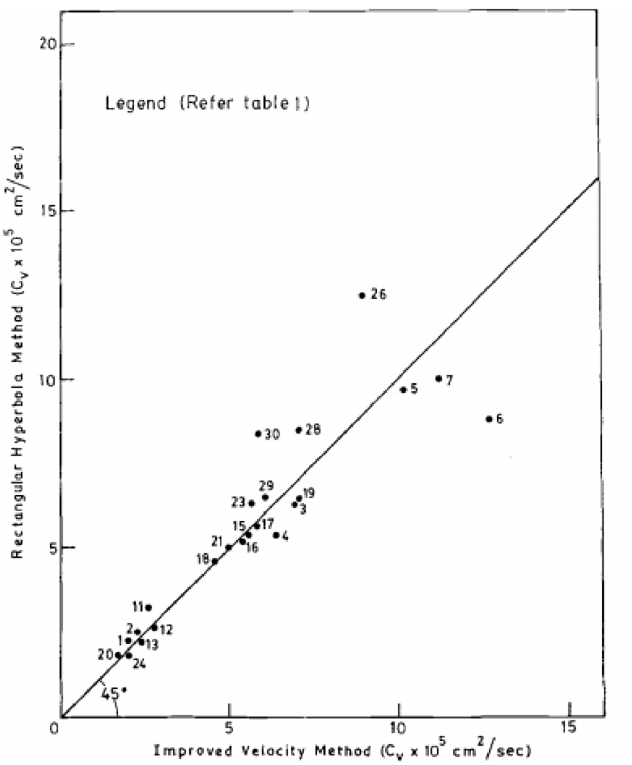

Figure 2-27: Comparison of value of C_v obtained from the Rectangular Hyperbola method and Improved velocity method (Pandian et al. ,1994)

Naveen et al (2018) conducted several one-dimensional consolidation test for dry and dumped specimen collected form Mavallipura landfill in India. Cell with diameter of of 76mm and depth of 40mm is used for the experiment. Data of each loading stages were used to develop the e vs log(σ) curves for MSW and obtained graph is as follows; (Figure 2-28)

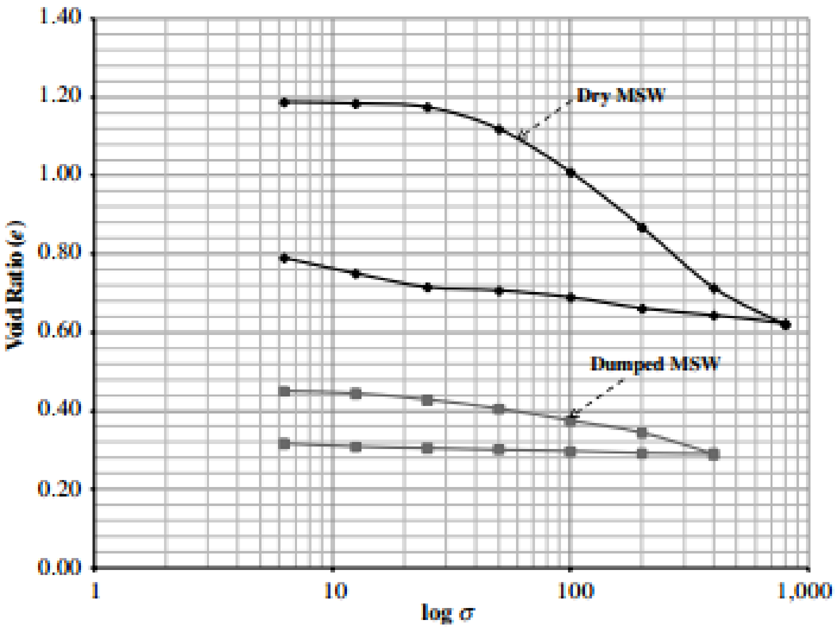

Figure 2-28 : Void ratio vs pressure graph (after Naveen et al., 2018)

Obtained values of compression index (C_c) were found to be 0.47 for the dry MSW and 0.15 for dumped MSW. Secondary compression coefficient (C_α) values were 0.071 and 0.005 for dry MSW and dumped MSW respectively. Square root time method, Casagrande method and Rectangular hyperbola method were used to calculate the Coefficient of Consolidation and obtained results are as summarized in below Table 2-5.

Table 2-5: Comparison of C_v from various method (after Naveen et al, 2018)

Specimen	Load Increment (kPa)	Casagrande's C_v (cm²/min)	Taylor's C_v (cm² /min)	Rectangular Hyperbola C_v (cm²/min)	
				t_{60}	t_{90}
Dry MSW	50-100	0.82	0.074	0.041	0.05
	100-200	0.6	0.016	0.014	0.034
	200-400	0.46	0.21	0.45	0.51
	400-800	0.12	0.12	0.41	0.5
Dumped MSW	50-100	0.88	0.084	0.061	0.061
	100-200	0.72	0.026	0.024	0.054
	200-400	0.58	0.36	0.59	0.61
	400-800	0.21	0.25	0.52	0.6

Finally, Naveen et al (2018) made following conclusions based on the obtained results;

- For the determination of the coefficient of consolidation values of MSWs, t_{30} values were not very reliable, and hence t_{60} or t_{90} were recommended.
- As obtained C_v values in closer range, applicability of rectangular hyperbola method was suggested as best alternative in cases where time settlement curves does not follow the standard shape related to Taylor's and Casagrande's method
- The computed coefficient of consolidation values of MSW using the rectangular hyperbola method lied between the C_v values obtained from Casagrande's and Taylor's method.

2.10 Specific Gravity of MSW

Specific gravity is the ratio of the mass of a unit volume of soil solids to the mass of the same volume of gas free distilled water at 20°C. Due to the presence of large particles, heterogeneous nature in waste material, complex interaction between waste component and water, it is difficult to determine the specific gravity of MSW and also values are varied significantly. Further, during the test, particles which were having a lower density than water may float. When the waste sample contains the material types which are having intraparticle voids and compressible particles, it may influence the measurement of specific gravity. Moreover, absorption or dissolution potential of waste materials may have impact on the specific gravity value (Yesiller, et al., 2014). However, several researchers conducted laboratory test to estimate the specific gravity of MSW using large pycnometers. Yesiller et al. (2014) summarized the specific gravity values of MSW from published studies (Table 2-6).

Table 2-6: Specific Gravity values of MSW from literature (Yesiller et al., 2014)

Material	Test	Details	Gs	Reference
Manufactured waste	ASTM D854	US representative waste stream 100g specimens Particle size less than 5 mm	1.6	Hettiarachchi (2005)
Mechanically and biologically pre-treated waste	Water Pycnometry	Waste sample obtained prior to disposal from a German landfill	1.588-1.98[a]	Entenmann and Wendt (2007)
Fresh shredded waste	ASTM D854	Sample obtained from active face of a landfill in US Sample collection prior or post compaction not reported Max. particle size was 40 mm	0.85	Reddy et al. (2009a)
Old shredded waste	ASTM D854	Sample obtained from 20 m depth at a landfill in US Waste age was 1.5 years Max. Particle size was 40 mm	0.97	Reddy et al. (2009a)
Manufactured waste	ASTM D854	US representative waste stream Max. particle size was 40 mm Un-degraded	1.09	Reddy et al. (2011)
Manufactured waste	ASTM D854	US representative waste stream Max. particle size was 40 mm Degraded	2.05-2.47	Reddy et al. (2011)
Relatively fresh waste	Modified ASTM D854	Shredded and recombined relatively fresh (3-4 months old) wastes Obtained from a landfill in US Max. particle size was 25 mm	1.34	Breitmeyer (2011)
Laboratory degraded waste	Modified ASTM D854	Same waste as above after low(L), medium(M) and high(H) degradation in the laboratory Max. particle size was 25 mm	1.65(L), 1.80(M) ,1.90 (H)	Breitmeyer (20_11)
Old waste	ASTM D854	Wastes obtained from shallow(S), middle(M) and deep(D) layers form a landfill in China	1.51(S), 1.88(M) ,2.14 (D)	Wu et al. (2012

[a] Converted to G_s

Further, Yesiller et al, (2014) conducted specific gravity test for different types of MSW using an Erlenmeyer flask with a volume of 2000ml and specimens with 100-

350g. From the obtained results they concluded that the specific gravity of waste is increased with decreasing particle size, compaction level, degradation, and stress over the landfill. Obtained results are presented in Table 2-7.

Table 2-7 : Specific gravity test results (Yesiller et al, 2014)

Test[a]	Description	Test details	Specimen mass (g)	G_s (20⁰C)	G_s Average
M	As-prepared (uncompacted)	Coarse Medium Fine	103.6 100.54 99.53	1.339 1.376 1.419	1.378
M	As-prepared (uncompacted)	Coarse Medium Fine	100.06 100.3 100.08	1.326 1.372 1.429	1.376
M	Compacted – dry of optimum moisture content	Coarse Medium Fine	100.07 100.11 100.02	1.497 1.521 1.552	1.523
M	Compacted –wet of optimum moisture content	Coarse Medium Fine	100.07 100.11 100.03	1.500 1.542 1.570	1.538
F	Uncompacted	Active face	335.08	0.803	1.072
F	Uncompacted	Active face	324.92	1.248	
F	Uncompacted	Active face	186.69	1.388	
F	Uncompacted	Active face	184.04	1.178	
F	Uncompacted	Active face	261.03	0.741	
F	Compacted	Active face	186.09	1.254	1.258
F	Compacted	Active face	135.76	1.178	
F	Compacted	Active face	205.18	1.343	
F	Compacted	Active face	173.13	1.147	
F	Compacted	Active face	253.20	1.370	
O	BH 1	1.9 m depth	224.64	2.487	2.200
O	BH 1	6.2 m depth	144.26	1.962	
O	BH 1	14.2 m depth	149.97	2.151	
O	BH 2	1.9 m depth	311.40	2.113	2.166
O	BH 2	6.5 m depth	243.54	2.274	
O	BH 2	13.9 m depth	264.04	2.110	
O	BH 5	2.5 m depth	309.64	2.175	2.162
O	BH 5	3.7 m depth	281.52	2.288	
O	BH 5	5.3 m depth	335.60	2.251	
O	BH 5	7.7 m depth	316.35	2.166	
O	BH 5	12.1 m depth	290.88	2.041	
O	BH 5	13.3 m depth	342.57	2.051	
O	BH 6	1.5 m depth	283.64	2.247	2.276
O	BH 6	3.7 m depth	298.72	2.323	
O	BH 6	7.1 m depth	304.78	2.313	
O	BH 6	9.9 m depth	303.12	2.249	
O	BH 6	12.1 m depth	305.41	2.208	
O	BH 6	14.6 m depth	271.44	2.316	

[a] M-manufactured, F-fresh, O- old

Several researchers conducted specific gravity test for MSW samples collected from different sites in Sri Lanka and obtained values are summarized in Table 2-8.

Table 2-8 : Summary of Specific gravity values obtained from researchers for MSW in Sri Lanka

Dumping sites	Specific Gravity of MSW	Reference
Seeduwa	2.5	Nawagamuwa et al. (2014)
Bloemendhal	2.4	
Madampititya	2.12	
Negombo	2.38	
Jaffna 1 (Age < 5 years)	1.7247	Nawagamuwa et al. (2016)
Jaffna 2 (Age 5-7 years)	1.7652	
Jaffna 3 (Age 7-10 years)	1.8368	
Jaffna 4 (Age 10-13 years)	2.0814	
Jaffna 5 (Age 13-15 years)	2.2392	
Jaffna 6 (Age >15 years)	2.3822	
Jaffna 7 (Age 5-7 years)	1.1818	
Karadiyana 1 (Age 1 year)	1.7285	
Karadiyana 2 (Age 2 years)	1.6632	
Matara 1 (Age 1-3 years)	1.7521	
Bloemandhal bottom	1.72	Nawagamuwa et al. (2013)
Bloemandhal burnt	1.69	
Blomeandhal top	1.88	
Madampitiya	1.71	
Kolonnawa	2.4	
Bloemandhal	1.96	Nawagamuwa et al. (2015)

2.11 Waste Characterization

Proper waste characterization is required to establish systems for determining mechanical properties of waste samples. Waste characterization must provide necessary information to predict likely behavior and possible problems based on the type and engineering properties of waste materials (Dixon, Neil; Langer, Ulrich; Reddy, Krishna; Maugeri, Michele; Tinjum, James; Mahler, Claudio; Cho, Youngmin, 2008).

2.11.1 Existing waste classification systems

Classification system developed by Landva and Clark (1990) is based on the difference of organic and inorganic components. As illustrates in Figure 2-29, they subdivided the organic component of waste in to putrescible and non-putrescible and inorganic component of waste into degradable (corrodible) and non-degradable. Above system addresses factors on degradation and compressibility characteristics of waste and component related to particle shape and properties of material are not considered.

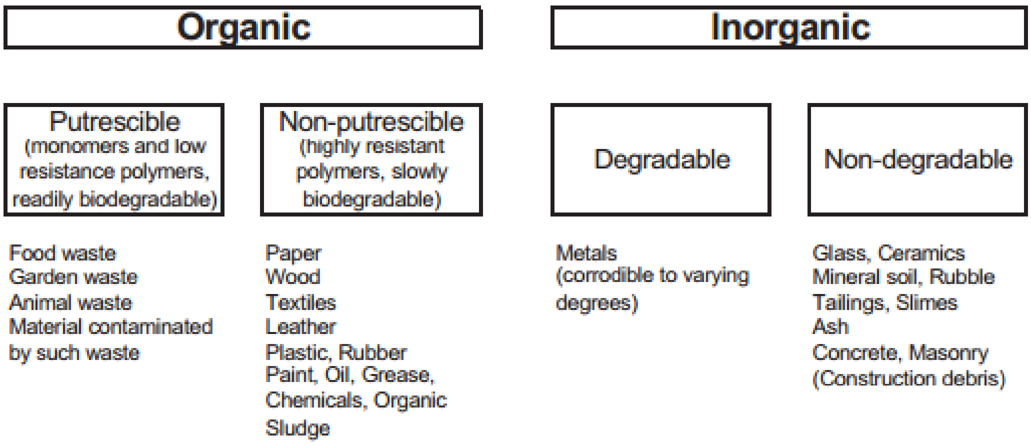

Figure 2-29: Waste classification (after Landva and Clark, 1990)

Further, the French Environmental Protection Agency introduced the protocol called MODECOM ™ to determine the waste composition of both fresh and old waste and to obtain the particle size distribution of waste. Initially, waste sample is passed through three sieves with size of 100mm, 50mm and 20mm and waste sample retained in each sieve sorted into 18 material categories. Subsequently, moisture content, weight and organic content are determined for each sorted component. Further, waste material in each category are subdivided based on the biodegradability. (i.e. easily, moderately, hardly, inert and residual fines). This system is having similarity with the system proposed by Landva and Clark (1990) in terms of degradation potential. However, this system does not address the compressibility aspects and shape factors of particles (Dixon, Neil; Langer, Ulrich; Reddy, Krishna; Maugeri, Michele; Tinjum, James; Mahler, Claudio; Cho, Youngmin, 2008).

Grisolia et al. (1995) proposed a classification system by plotting the percentages of each subgroup in a ternary diagram and defined sub group are inert, degradable and deformable. This system provides detailed information on compressibility and degradability of components. Main disadvantage is that same component can be included in several groups (e.g. food residues can be fit into both biodegradable and deformable groups). Also, any aspects related to shape of particle are not addressed in this system.

Kölsch (1996) developed a detailed classification system based on material groups and subdivided based on the size and dimensions of particles. A strength of this system is that it provides a more detailed analysis of material properties. However, this system does not address the aspects related to degradation and large data set is required for the classification. These kind of detailed classification system is more appropriate for research studies.

Dixon et al. (2008) summarized the existing classification systems including the parameters used for differentiation (Table 2-9).

Table 2-9: Overview of Existing Classification system (Dixon et al.,2008)

Author`	**Basis for Differentiation**	**Parameters used for Differentiation**
Turcynski(1988)	Waste type	Density, shear parameters, liquid/plastic limit permeability
Siegel et al (1990)	Material groups	Part of composition
Landva and Clark (1990)	Organic, inorganic materials	Degradability (easily, slowly, on) Shape (hollow, platy, elongated, bulky)
ADEME (1993)	Particle size distribution and composition	Size, material groups, moisture content and degradability
Grisolia et al. (1995)	Degradable, inert, deformable material groups	Strength, deformability, degradability
Kolsch (1996)	Material groups	Size, dimension
Manassero et al.	Soil-like , other	Index properties
Thomas et al. (1999)	Soil-like, non soil-like	Material groups
Dixon & Langer (2006)	Shape- related subdivision	Material groups, size, dimensions, shape related properties, degradation potential

Dixon and Langer (2006) developed a waste classification system incorporating the prevailing systems suggested by above mentioned researchers.

Dixon and Langer (2006) Classification System

Initially, waste sample is sorted by considering the type of material. Generally, municipal waste sample consists of various material types. Hence, it is difficult to identify each and every type of material. Therefore, authors selected several major material groups by considering the mechanical properties of components. Suggested material groups in this method are soil like; Paper/Cardboard; Flexible plastics; Rigid plastics and rubber; Metals; Minerals and glass; Wood, leather, textiles; and miscellaneous. Under soil like category, components that are too small to identify the type or having nature of soil are included and it may have high organic content. Index property test used in Soil Mechanics can be used to obtain detailed classification in such material type.

