5.1 GENERAL

The model parameters proposed in Chapter 4 to describe the pre-failure stress-deformation behaviour of MSW have been observed to exhibit scatter similar to other mechanical properties of waste, reflecting variability in sample composition, testing methods and the extent of degradation of the tested samples. The degradation of waste constituents over time is likely to cause changes in mechanical properties, potentially leading to instability and/or serviceability concerns. While for conventional landfills, it has been observed that waste does not become significantly weaker over time; in bio-reactor landfills, which are subjected to rapid stabilization techniques, there may be changes in the stress-deformation behaviour of waste with increasing degradation. This study presents the results of a laboratory test program of MSW subjected to degradation in a one-dimensional compression cell. The evolution of compressibility and at-rest lateral pressure of waste during degradation is explored and the results compared with similar published results from the literature. The mechanism of secondary compression in waste is explained. The findings from this study address the third objective of this research i.e. to measure the compressibility behaviour of MSW with degradation and verify the mechanism of secondary compression in waste.

This study presents the results of a laboratory test of municipal solid waste subjected to accelerated degradation and one-dimensional compression. Incremental vertical stresses were applied to simulate staged construction of a landfill. Degradation was quantified by methane yield, leachate quality and loss of volatile solids. Lateral and vertical stress, pore pressure and vertical settlement were continuously monitored during the 150 day duration (17-01-2011 to 15-06-2011) of the experiment. Data were collected regarding the evolution of the at-rest lateral earth pressure, the compressibility and the constrained modulus. The
results show a significant influence of degradation on compressibility parameters ($C_{ce}$ and $C_{ae}$). The $K_0$ value did not change significantly during degradation and it is proposed that it might be considered a constant regardless of applied stresses or age. The mechanism of compression and development of lateral stresses with time are discussed.

The condition of MSW inside a landfill changes over time due to degradation, compression, decomposition and creep. The mechanical properties of MSW therefore, may also change over time, potentially leading to stability and/or serviceability concerns. While there is not, at present, a consensus regarding the net effect of degradation on the global stability of waste slopes, there is some basis to suggest that the waste in many conventional landfills does not become significantly weaker over time (Kavazanjian, 2008). Given that these facilities incorporate significant buried infrastructure representing a substantial financial investment, it is reasonable to consider how the relevant material properties might change during the course of degradation.

The mechanical properties required to evaluate stress-deformation behaviour are Young’s modulus ($E'$) and Poisson’s ratio ($\nu'$), the later can also be expressed in terms of at-rest lateral earth pressure ($K_0$). The published literature regarding the elastic properties of