Further, Dixon and Langer (2006) suggested to subdivide the material group by considering the aspects related to shape of waste fragments. Two basic groups related shape characteristics to be used in conjunction with associated subdivisions are introduced;

- Reinforcing material elements; one dimension or two dimension (e.g. paper, plastic bags)
- Three-dimensional material elements
    a) Compressible material
        - High compressibility (e.g. plastic packaging , putrescible materials)
        - Low compressibility (e.g. beverage cans)
    b) Incompressible material (e.g. pieces of metal ,bricks)

After subdividing the component considering the shape related aspects, waste materials are graded in to following size ranges; <20mm, 20-40mm, 40-120mm, 120-500mm, 500-1000mm, >1000mm. As stated above, fragments smaller than 20mm are considered as soil like in nature and index property tests used in Soil Mechanics can be used to obtain detailed particle size distribution. It is difficult to grade the component with irregular shapes and highly deformable particles (polythene sheets, plastic packaging). It is recommended to obtain maximum dimension when the fragments are in unstressed state (i.e. not compressed, folded or deformed). Fragments included in reinforcing shape related subgroup should be further subdivided by considering the size ranges in the other two sub-divisions to assess their potential to act as reinforcing elements. Details regarding degradability of constituents should be addressed in order to represent the changes in classification that caused due to degradation. The framework currently only considers biodegradation as the largest degradation alteration of waste components occurs by bio-degradation. The suggested methodology for waste classification is described in Figure 2-30 .

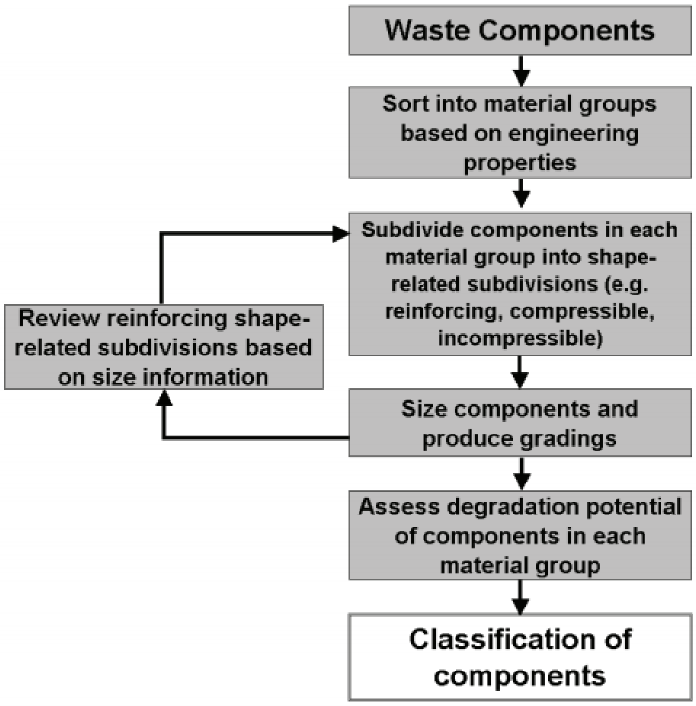

Figure 2-30: Procedure of proposed waste classification framework (after Dixon and Langer 2006)

2.11.2 General Waste Composition in Sri Lanka

In Sri Lanka, more than 60 % of MSW contains biodegradable organic matters. While short term bio degradable waste occupied significant amount from the biodegradable component, long-term biodegradables such as banana stalks, king coconut shells, paddy husks and tree cuttings also can be found in MSW (Basnayake, B.F.A.;

Visvanathan, C.;, 2014). With the economic development, amount of non-degradable material such as polythene, plastic, glass and metal observed in waste dump are increased in recent years (Sumathipala, 2005). Figure 2-31 presented the composition of MSW collected by Local Authorities in Sri Lanka (Basnayake, B.F.A.; Visvanathan, C.;, 2014). In present, non-bio degradable components such as plastic, polythene, glass and metal are commonly found in MSW dumps in Sri Lanka, resulting sever environmental pollution.

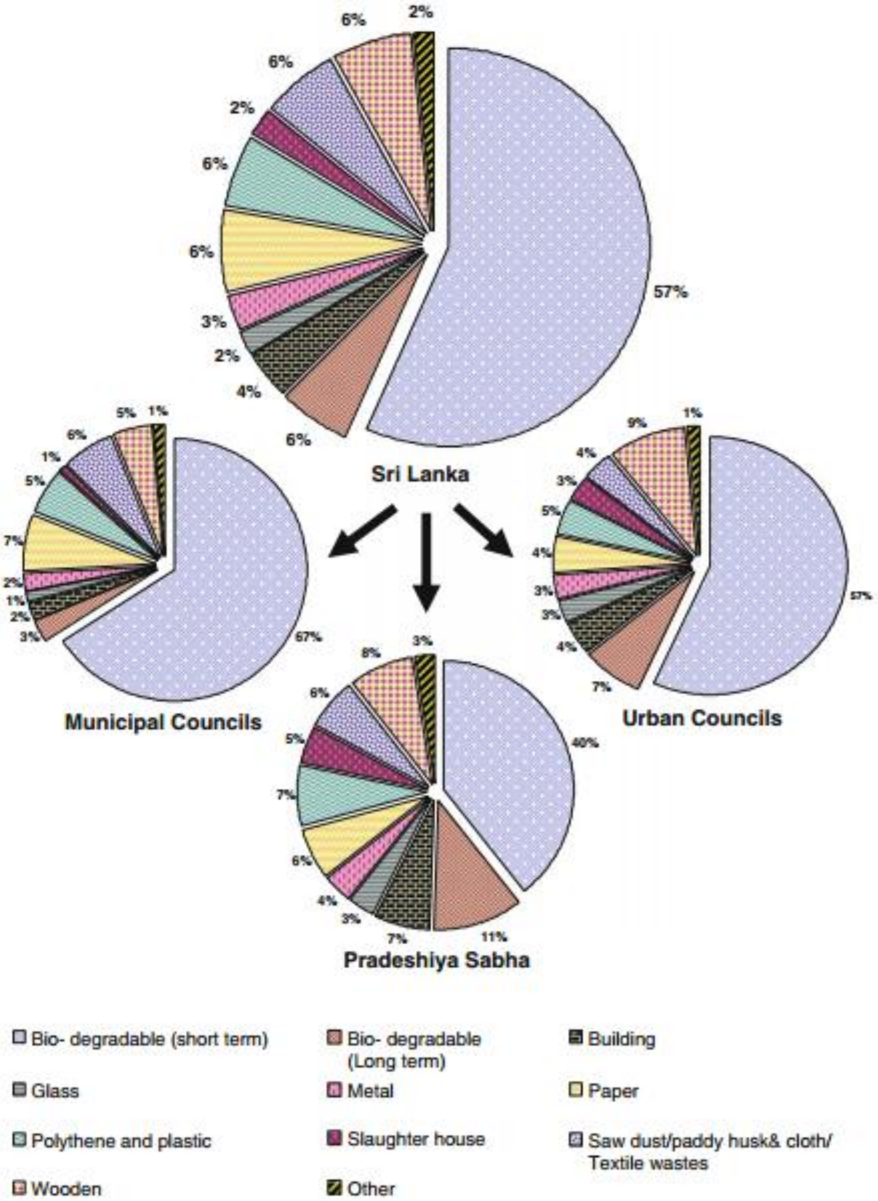

Figure 2-31: Composition of MSW collected by Local Authorities in Sri Lanka (Basnayake & Visvanathan, 2014)

CHAPTER 3 LABORATORY TESTING PROGRAM

This chapter describes the sample preparation, laboratory tests and procedures and experimental program adopted during the research.

3.1 Collection of Intact MSW samples

Municipal solid waste for laboratory tests were obtained from Meethotamulla waste dump site which is having waste older than 20 years and maximum height of waste dump is about 50 m. Rehabilitation of waste mound by converting into a recreational park is currently undertaken by Urban Development Authority, Sri Lanka. During the ongoing rehabilitation project at Meethotamulla waste fill site, two specimens form excavated material at the bottom of waste fill and from the middle part of the waste fill were collected for laboratory testing. The location for sample collection were selected to represent the waste dumped at different time scale (Figure 3-1 and Figure 3-2). Hereinafter sampling location which is situated at bottom of waste fill is referred as Location 01 and sampling location which situated at middle of waste fill is referred as Location 02.

Figure 3-1: Location selected for sample collection

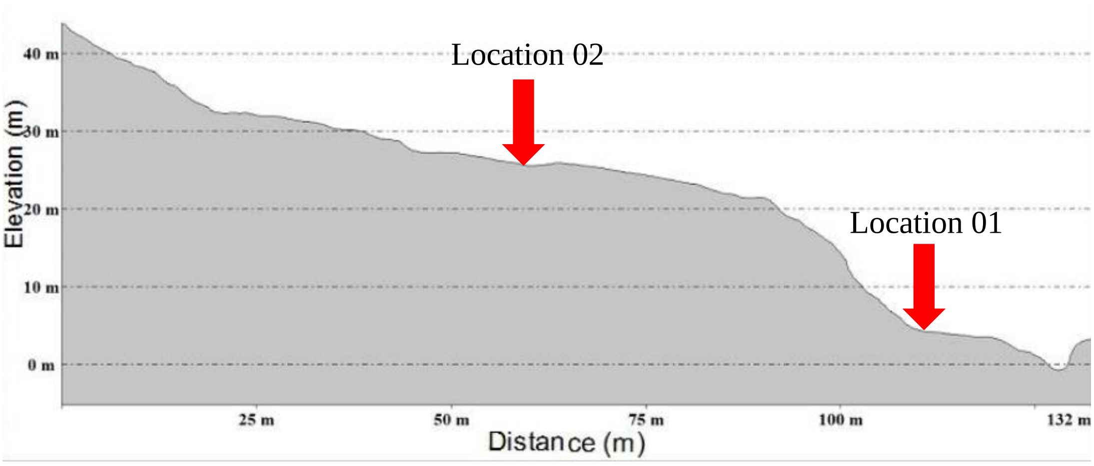

Figure 3-2: Cross section showing the sampling locations

Figure 3-3 and Figure 3-4 show the condition of collected samples. From the visual observations it indicates that sample 1 contain more degraded material than sample 2 and polythene percentage is higher in sample 2.

Figure 3-3: Sample 1 obtained from the bottom of the waste fill

Figure 3-4 : Sample 2 obtained from the middle of the waste fill

3.2 Preparation of Recompacted Samples

There are some limitations on the maximum particle size, which can be used for specimen preparation. Generally, the largest particle size of sample should be 1/6 of the diameter of sample. As used cell diameter is 151.2 mm largest particle size should be about 25mm. Hence, fragments greater than 25mm in specimen that were too large to fit inside the cell were either broken by hand / cut into small pieces or discarded where it is not possible to processed to reduce the size of component.

3.3 Description of the Rowe Cell and Pre-Test Checks

Cells of diameter; 75.7 mm and 151.2 mm were used for performing compressibility tests. Before commencing the experiments using Rowe Cell all the components of the Rowe Cell were checked properly. Specially, the bottom porous area and porous plate were checked to ensure absence of clogging particles in pore pressure measurement point. Further, Rowe Cell was filled with the water and loaded to check the accuracy of pore pressure measuring devices.

3.4 Test Method

Head (1997) stated that test with equal strain loading condition and vertical single drainage can be considered as the most related test to traditional oedometer tests and settlement reading and volume change measurement taken form the drainage line can be directly correlated under above condition. Hence, vertical single drainage with equal strain test method is selected for the testing programme. According to the selected test method, vertical drainage occurred only through top surface of the sample and pore pressure measured at the center of the base. Rigid porous disk which maintain a plane surface to the sample is placed on top of the sample. Typical arrangement of test method is presented in Figure 3-5.

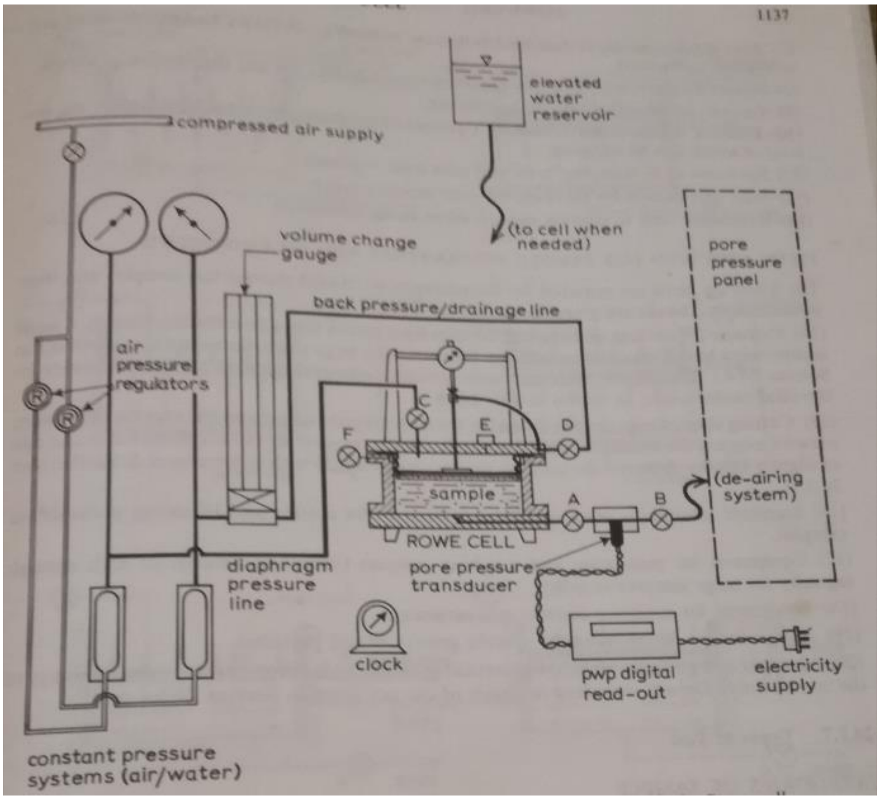

Figure 3-5: Typical arrangement of Rowe cell test apparatus

3.5 Experimental Procedure

Sample were tested under saturated and unsaturated conditions. Densities of the samples under saturated and unsaturated condition were maintained approximately equal to get a better comparison of data (Table 3-1).

Table 3-1: Details of sampling locations and size of specimen

Test Set	Sampling location	Approximate Elevation of Location	Saturation condition	Diameter of sample (mm)	Initial Sample Thickness (mm)
1	Location 01	5m	Saturated	150.10	46.77
2			Unsaturated	150.10	46.43
3	Location 02	25m	Unsaturated	150.10	43.72
4			Saturated	*74.93	28.16

*Due to defect occurred in 150mm Rowe cell, 75mm diameter Rowe cell was used.

Test were performed with loading, unloading, reloading and again unloading increments. The following loading, unloading and reloading were carried out during the experiment.

Loading – 25kPa(1day) > 50kPa(1day) > 100kPa(1day) > 200kPa(3day)

Unloading – 100kPa (1day) > 50kPa(1day) > 25kPa(1day)

Reloading –50kPa(1day)> 100kPa(1day)> 200kPa(1day)> 400kPa(3day)

Unloading –25kPa(3day)

The arrangement of Rowe Cell apparatus used in the experiments are shown in Figure 3-6 .

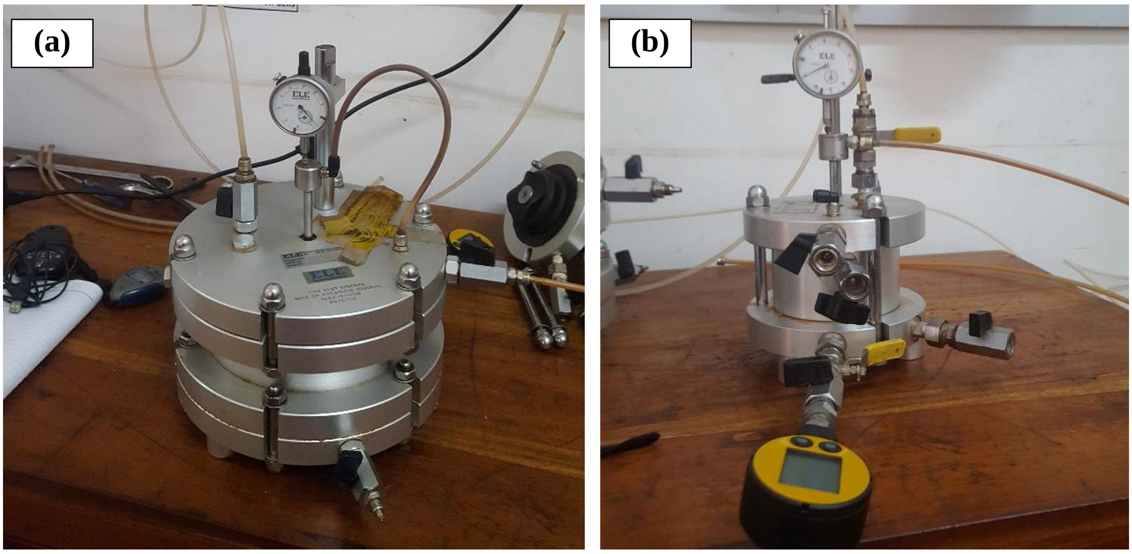

Figure 3-6: Rowe cell apparatus used for the study (a) Rowe cell with diameter of 151.2 mm (b) Rowe cell with diameter of 75.7mm

3.6 Determination of Basic Properties of MSW

3.6.1 In-situ Density

In situ densities were measured in sampling location in order to achieve conditions close to site conditions in remoulded samples. Water replacement method in a test pit was used to determine the in-situ densities of samples (Figure 3-7).

Figure 3-7: Determination of in-situ density

3.6.2 Moisture Content

In order to determine the moisture content air dried method was adopted for specimens obtained from tested samples.

3.6.3 Specific Gravity

Laboratory specific gravity tests for waste samples were performed using large pycnometer which having volume of 1000ml and followed the procedure recommended in the ASTM D854 for soils (Figure 3-8).

Figure 3-8: Pycnometer with waste sample and water

Accordingly, summary of obtained basic properties of MSW are presented in Table 3-2.

Table 3-2: Basic Properties of test specimens (MSW)

Test Set	Sampling location	Bulk Unit weight (kN/m^3)	Specific Gravity	Moisture Content (%)
1	Location 01	12.7	2.34	74.3
2				55.2
3	Location 02	11.2	1.92	41.5
4				66.9

3.7 Determination of Waste composition

Waste classification framework proposed by Dixon and Langer (2006) is used in this study based on the relevancy to nature of MSW in Sri Lanka. As suggested in the Dixon and Langer framework, following major group of materials are used for classification: Soil like, Flexible Plastic, Rigid Plastic, rubber, Metals, Minerals, glass, Wood, leather, Textiles, and miscellaneous.

For the classification works, waste specimens were air dried and then material components were sorted. Segregated waste material are shown in Figure 3-9 and waste composition of each location is presented in Table 3-3.

Figure 3-9: Waste materials after sorting into major groups

Table 3-3: Waste composition for sampling location 1 and 2

Material (Dry)	Location 01		Location 02	
	Dry weight (g)	%	Dry weight (g)	%
Soil like	388.23	54.47	282.88	43.66
Paper/ Cardboard	0	0.00	0	0.00
Flexible plastics	94.56	13.27	128.96	19.90
Rigid Plastics, rubber	0	0.00	0	0.00
Metals	0	0.00	0	0.00
Glass, Minerals	91.24	12.80	85.2	13.15
Wood, Textiles	120.44	16.90	130.44	20.13
Miscellaneous	18.25	2.56	20.47	3.16
Total	712.72	100	647.95	100.00

As fragments greater than 25mm of MSW specimen used in this study were broken/cut to make them fit inside the cell, subdivision of components using shape related properties in each material group was not carried out in this study.

As the identifiable paper, cardboard or any organic material were not encountered from samples, it can be stated that all degradable components were fully degraded in both samples. Further, sample 1 contain more degraded materials and sample 2 contains more polythene and textiles. Currently at site at upper levels of waste dump, rubber tires, wooden trunks, broken plastics are also present. However, those large material components were not considered in this classification.

CHAPTER 4 RESULT OF COMPRESSIBILTY TEST AND DISCUSSION

This chapter presents the findings of this study regarding the settlement behavior of Municipal Solid Waste in Sri Lanka. Further, Compressibility characteristics obtained from this study are compared with the data reported in similar studies and compressibility characteristics of soil. Comparison is done with two soil types in extreme ends; residual soils and peaty clays.

Test samples in the Rowe Cell were prepared to a bulk density of 12 kg/m^3 to simulate the site conditions in the preparation of unsaturated samples. In the preparation of saturated samples, attempts were made to achieve the fully saturation level by adding water to sample by calculating amount of water required for 100% saturation level.

Rowe cell has the arrangements to measure pore water pressure. However, in all tests done with both unsaturated and saturated samples the pore water pressure variation with time is quite erratic. It did not show a trend of gradual or rapid dissipation. The variation of Void ratio and Pore water pressure with time for the loading increment of 25-50kPa and 50-100kPa are shown in Figure 4-1 and Figure 4-2.

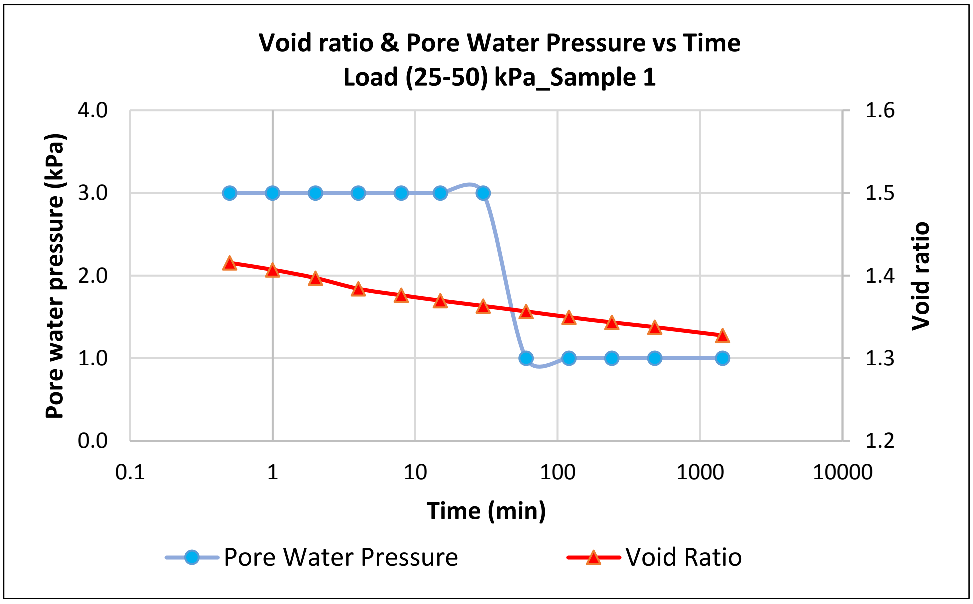

Figure 4-1: Void ratio and pore pressure variation with time for load increment of 25-50 kPa (Sample 1)

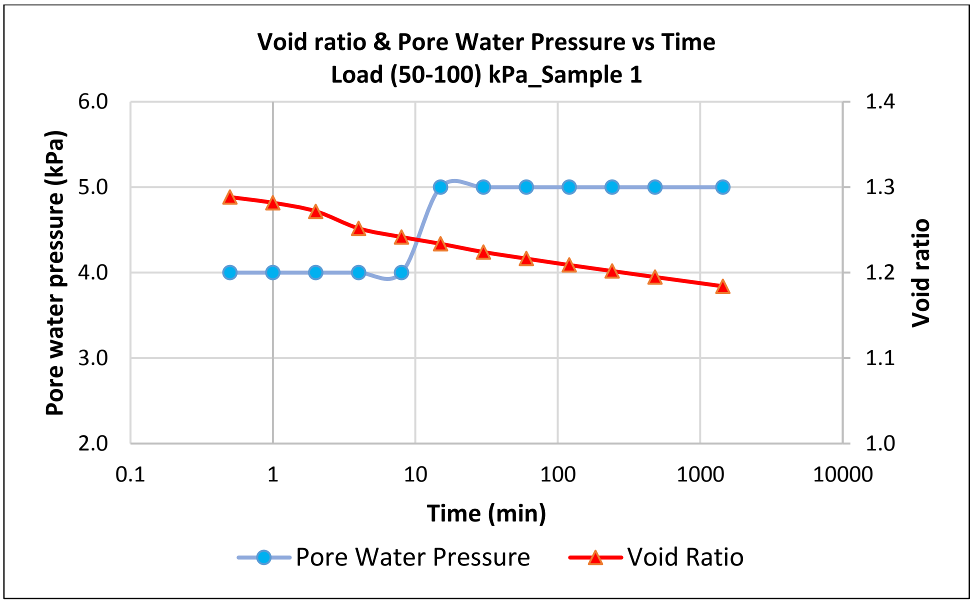

Figure 4-2: Void ratio and pore pressure variation with time for load increment of 50-100 kPa (Sample 1)

This could be attributed primarily to the non-uniform nature of the sample in comparison to a soil sample. The pore pressure value read by the transducer depends on the nature of the sample in close proximity to the pore pressure sensor. With a large variation in the constituents of the sample a uniform response could not be expected. Hence, the settlement behaviour of the sample should be studied based on the average respond of the complete sample. As such, the settlement is the only parameter that can be monitored even with the Rowe Cell.

4.1 Result of the tests

Settlement vs log (time) plots were done for all loading and reloading increments in testing done with both saturated samples and unsaturated samples. The results of loading increments of samples from Location 1 (Saturated and unsaturated) are presented in Figure 4-3. The results of reloading increments of the same sample are presented in Figure 4-4. Similarly, results of loading and reloading increments for unsaturated and saturated samples obtained from location 2 are presented in Figure 4-5 and Figure 4-6.

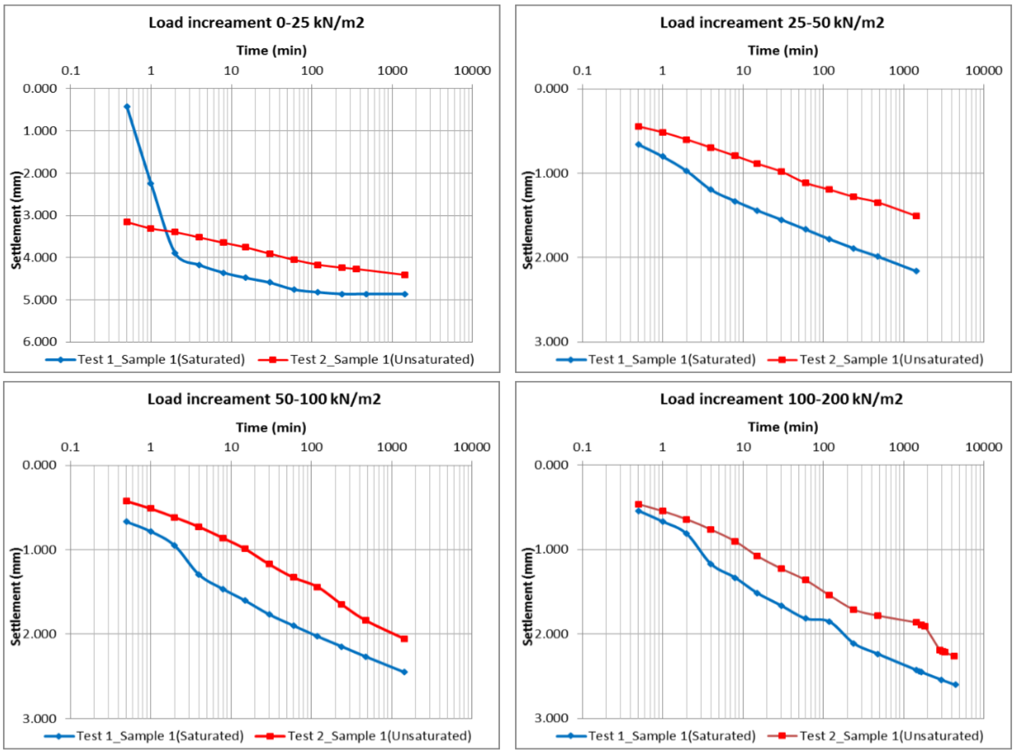

Figure 4-3: Settlement vs log (time) for Loading stage of Sample 1 (Saturated and Unsaturated condition)

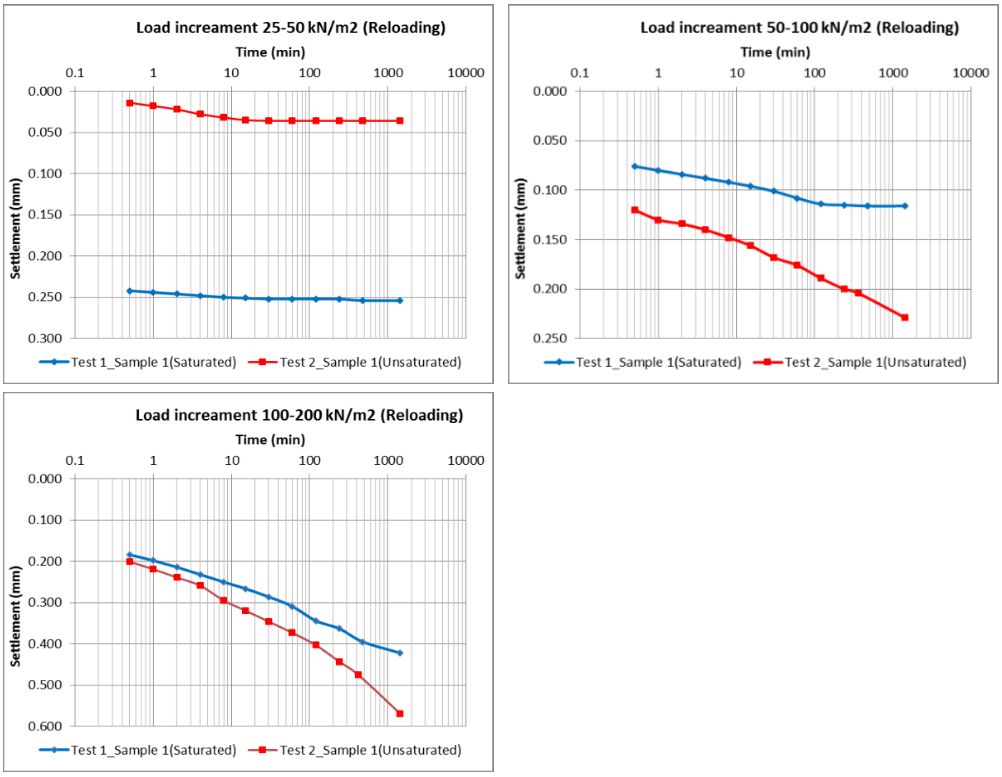

Figure 4-4: Settlement vs log (time) for Re-loading stage of Sample 1 (Saturated and Unsaturated condition)

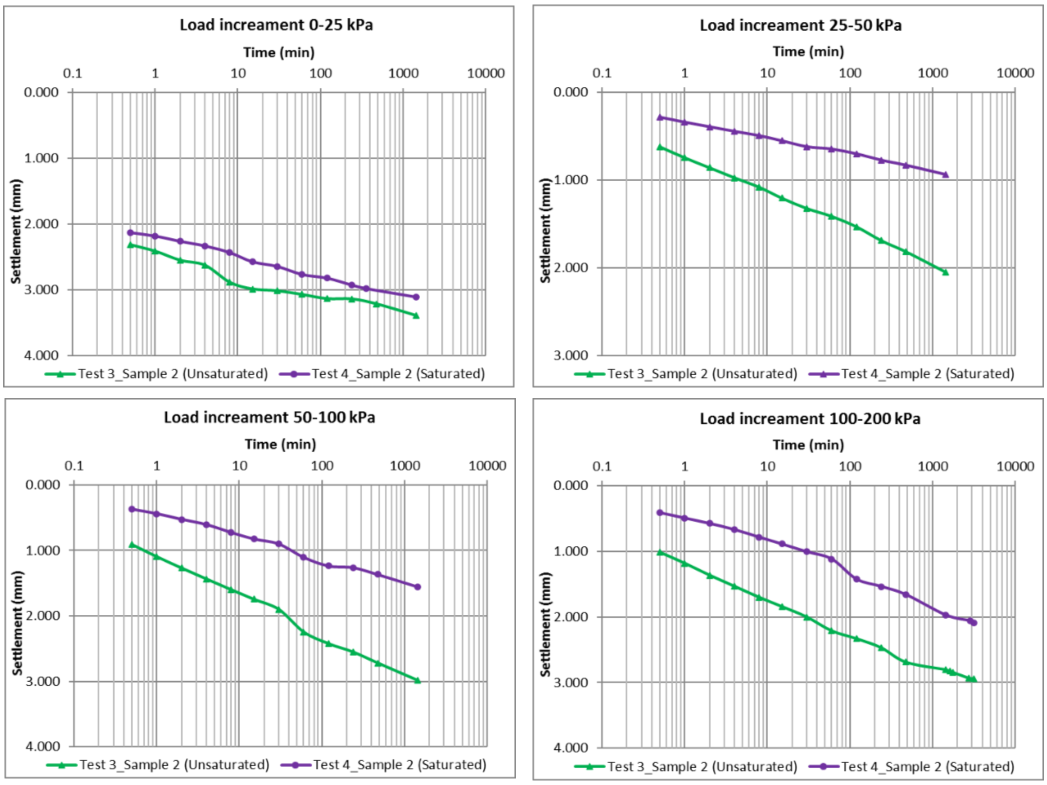

Figure 4-5: Settlement vs log (time) for Loading stage of Sample 2 (Saturated and Unsaturated condition)

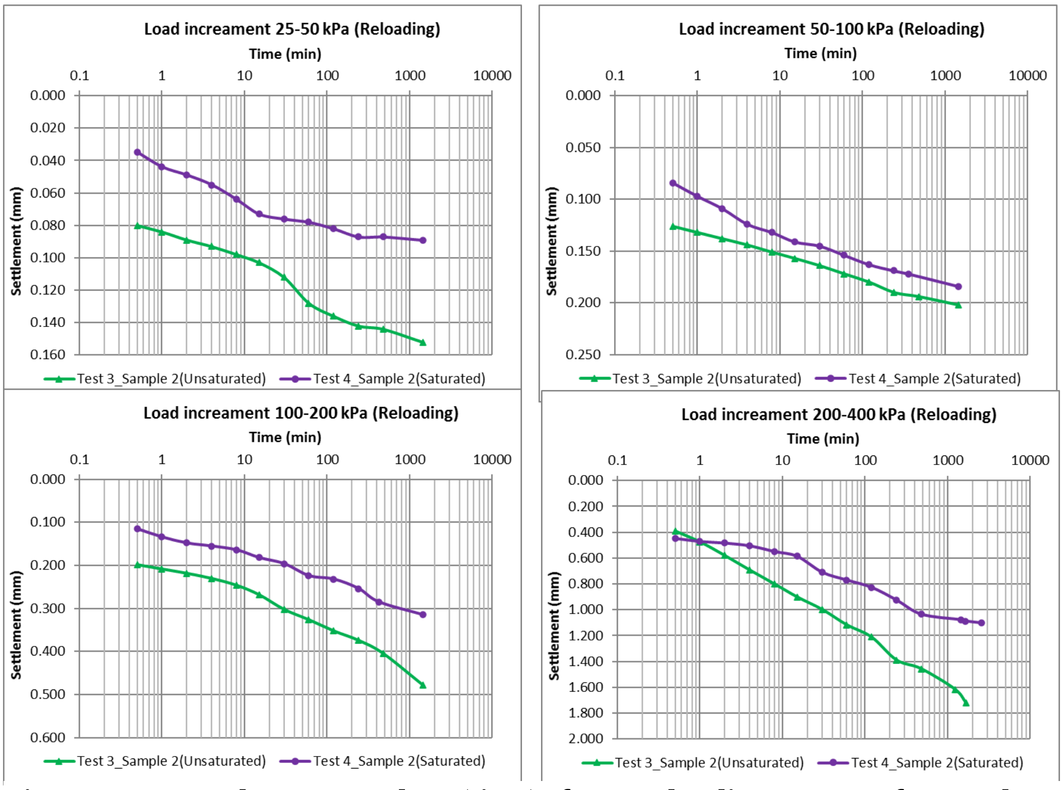

Figure 4-6: Settlement vs log (time) for Re-loading stage of Sample 2 (Saturated and Unsaturated condition)

The settlement plots do not show a reduction in gradient with time as seen with inorganic clays. The plot of similar gradient as seen in peaty clay clearly indicate that MSW samples have high secondary consolidation settlement. Settlement in the saturated samples are much larger than those in unsaturated samples. In the reloading stage settlements are much smaller as seen by change of the vertical scale of plots.

MSW is made up of particles from different sources and different sizes as seen in Table 3-3. As such, it is difficult to define a single specific gravity. However, different researchers have estimated an average specific gravity with the measurements done in the Pycnometer. Hence, initially a parameter (H-Δh) /H was evaluated which is proportioned to the void ratio. Subsequently, void ratio e was evaluated with the average specific gravity obtained and plots were done to deduce compressibility indices.

(H-Δh) /H vs log (σ) plots obtained for both saturated and unsaturated sample 1 and sample 2 are presented in Figure 4-7 and Figure 4-8. The tests are carried out with loading, unloading and reloading increments.

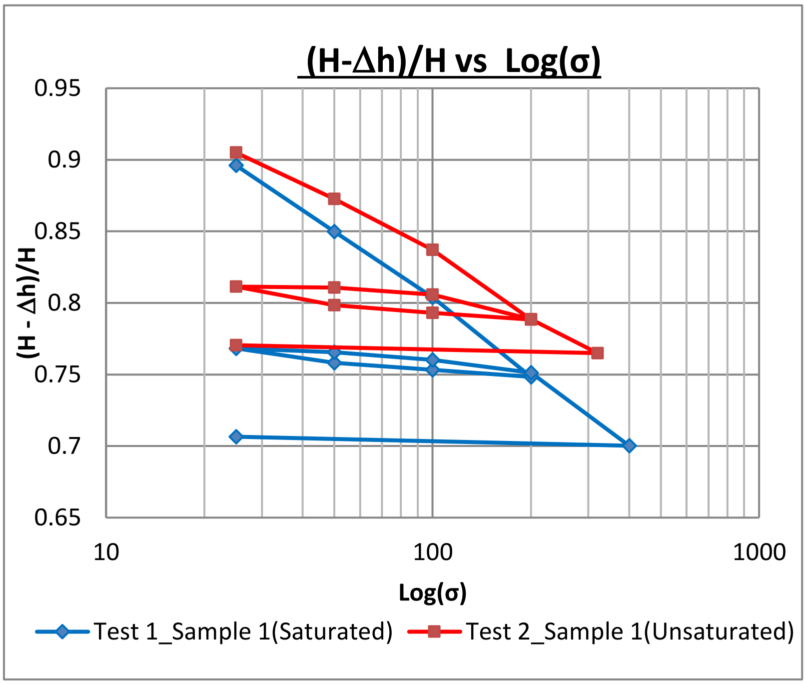

Figure 4-7: Compression curve for sample 1 under saturated and unsaturated conditions

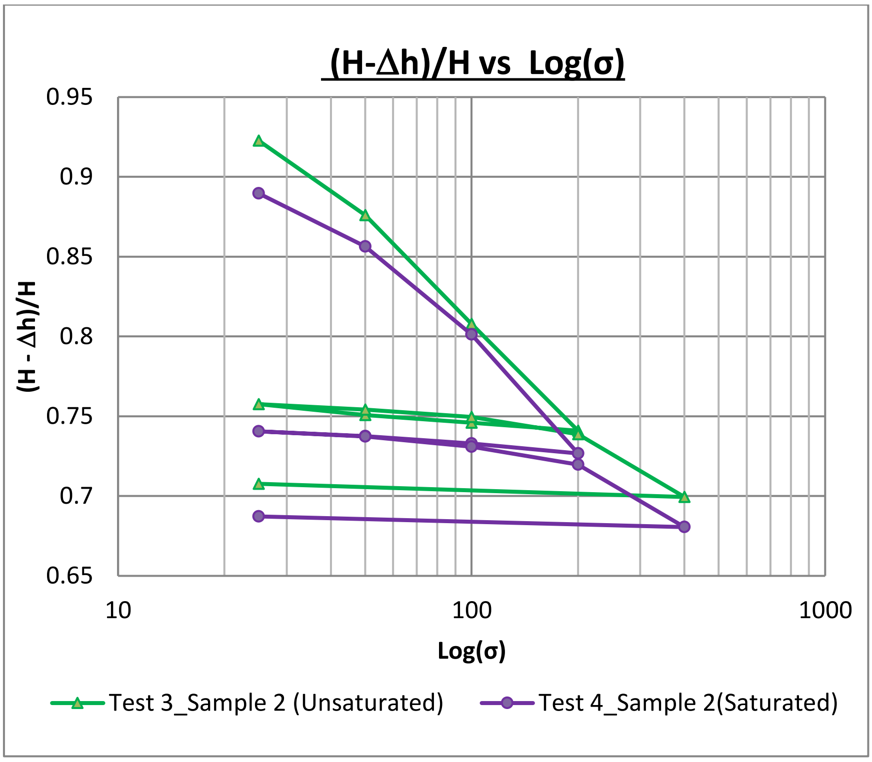

Figure 4-8: Compression curve for sample 2 under saturated and unsaturated conditions

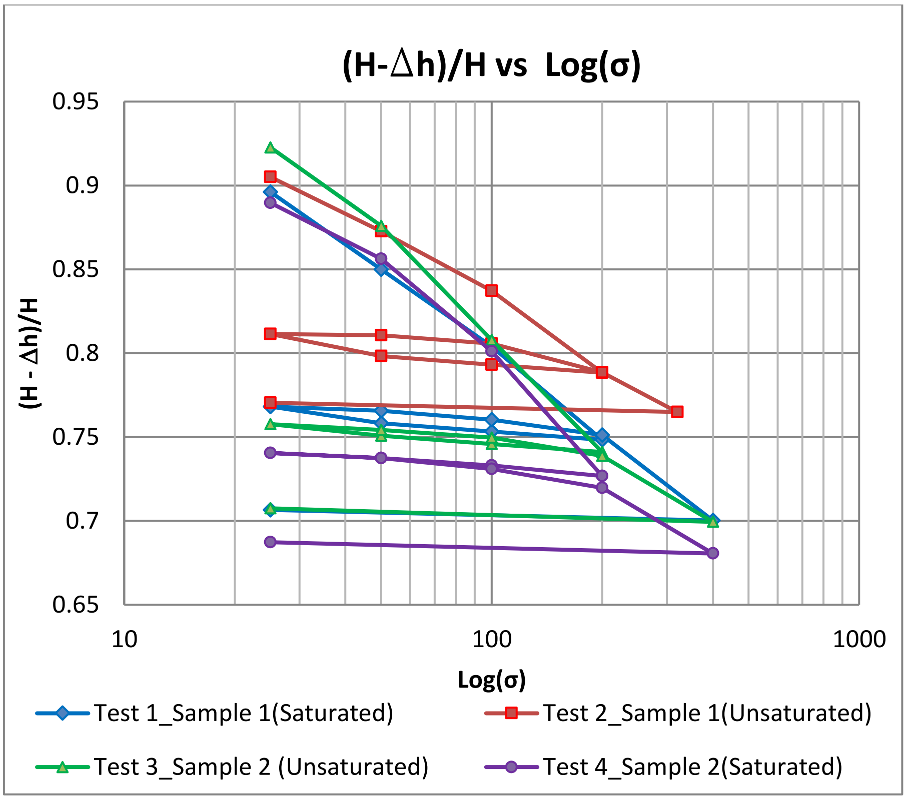

Figure 4-9: Comparison of compression curves of sample 1 and 2

As shown in above Figure 4-9 (H-Δh /H) vs log (σ) curves for MSW exhibit similar behavior as the e vs log (σ) for intact or engineering soil.

The e vs log (σ) plots of MSW samples are presented in Figure 4-10 and Figure 4-11.

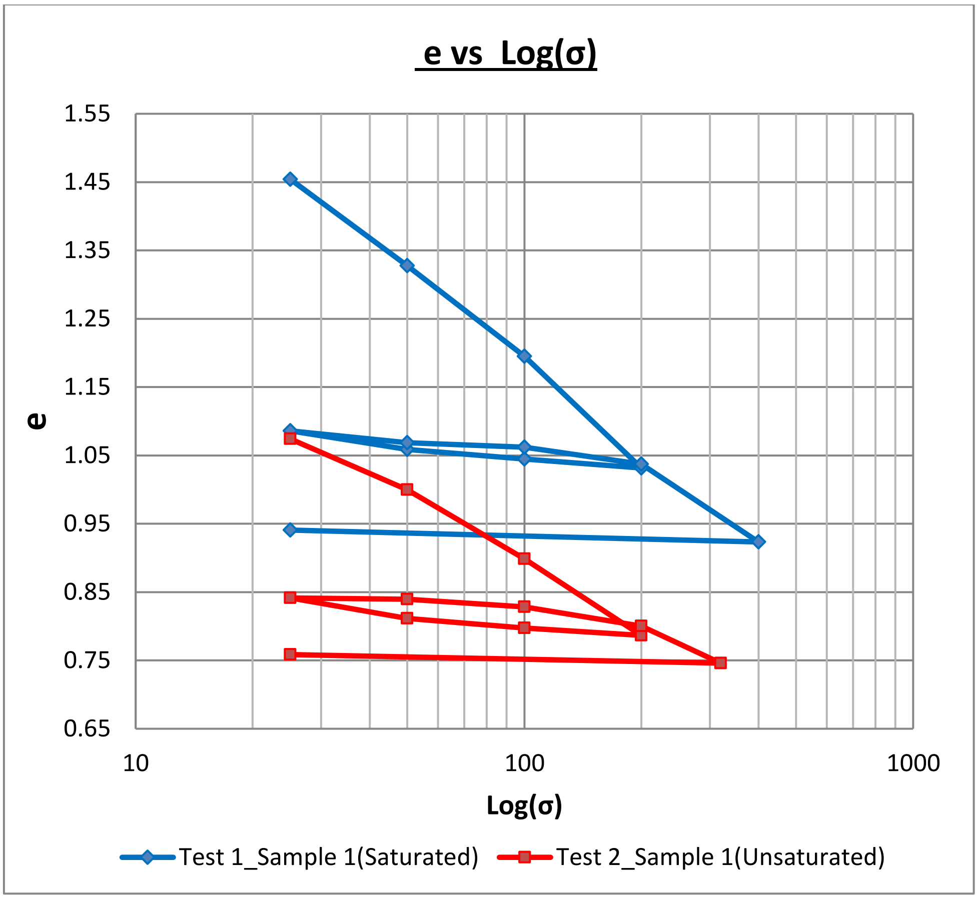

Figure 4-10: e vs log (σ) curve for sample 1 under saturated and unsaturated conditions

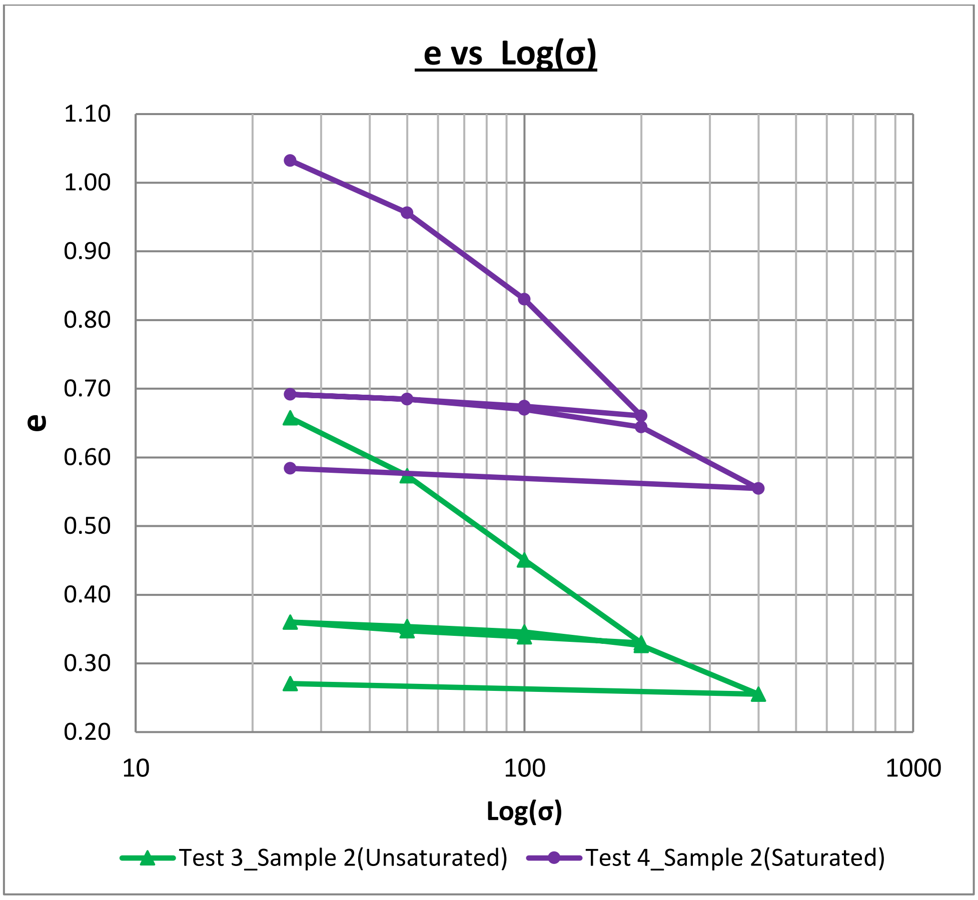

Figure 4-11: e vs log (σ) curve for sample 2 under saturated and unsaturated conditions

Figure 4-12 compares the two types plots [e vs vs log (σ) and (H-Δh /H) vs log (σ)] of sample 1 under saturated state. The comparison in the Figure 4-12 illustrates that the two plots are of identical shape.

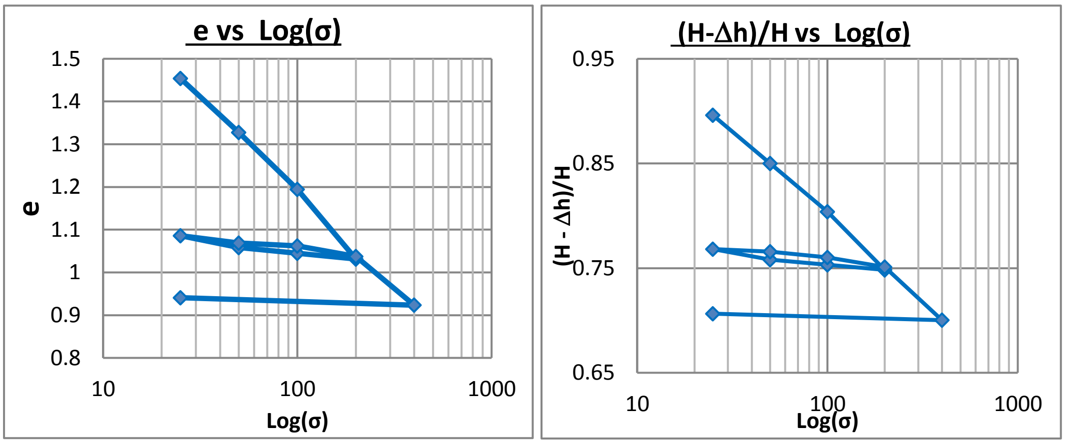

Figure 4-12: e vs log (σ) and (H-Δh /H) vs log (σ) plots for sample 1_saturated condition

Figure 4-13 and Figure 4-14 show the e vs log (σ) plot developed by Naveen et al. (2018) and Powrie et al. (1999) respectively. Therefore, it can be seen that the e values obtained from this study on MSW are within the same range of the values obtained in literature.

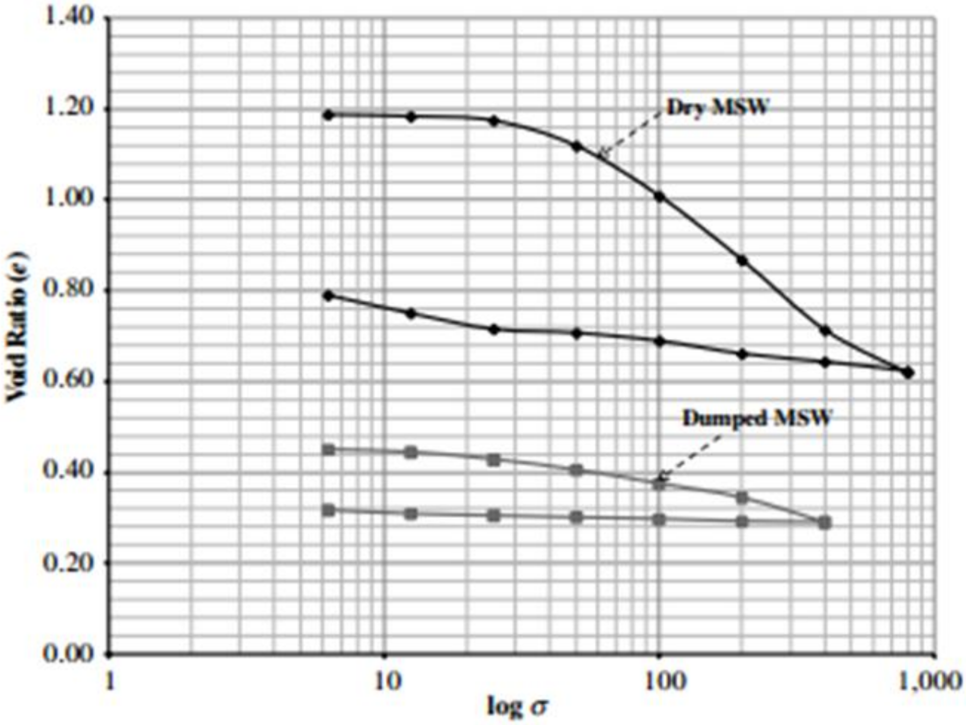

Figure 4-13: e vs log(σ) plot for MSW(after Naveen et al,2018)

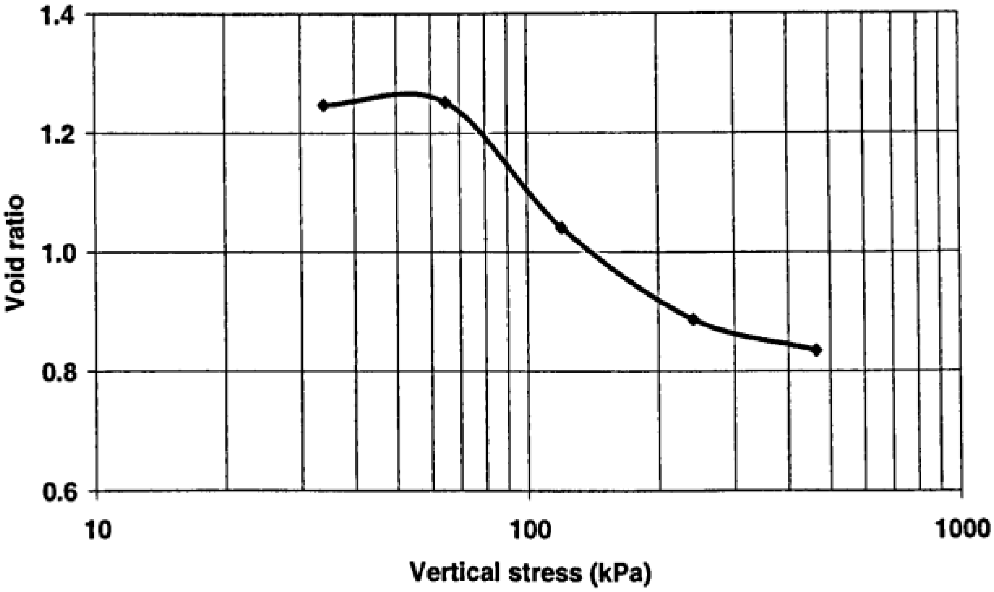

Figure 4-14: e vs log (σ) plot for MSW (after Powrie et al, 1999))

4.1.1 Variation of Compression Index (C_c) and Recompression Index (C_r)

As described in section 2.8.2, compression index and recompression index values were determined using e vs log (σ) and obtained results are presented in Table 4-1.

Table 4-1: Compression index and Recompression index values

Test Set	**Values of compression index (Cc)**	**Values of recompression index (Cr)**
Test 1_Sample 1(Saturated)	0.5421	0.0438
Test 2_Sample 1(Unsaturated)	0.3707	0.0352
Test 3_Sample 2(Unsaturated)	0.4010	0.0296
Test 4_Sample 2(Saturated)	0.5647	0.0472

The value of the compressibility index C_c and recompression index for the MSW specimens under saturated condition have higher value than the specimen under unsaturated condition. Further, above results clearly shows significant reduction in C_r to the respective values of C_c. The C_r values are less than 10% of C_c values.

The C_r values represent the primary consolidation behavior of a preloaded MSW. The much reduced C_r values indicate that the primary consolidation settlement of MSW can be significantly reduced by preloading. This compares well with the behavior shown by peaty clays.

Kavazanjian et al (1999) reported C_c values varies from 0.121 to 0.247 and C_r is between 0.003 and 0.017 for MSW. According to Hossain et al (2009) the range of C_c is in between 0.16 to 0.37. Further, Naveen et al (2018) recorded that obtained Cc values for MSW varies from 0.105 to 0.47.

Thus, the values obtained in this study are relatively higher than the values reported in literature.

4.1.2 Variation of Coefficient of Volume Compressibility (mv)

Co-efficient of volume compressibility values which were determined by analyzing the experiment results are presented in Table 4-2 and Figure 4-15.

Table 4-2: Coefficient of volume compressibility values

Stress (kPa)		Coefficient of Volume Compressibility (m^2/MN)			
		Test 1_Sample 1 (Saturated)	**Test 2_Sample 1 (Unsaturated)**	**Test 3_Sample 2 (Unsaturated)**	**Test 4_Sample 2 (Saturated)**
Loading	25	4.16	3.80	3.09	4.41
	50	2.06	1.43	2.03	1.50
	100	1.08	0.81	1.55	1.29
	200	0.69	0.58	0.83	0.93
Reloading	50	0.13	0.04	0.18	0.17
	100	0.14	0.12	0.12	0.18
	200	0.12	0.21	0.14	0.15
	400	0.28	0.25	0.27	0.27

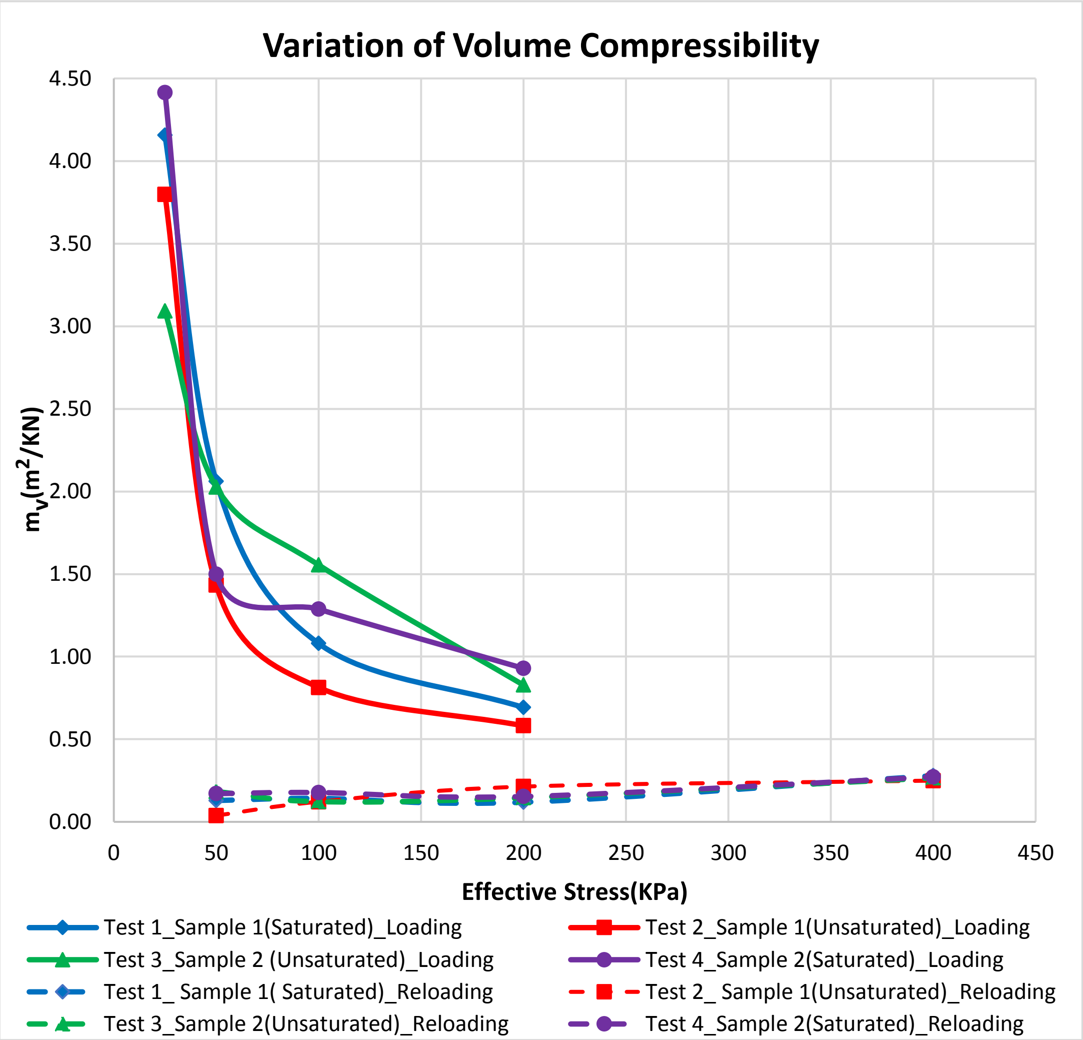

Figure 4-15: Variation of m_v for Sample 1 and Sample 2 (under saturated and unsaturated condition)

The observed variation of m_v can be summarized as follows;

- m_v values of all samples decrease as the effective stress increases. They followed the same trend.
- m_v values of unsaturated sample are less than the values of saturated samples.
- The coefficient of volume compressibility values in reloading increments were much smaller compared to that of loading increment

4.1.3 Variation of Coefficient of Secondary Consolidation (Cα)

As stated under section 2.8.3 Coefficient of secondary consolidation Cα values were calculated for each loading stage and reloading stages using the gradient of Void ratio vs log time (later stage of the curve used for the calculations) and obtained results are presented in Table 4-3.

Table 4-3: Coefficient of Secondary Consolidation values

Stress (kPa)		**Coefficient of Secondary Consolidation (Cα)**			
		Test 1_Sample 1 (Saturated)	**Test 2_Sample 1 (Unsaturated)**	**Test 3_Sample 2 (Unsaturated)**	**Test 4_Sample 2 (Saturated)**
Loading	25	0.0078	0.0113	0.0152	0.0172
	50	0.0203	0.0166	0.0199	0.0180
	100	0.0226	0.0223	0.0226	0.0313
	200	0.0226	0.0183	0.0178	0.0339
Reloading	50	0.0004	0.0002	0.0007	0.0013
	100	0.0014	0.0020	0.0007	0.0016
	200	0.0033	0.0087	0.0063	0.0045
	400	0.0165	0.0161	0.0160	0.0063

Variation of coefficient of secondary compression for each stress level is illustrated in the Figure 4-16.

Primary Consolidation is considered to be the end of excess pore pressure dissipation. Traditionally, secondary consolidation was considered to be commencing after the completion of primary consolidation. Recent researchers however have commented that the secondary consolidation behavior starts during the primary consolidation stage (Karunawardena , 2002).

The settlement curves of MSW are similar to those of peaty clay as a change of gradient could not be identified. Thus, it can be concluded that MSW has high secondary consolidation. However, the magnitudes of the secondary consolidation coefficients are lower than that of peaty clay.

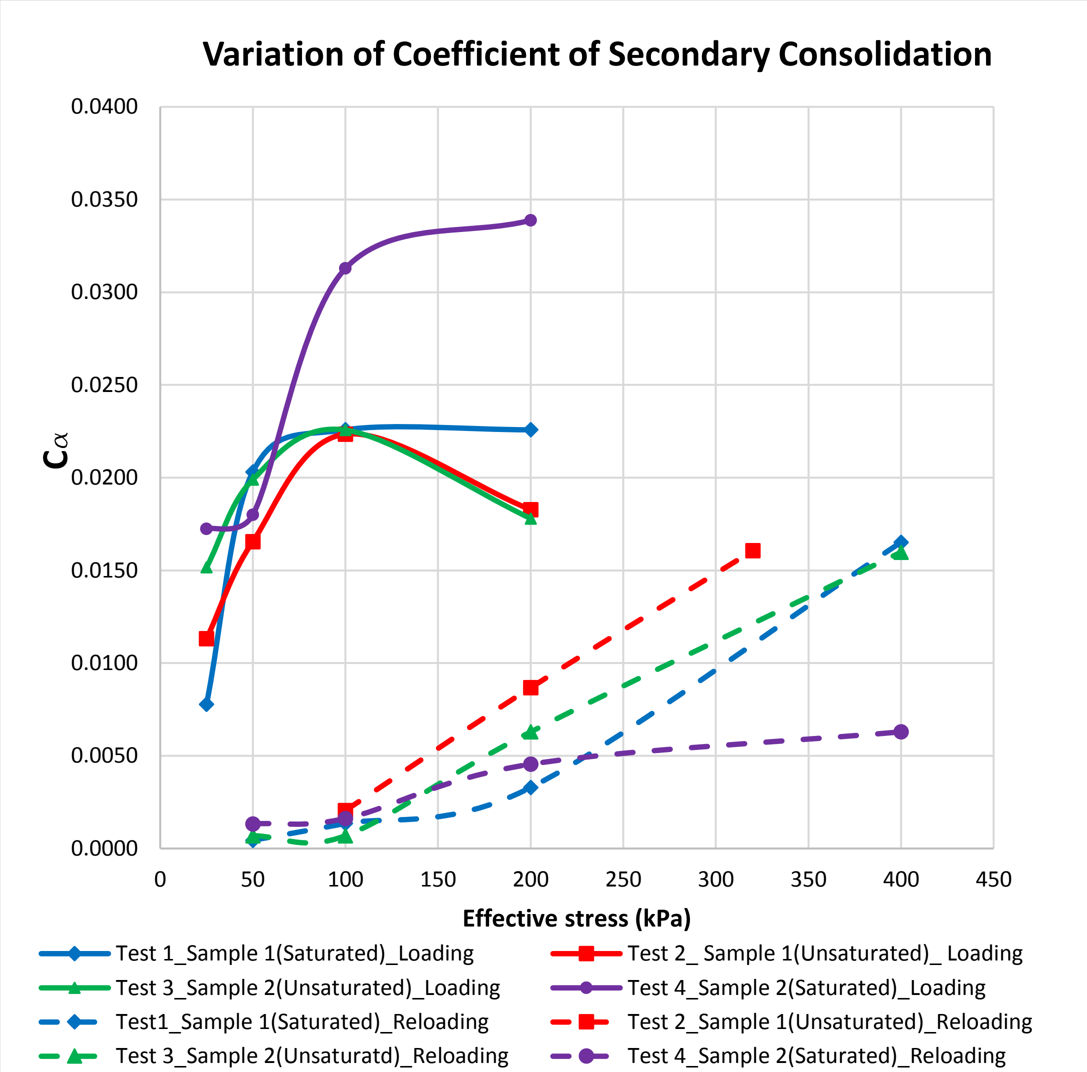

Figure 4-16: Variation of C_α for Sample 1 and Sample 2 for loading and reloading stages

The C_α values of unsaturated and saturated samples were of the same order. There is no notable difference due to the saturation. In general C_α values has increased with the stress level in the loading increments. The coefficient of secondary consolidation in reloading increments were much smaller compared to that of loading increment.

Hence, it confirms that the secondary consolidation characteristics of MSW can be significantly improved by preloading. This behavior compares well with that of peaty clays. In the reloading increments C_α values increases with the stress level. This can be attributed to the reduction of OCR. This aspect will be discussed in detail in next section.

According to Hossain et al (2009) the range of C_α obtained for MSW samples is in between 0.01 to 0.0000066. Further, Naveen et al (2018) recorded that obtained C_α values for MSW varies from 0.071 to 0.005.

Thus, the values obtained in this study are in close agreement with values reported in literature.

4.1.3.1 Variation of Secondary Consolidation Index with Over Consolidation Ratio (OCR)

C_α ' / C_α was plotted against the over consolidation ratio achieved during the loading stages to identify the reduction of C_α by the loading process (Figure 4-17). Here symbol C_α' was used to denote the coefficient of secondary consolidation corresponding to reloading increment.

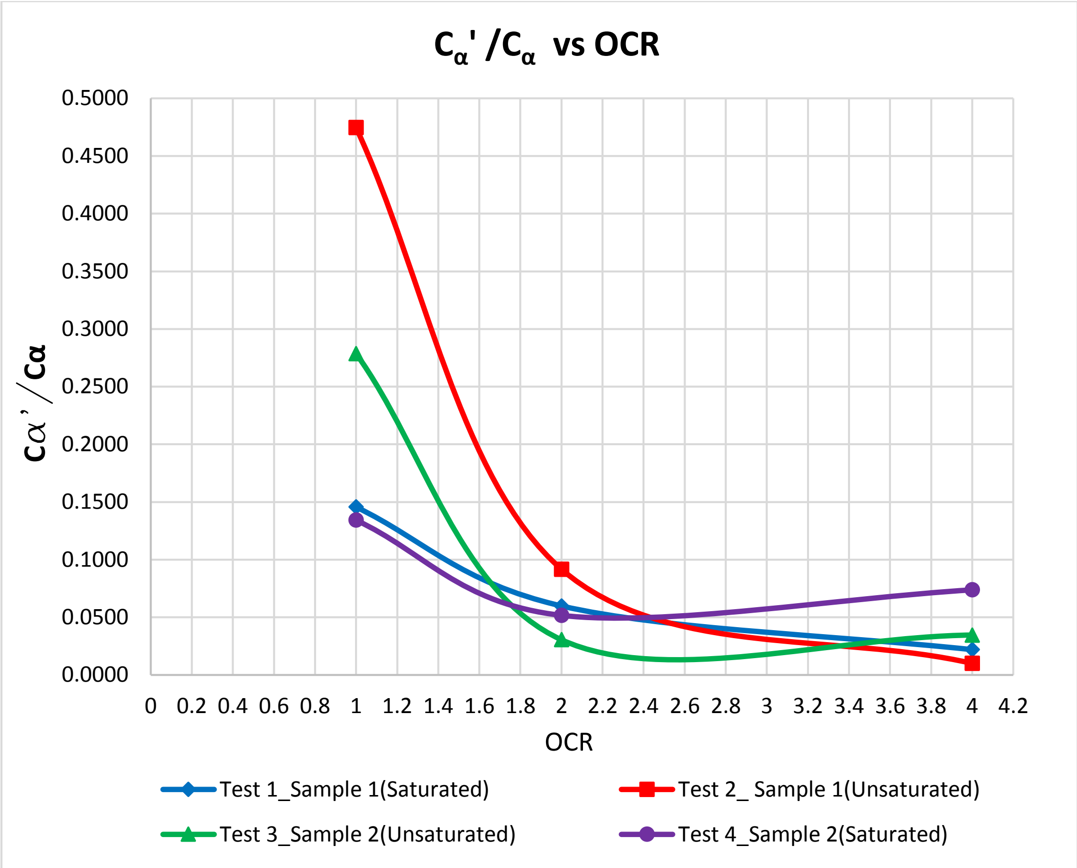

Figure 4-17: Variation of C_{α} ' / C_{α} with over consolidation ratio

All curves shows that the reduction of C_{α} achieved is larger with the larger OCR. Practically OCR values of the range of 1.2 can be achieved in a field preloading process. The results indicates that significant reduction of C_{α} can be achieved with preloading of that extent. Considerable reduction of C_{α} would be achieved with OCR values in the range of 1.2 to 2.0.

4.1.3.2 **Conformity with Cα/ Cc Concept**

Attempts were made to assess the C_{α}/C_{c} concept using the obtained results. The C_{α}/C_{c} values for each loading increments are presented in Table 4-4 . According to the Mesri et al (1997), C_{α}/C_{c} values for peat was in the range of 0.05 to 0.07. Thus, most of the values obtained from this study are lies in between the above range and it can be concluded that secondary consolidation behavior of MSW has similarity with peaty clays.

Table 4-4: Variation of C_α/C_C with stress levels

Stress Level (kPa)	Test 1_Sample 1 (Saturated)	Test 2_Sample 1 (Unsaturated)	Test 3_Sample 2 (Unsaturated)	Test 4_Sample 2 (Saturated)
25	0.0144	0.0305	0.0378	0.0305
50	0.0375	0.0447	0.0496	0.0319
100	0.0417	0.0603	0.0563	0.0554
200	0.0417	0.0493	0.0444	0.0600

4.1.4 Variation of Coefficient of Consolidation (C_V)

The coefficient of consolidation C_V is essential to predict the rate of settlement of municipal solid waste sites. The value of the coefficient of consolidation (C_V) is estimated here using laboratory consolidation test results.

In the formulation of the Terzaghi's theory of consolidation the coefficient of consolidation is defined as $C_V = k/\gamma_w m_v$ and expected to be a constant. However, it is known that it varies with the stress level. In a conventional test the C_V value is estimated for each loading increment.

In a laboratory test, it is difficult to clearly identify the ends and beginning of each phases. Hence, identification of type of settlement that correspond to different degree of consolidation is complex. Further, compression behavior in actual field condition is slightly different from the behavior observed in laboratory test. Therefore, special curve fitting methods are generally adopted to interpret the laboratory test.

Hence, four methods were considered to find the coefficient of consolidation for each loading step.

1. Square root of time method per Taylor (1948)
2. Log time method (Casagrande's method)
3. Rectangular Hyperbola Fitting method proposed by Sridharan and Rao (1981)
4. Velocity method proposed by A.K.Parkin (1978)

As settlement versus log time curve for waste samples obtained from this study has not followed the S-shape (classical shape of Casagrande curve), transition from primary consolidation to secondary consolidation was not clearly identified. Therefore, conventional Casagrande's method cannot be adopted for this study.

The estimation of C_V by the three methods for a selected load increment is presented here.

4.1.4.1 **Square root of time method per Taylor (1948)**

Using the settlement-time curves time factor (T_V) can be obtained and subsequently C_V is determined from Equation.

$$C_v = \frac{T_v x H^2}{t}$$

Where, T_V – Time factor H – Drainage path t – Time

Settlement readings verses root-time for each increment of load were plotted for Taylor's method. Graphical construction method to derive T_V is illustrated Figure 4-18. The load increment 50 -100 kN/m^2 of saturated sample 1 is used to illustrate the behavior.

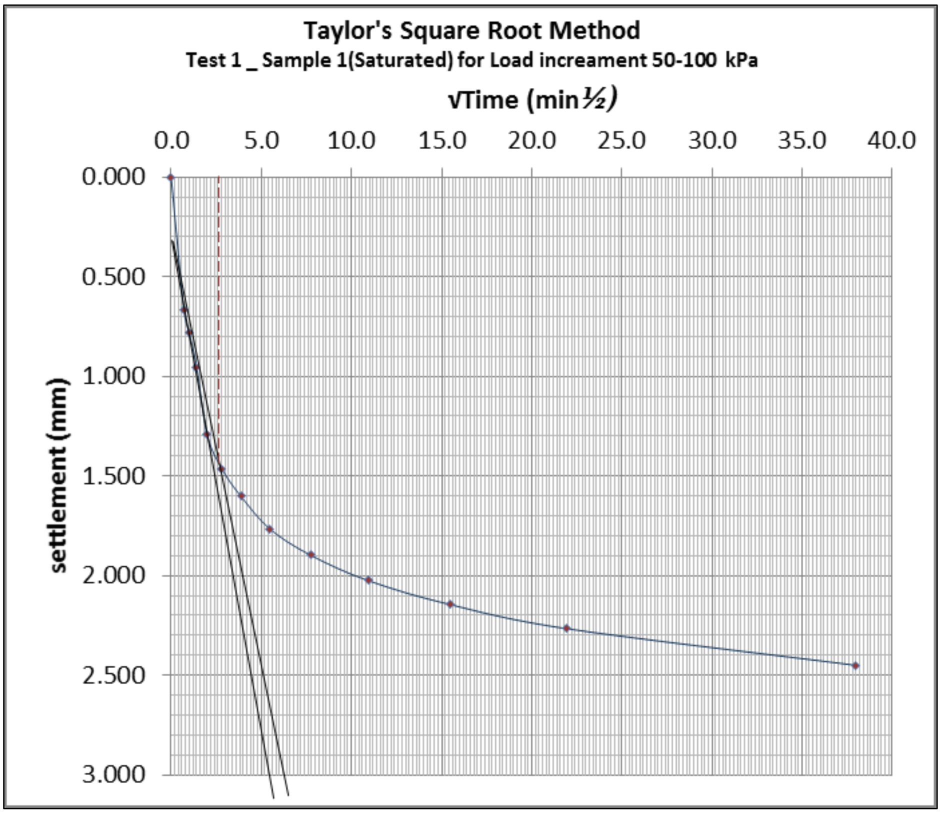

Figure 4-18: Graph representing Taylor's Square root of time method

According to Taylor's Construction.

$\sqrt{t_{90}} = 2.6$

Hence, t_{90} = 6.76 min

Time factor (T_V) corresponding to 90% consolidation is 0.848

$C_v = \frac{T_{90} x H^2}{t}$ = 104.18 m^2/year

4.1.4.2 Rectangular Hyperbola Fitting method

According to method describes in sub section 2.9.4.3, value of slope (m) and intercept (c) of t/(δ-δ_i) vs t plot is obtained for each load increment and C_V is calculated accordingly.

Figure 4-19 show the t/ (δ-δ_i) vs. t curves for the test data and analyzed by the rectangular hyperbola method.

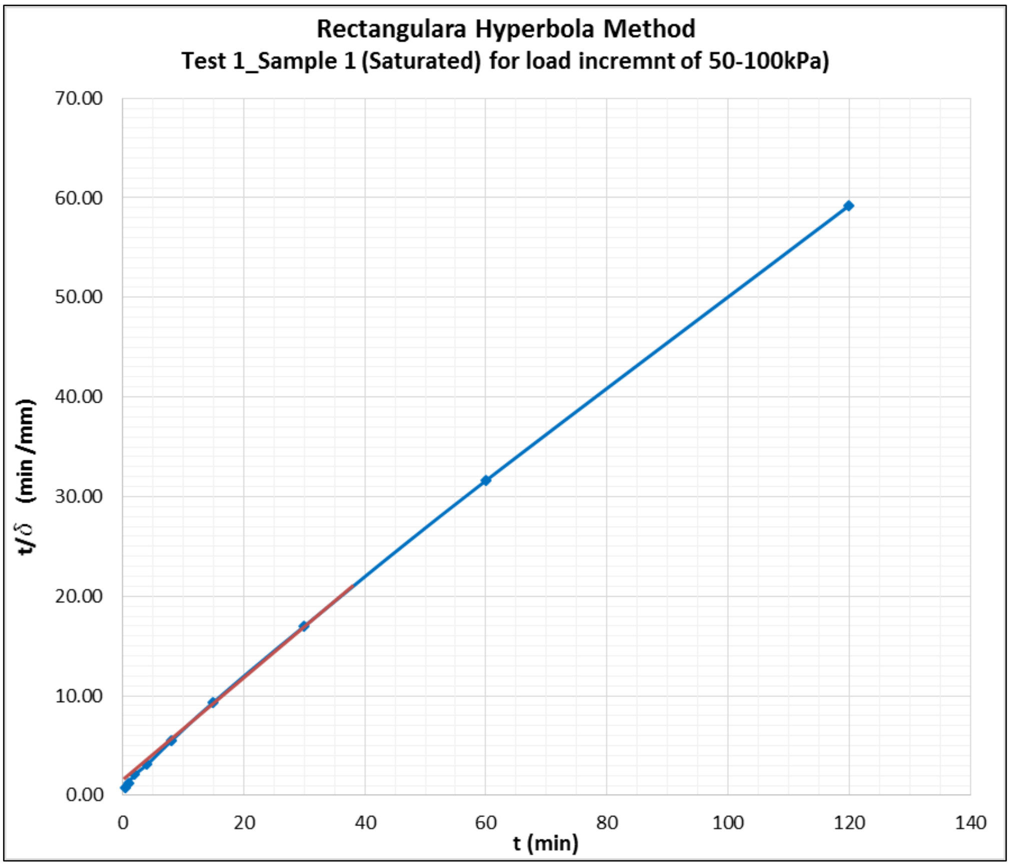

Figure 4-19: Experimental graph for Rectangular Hyperbola method

Slope (m) = 0.5083

Intercept (c) = 1.8

$C_v = \frac{0.24mH^2}{c}$ = 56.28 m^2/year

4.1.5 Improved Velocity Method

log (dδ/dt) against log (t) is plotted using experimental data and it shows that the experimental points lie scattered (Figure 4-20). As stated in the literature review under Section 2.9.4.4 , when the experimental points lie scattered, velocity method proposed by Parkin (1978) cannot be adopted due to difficulties occurred in identification of point where the straight line deviates to a nonlinear segment and the t corresponding to T=1. Hence, improved velocity method proposed by Pandian et al (1994) was used to determine the C_V values.

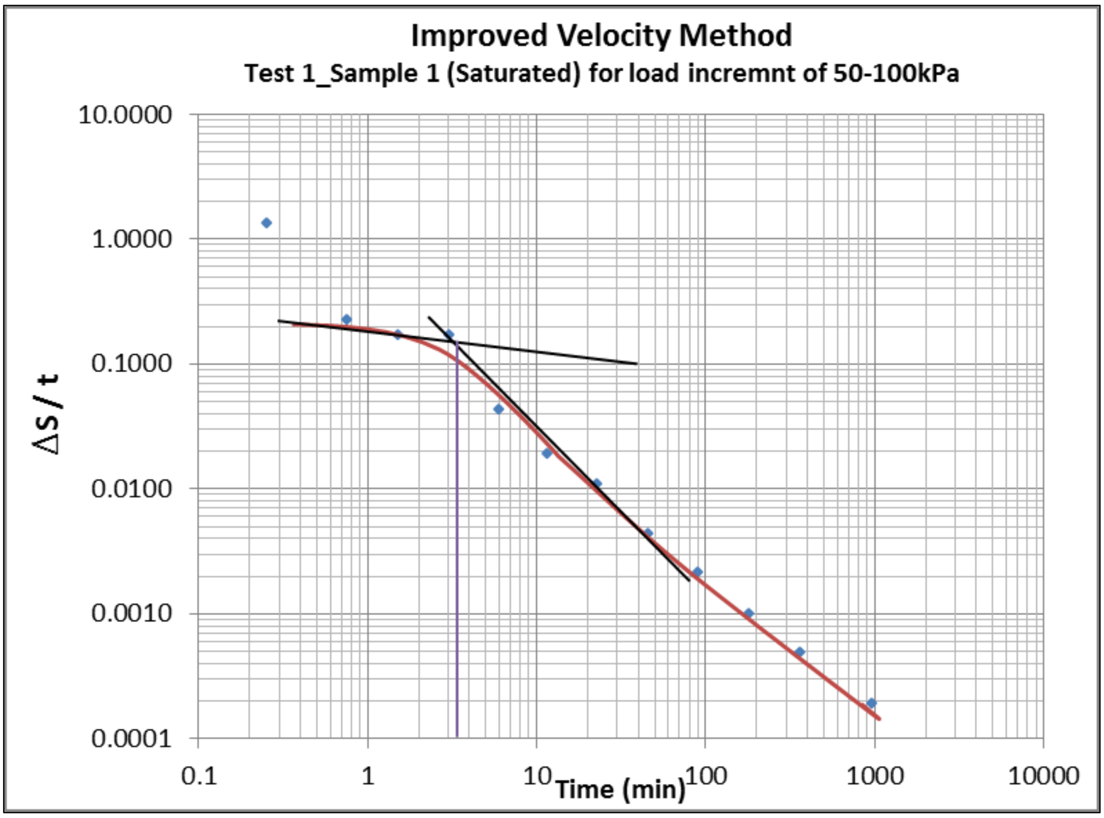

Figure 4-20: Experimental graphs for improved velocity method

By extrapolating the first two straight line (a and c), the value of t corresponding to their intersection

Accordingly, t = 3.2

$C_v = \frac{0.524d^2}{t}$ = 135.99 m^2/year

Table 4-5 gives the coefficient of consolidation values for sample 1 and 2 under saturated and unsaturated conditions.

Table 4-5: Summarized C_V values obtained from different methods

Test No.	Stress Level (kPa)	Coefficient of Consolidation (C_V) – m^2 /year		
		Square Root Time Method	Rectangular Hyperbola Fitting method	Improved Velocity method
Test 1_ Sample 1 (Saturated)	0-25	677.05	273.15	207.74
	25-50	177.52	94.30	161.25
	50-100	104.18	56.28	135.99
	100-200	38.76	47.53	76.64
Test 2_ Sample 1 (Unsaturated)	0-25	490.14	167.10	197.87
	25-50	401.48	50.79	162.08
	50-100	225.77	44.63	90.40
	100-200	45.65	38.08	50.92
Test 3_ Sample 2 (Unsaturated)	0-25	147.89	238.66	131.60
	25-50	137.04	93.36	109.26
	50-100	113.40	79.11	36.69
	100-200	48.04	62.08	11.44
Test 4_ Sample 2 (Saturated)	0-25	52.28	368.31	54.60
	25-50	41.38	33.31	49.39
	50-100	36.70	29.83	22.88
	100-200	27.30	13.81	12.98

Figure 4-21 shows the variation of C_V values for different curve fitting methods.

The variations of C_V value against effective stress for each method of analysis are presented from Figure 4-22 to Figure 4-24. In most cases, C_V value obtained from Square root time method is higher than other two methods and rectangular hyperbola method gives lower C_V values.

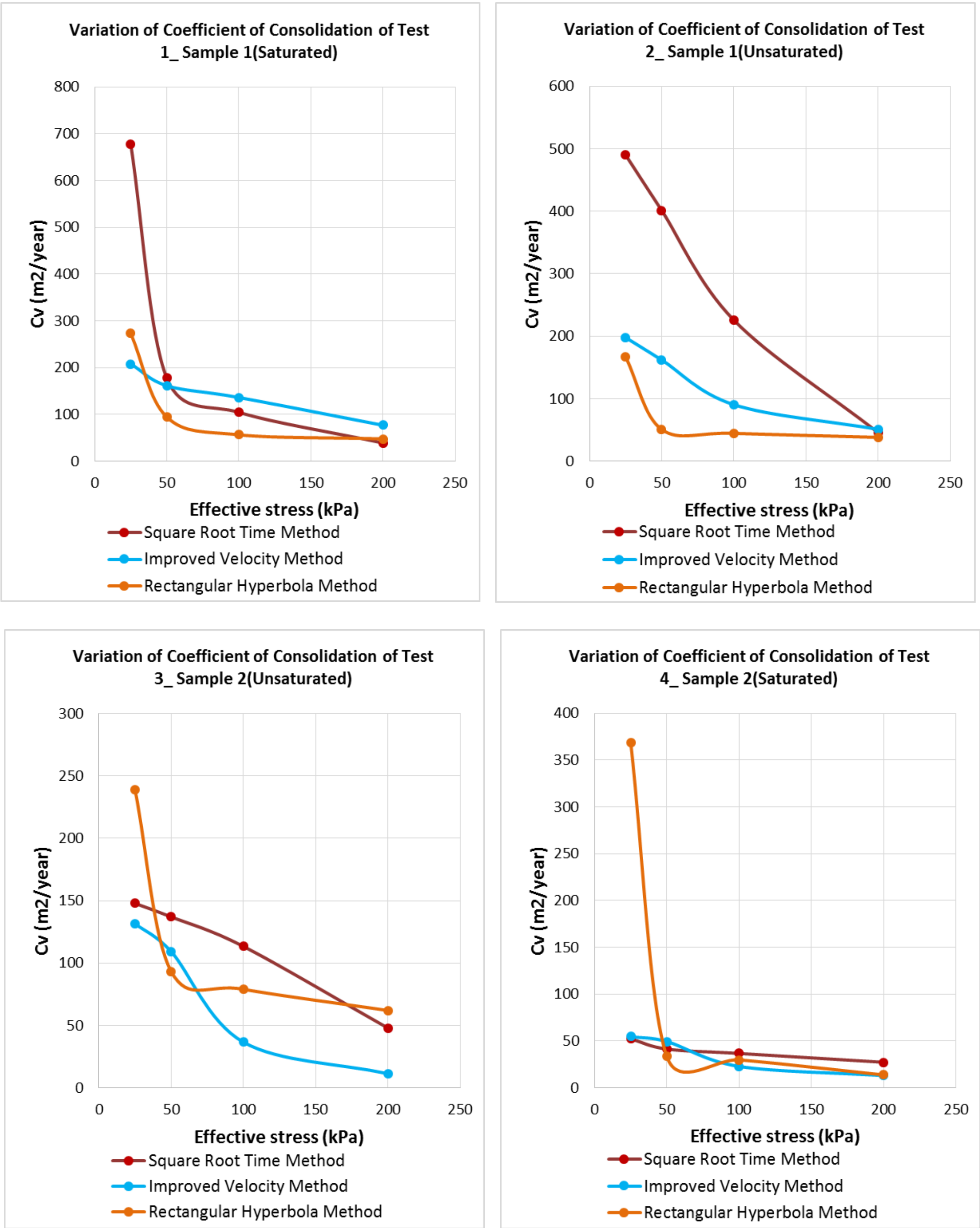

Figure 4-21: Variation of Coefficient of Consolidation for different analysis methods of analysis

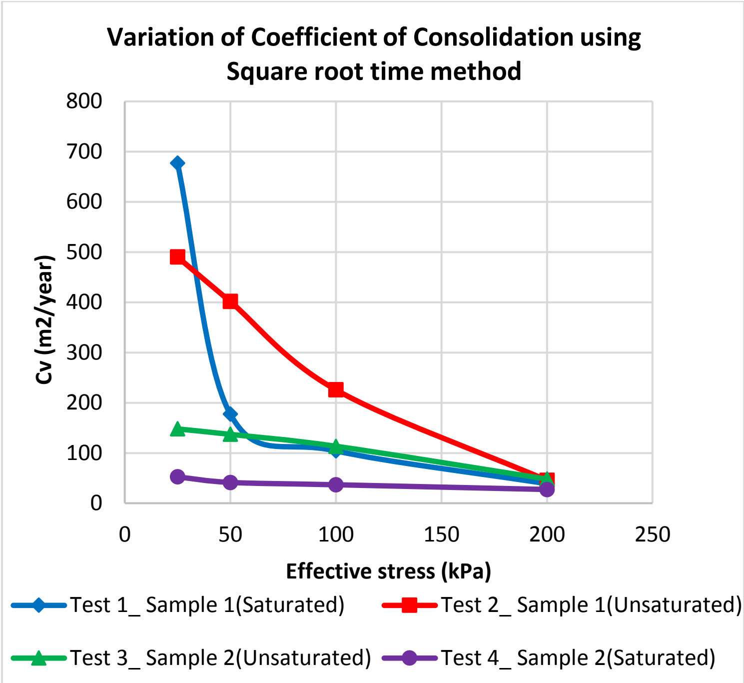

Figure 4-22: Variation of Cv using Square root time method

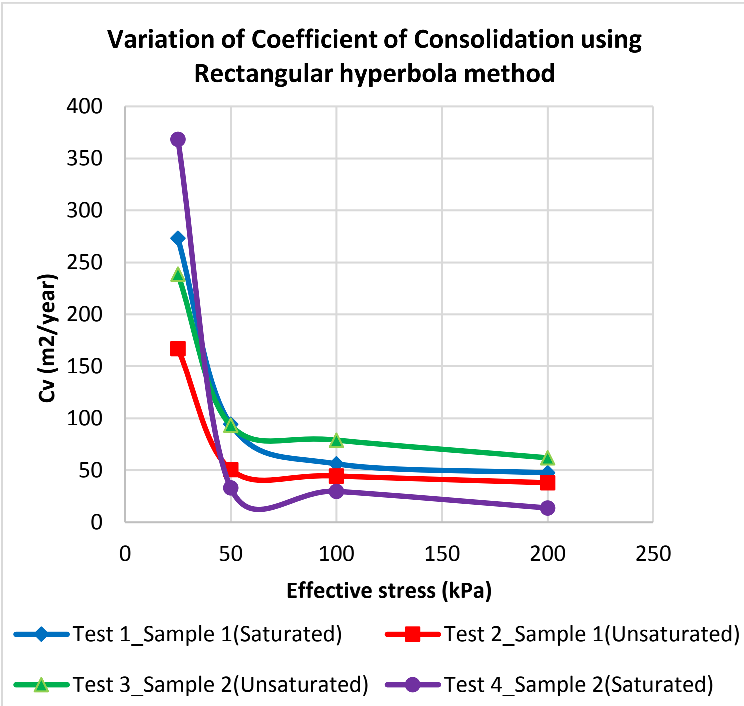

Figure 4-23: variation of Cv using Rectangular hyperbola method

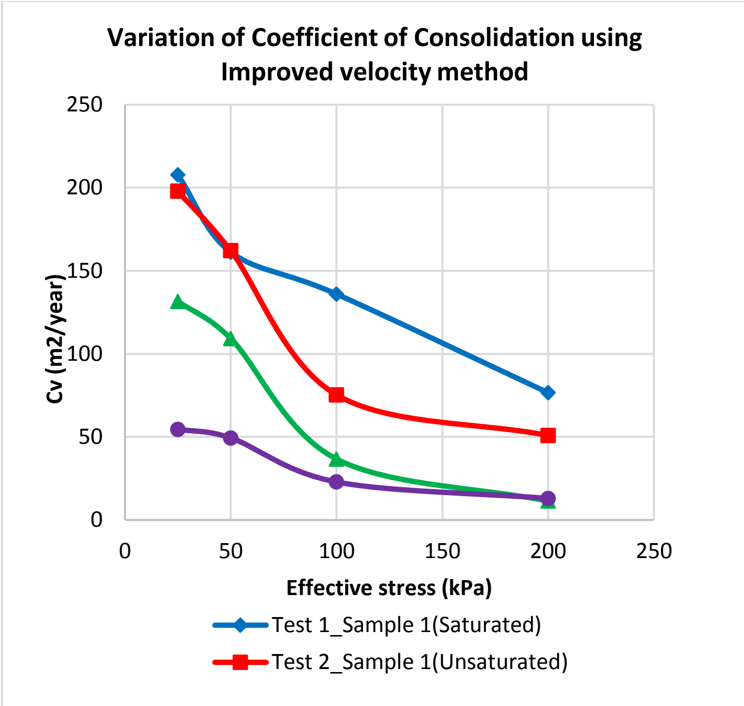

Figure 4-24: variation of C_V using Improved velocity method

4.1.5.1 Summary on the variation of computed C_V

- The coefficient of consolidation values obtained by all methods are showing the same trend on increasing stress level. Apart from the initial increment of 0–25 kN/m^2 the coefficient of consolidation values were of the same order in other higher stress levels. C_V values are much greater than those observed for soils.
- There is no clear difference in C_V values of saturated and unsaturated samples.
- C_V values of sample 1 are higher than the respective values of sample 2. As sample 1 contains older degraded waste, this result proves that degradation level has significant impact on the rate of consolidation.
- Most of the time rectangular hyperbola method gives lower C_V values than other methods.
- C_V values for all tests are not showing same trend with respect to used method. Hence, it is difficult to judge which method is a reasonable for evaluation of C_V of MSW. However, by considering the assumptions and limitations involved in the Rectangular hyperbola method and Square root time method,

Improved Velocity method can be considered as very quick, simple and versatile.

4.2 Comparison of Compressibility behavior of Municipal Solid Waste with conventional soils

The compressibility characteristics of MSW is compared herewith characteristics observed for two types of soils in the extreme ends of all soils; namely residual soils and peaty clay. These results were also obtained from research conducted at the University of Moratuwa.

4.2.1 Amount of settlement

Figure 4-25 presents the settlement vs time curve for MSW, Residual soil and Peaty soils.

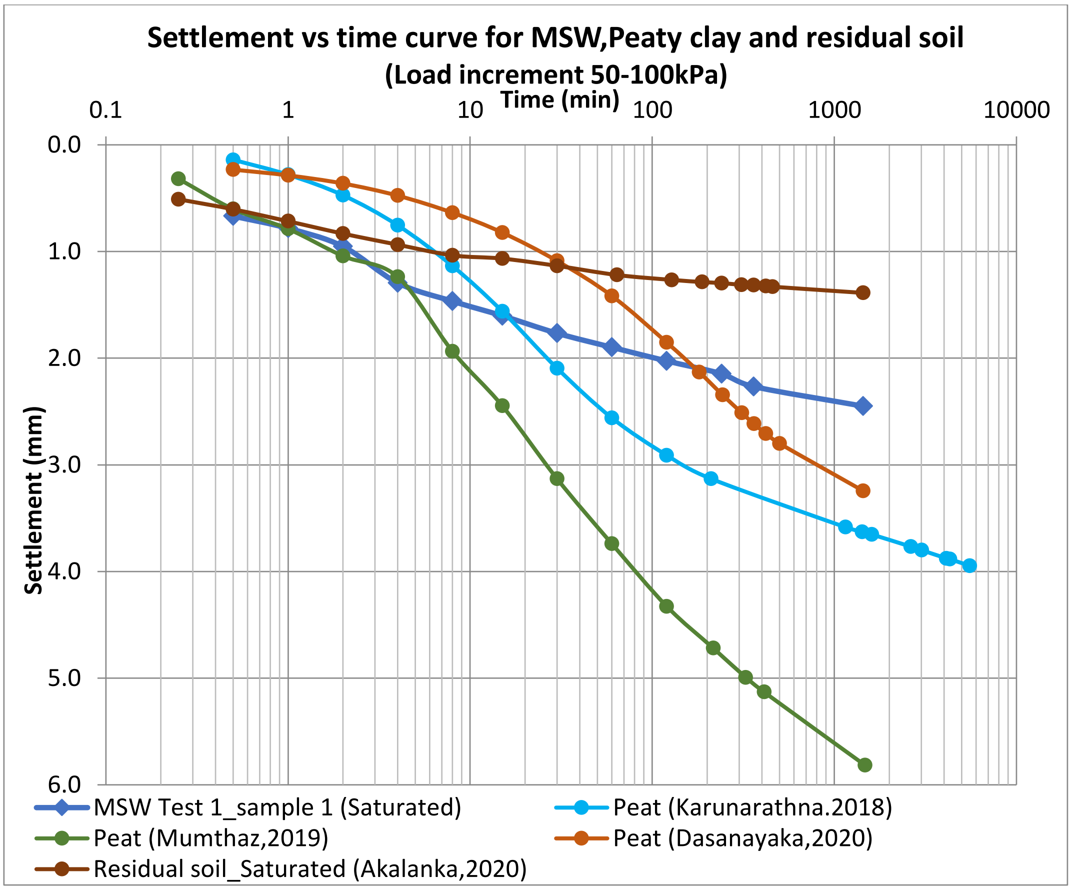

Figure 4-25: Settlement vs time curve for MSW with Residual soil and Peat from different researchers

The reduction of the gradient of the curve after completion of primary consolidation usually seen in inorganic soils is clearly observed in curve for Residual soil and it is not seen in both Peat and MSW. The gradient remained high in settlement vs time curve of MSW and peaty soil. Generally, this is due to the high secondary consolidation of Peaty soils. Hence, it illustrates that the MSW undergo significant secondary consolidation settlement and behavior of MSW has similarity with compressibility behavior of Peaty soils.

4.2.2 Compression Index

Variation of compressibility indices of MSW, peaty soil and residual soil are compared in Figure 4-26 and Figure 4-27.

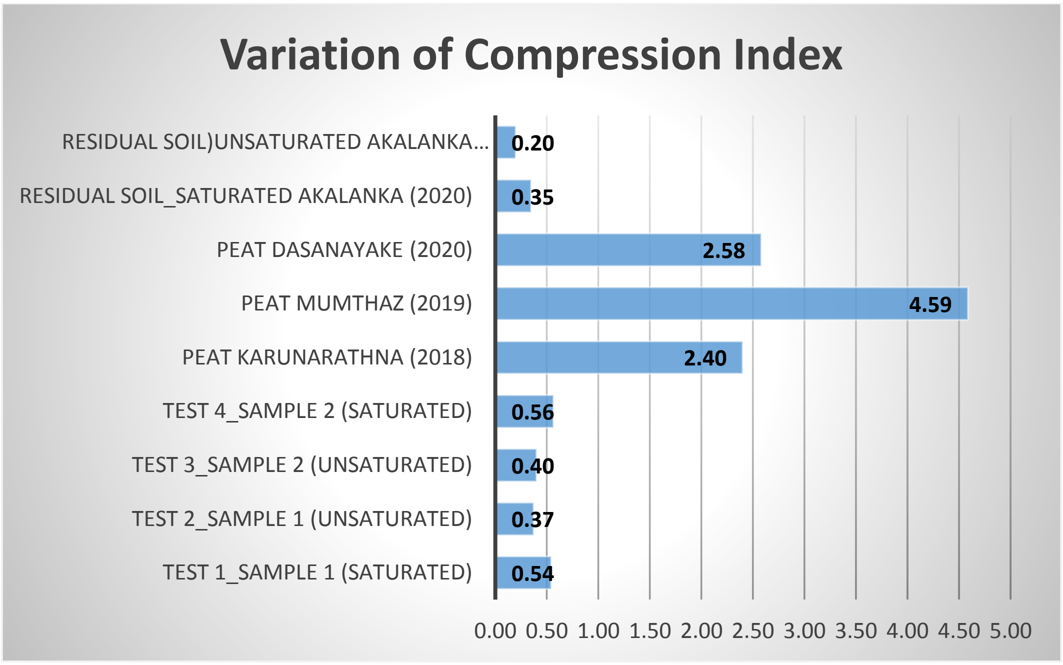

Figure 4-26: Comparison of C_C values of MSW with peaty soil and residual soil

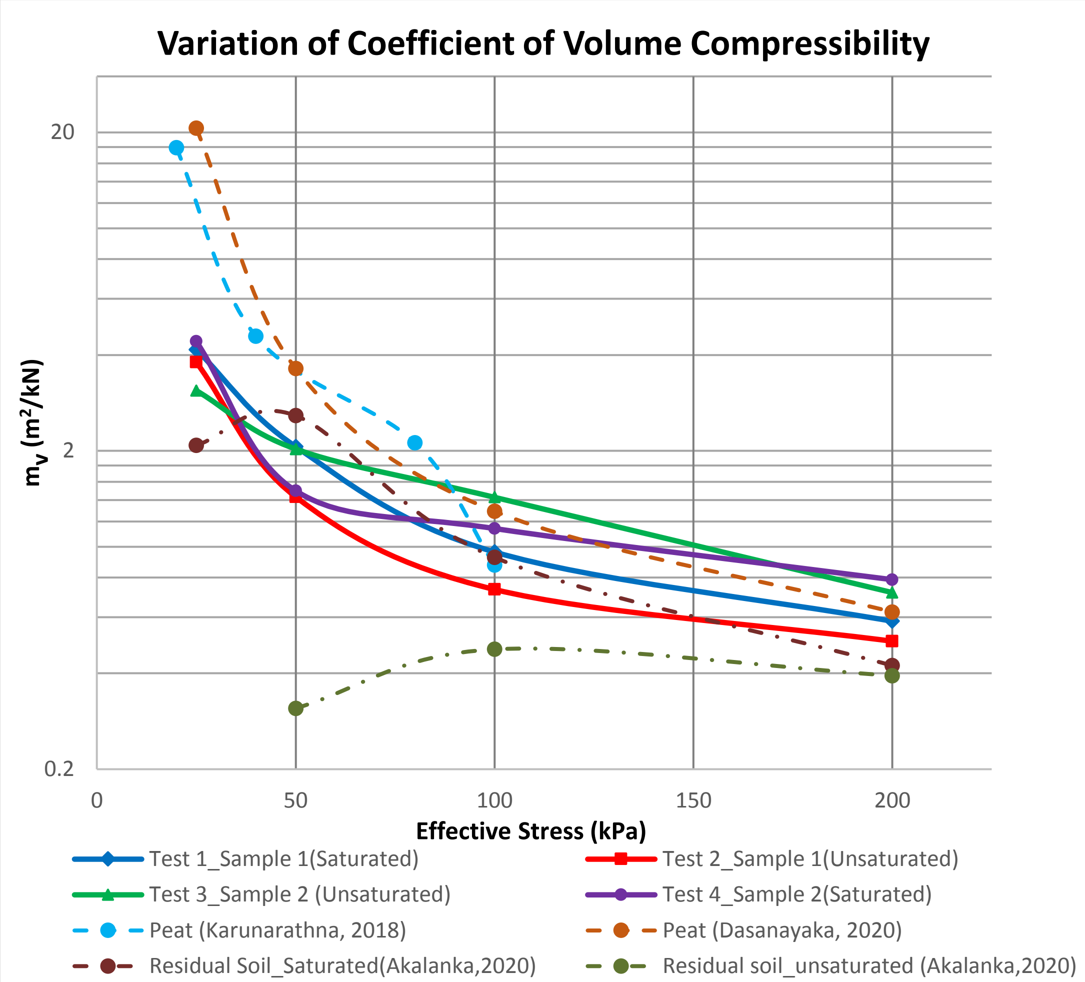

Figure 4-27: Comparison of m_v values of MSW with peaty soil and residual soil

According to above graphs, both compression index values and coefficient of volume compressibility values lies in between corresponding values for Peaty clays and residual soils. Values are close to those of residual soil.

4.2.3 Coefficient of Secondary Consolidation

Further, Variation of coefficient of secondary consolidation of MSW is compared with experimental results of peaty soil. As shown in Figure 4-28, Coefficient of secondary compression of MSW is much lower than the values of Peat. Lower values of C_α in reloading increments indicates that with preloading secondary consolidation of MSW can be reduced (Figure 4-29). This reduction is proportionated to OCR achieved as illustrated in Figure 4-17. As C_α values of residual soils are very low, those are not plotted here. A comparison of this reduction observed for peaty clay and MSW are compared in Figure 4-30.

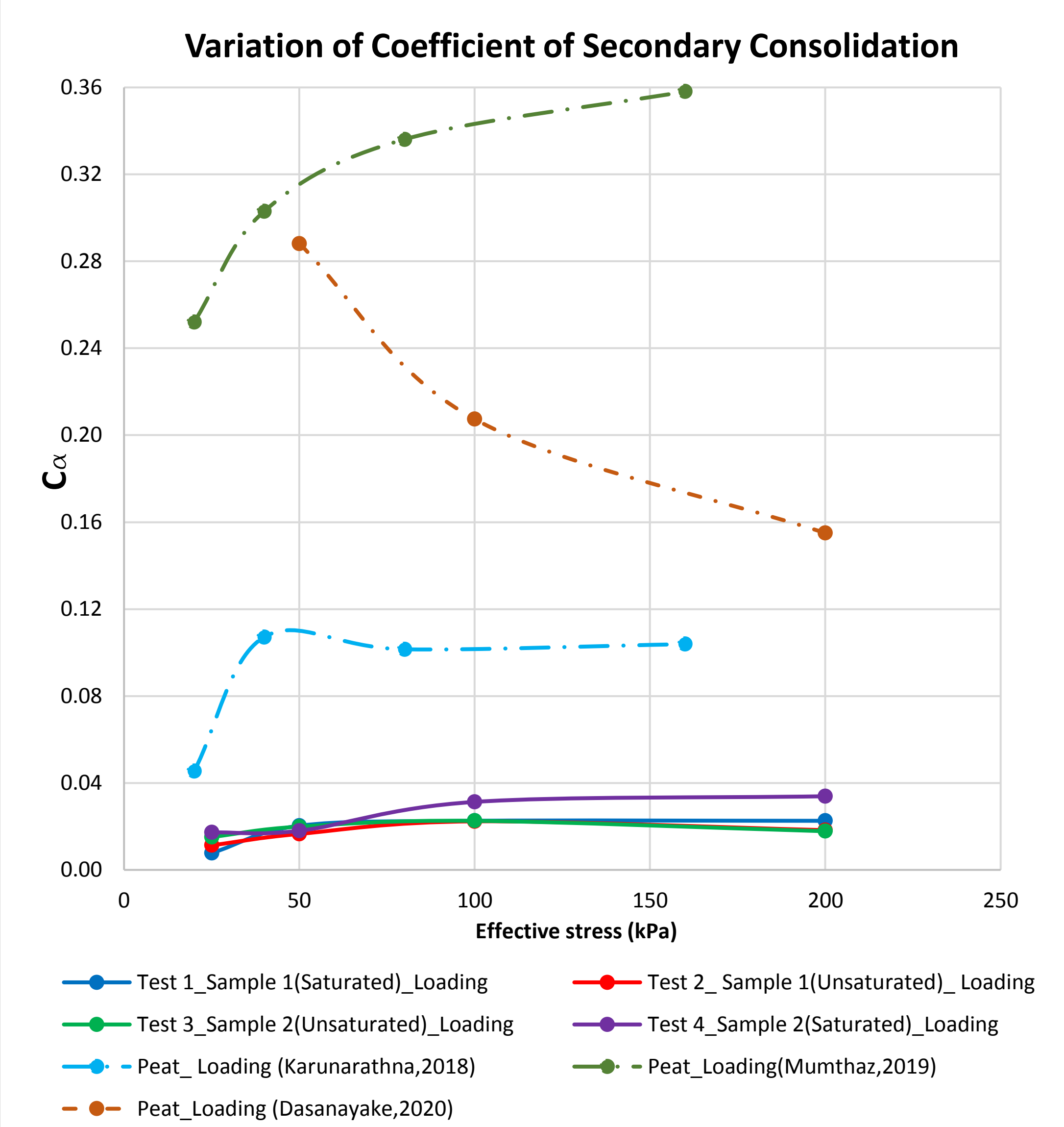

Figure 4-28: Comparison of Cα values of MSW with peaty soil (Loading increments)

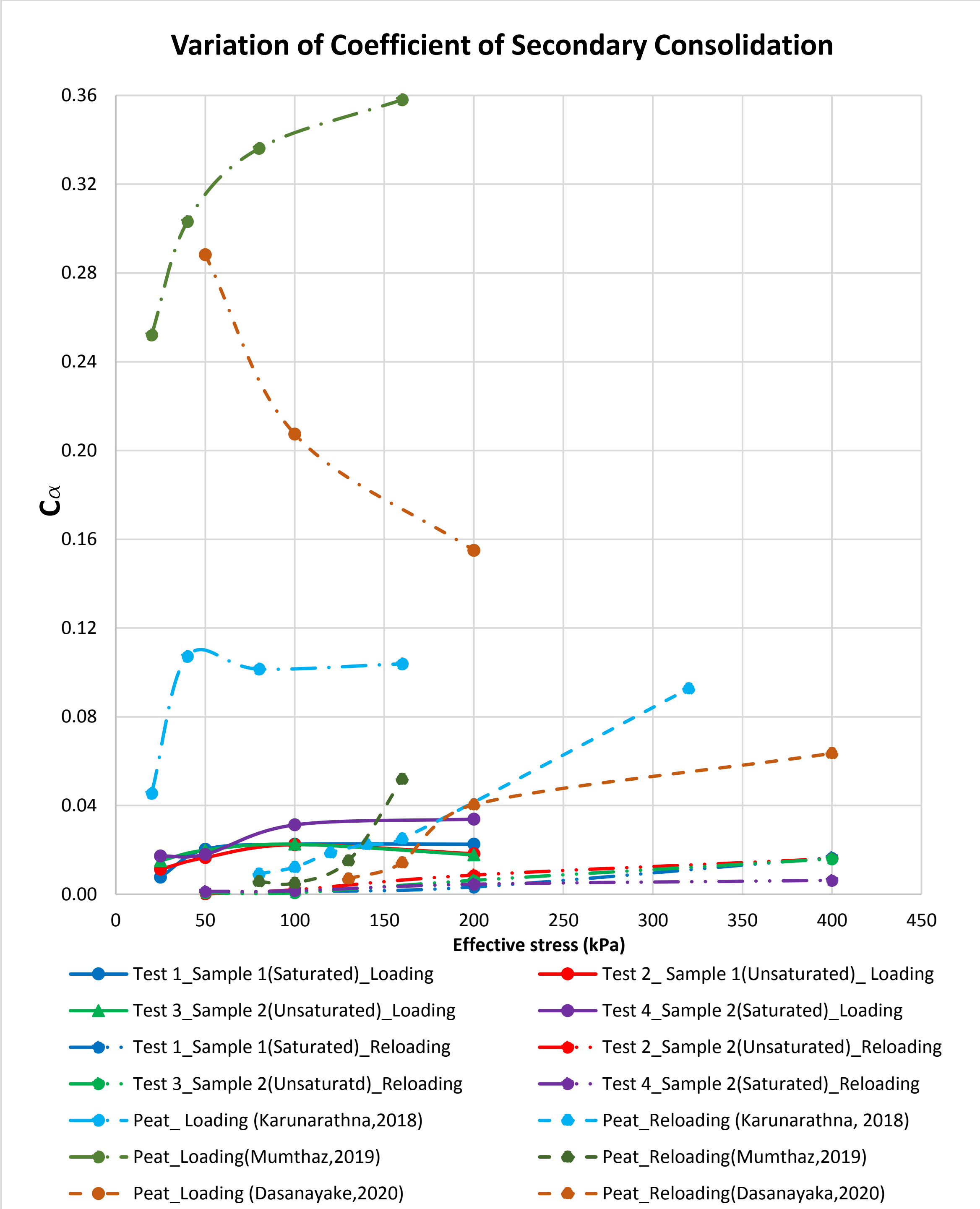

Figure 4-29: Comparison of C_α values of MSW with peaty soil (Both loading and reloading increments)

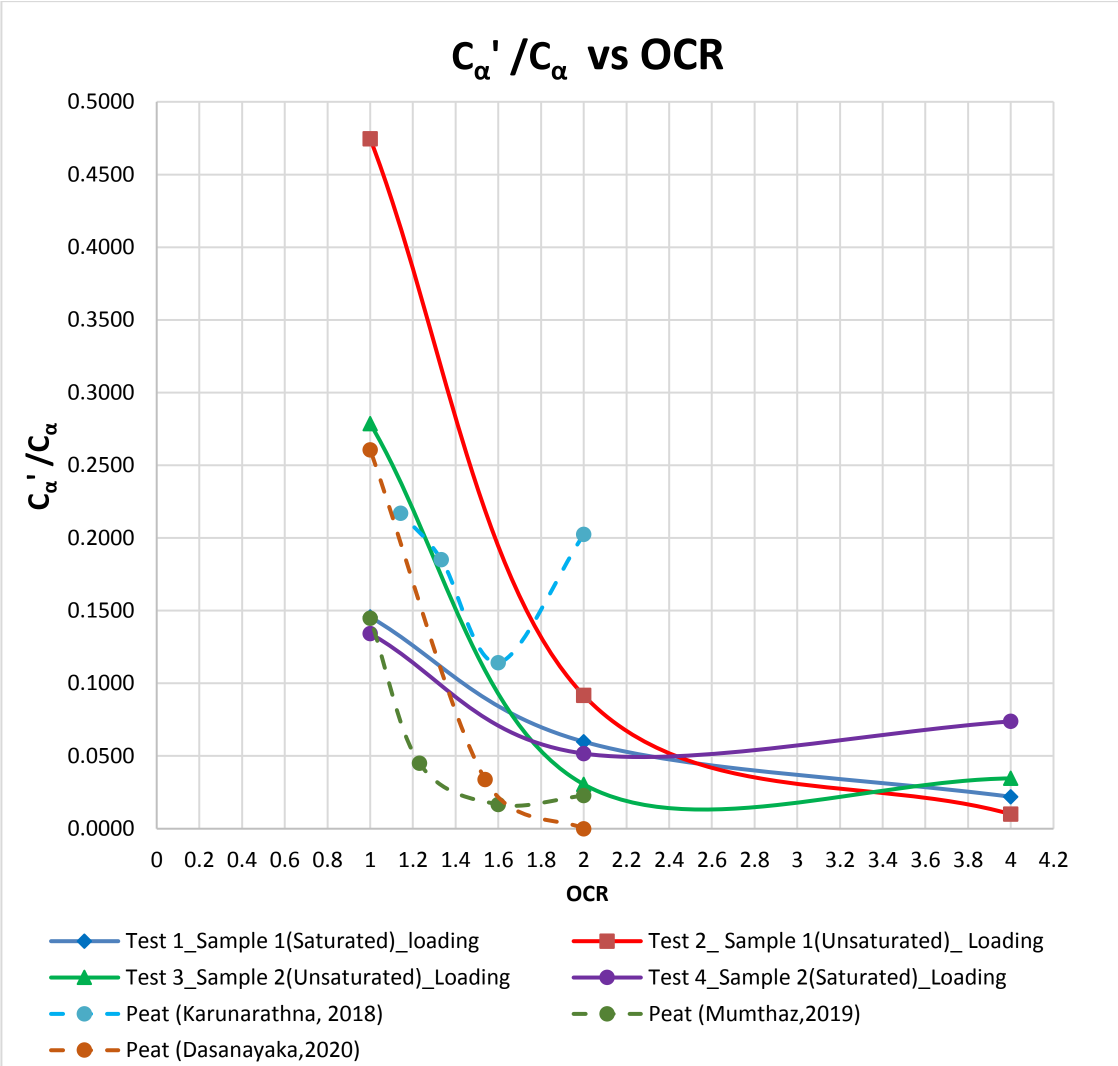

Figure 4-30: Comparison of variation C_α'/ C_α with OCR of MSW with peaty soil

CHAPTER 5 - SUMMARY AND CONCLUSIONS

Municipal Solid Waste Management was an ignored problem but is became a growing concern in Sri Lanka with the Catastrophic landfill failures occurred at Meeethotamulla. In order to minimize the future risk of failure, it is necessary to establish a proper assessment of stability and deformation of municipal solid waste landfill in Sri Lanka. These landfill will have to be restored into safe useful land by appropriate geometric modification. As it is not feasible to move away the MSW accumulated there at present, the process of rehabilitation must contain MSW also. Relevant studies related to landfill sites in Sri Lanka are very limited. As MSW is highly heterogeneous, its engineering properties vary from landfill to another. Hence, site-specific evaluation of these properties is very essential, and this study is mainly focused on compressibility characteristics.

The samples representing two degradation levels from Meethotamulla dump site were used in this study to determine the compressibility characteristics through consolidation test. These sample are more than 15 years old and the primary bio degradation is completed. Consolidation tests for MSW are performed using the Rowe cell. As the size of Rowe Cell sample is larger than Oedometer sample, it can accommodate a more representative sample.

Consolidation tests were done with loading, unloading and reloading increments. The results of the compressibility test were compared with results obtained from residual soils and peaty clay; two soils that are in the two extreme ends with regards to compressibility.

Basic index properties test; insitu densities, moisture content test and specific gravity test were conducted as prerequisite for consolidation test. Obtained results showed that values of Specific gravity increases with the degradation and moisture content and density lies in the similar range.

Coefficient of volume compressibility values of all samples tend to decrease as the effective stress increases and m_v values for saturated sample shows higher compressibility values at each stress levels. The coefficient of compressibility values were much smaller than peaty clay but were larger than in residual soils.

The values of the Compressibility index and Recompression index for the MSW specimens under saturated condition are higher than under the unsaturated condition. Further, there was a significant reduction in C_r compared to value of C_C.

There was a considerable reduction of coefficient of secondary compression during reloading stage compared to loading stage. This revealed that the secondary consolidation characteristic of MSW can be significantly improved by Preloading.

These results indicate that the compressibility characteristics of MSW can be improved by preloading. In recent times the preloading was very effectively used in construction of roads through sites underlain by peaty clay. Hence, in the rehabilitation of MSW landfill and converting them to useful lands, preloading process can be adopted to ensure that the settlements of these improved grounds are well within acceptable limits during the service time.

Due to strange behavior of MSW, different analysis methods were adopted to determine the coefficient of consolidation. The values of coefficient of consolidation obtained by all methods (i.e. Rectangular hyperbola method, Square root time method and improved velocity method) are showing the same trend. The values decrease after initial load increment and did not show much variation thereafter. C_V values of sample 1 which contains more older degraded waste is slightly higher than the respective values of sample 2 Hence, it shows that degradation level has significant influence on the rate of consolidation. It is difficult to judge which method provides the most reasonable evaluation of C_V of MSW. However, by considering the assumptions and limitations involved rectangular hyperbola method and square root time method , improved velocity method can be considered as simple, very quick, reliable, and versatile methods. Coefficient of consolidation Cv values obtained are much higher than that of the peaty clay. As such, in the improvement of stiffness of MSW by preloading the process will be much faster. It would not be necessary to use technology such as Prefabricated Vertical Drains (PVD) to accelerate consolidation.

Further, from the comparison of MSW with peaty soils and residual soils, it shows that the behavior of MSW has similarity with settlement behavior of Peaty soils but less compressible.

It is better to continue this research using MSW samples from different landfills in Sri Lanka that are of different levels of degradation. Then, through further results and comparisons, a further understanding on compressibility characteristics of MSW can be clearly established. The tested samples are with a very high level of biodegradation. Behavior of much younger samples should also be studied. However, with rehabilitation we would mostly have to deal with aged MSW.

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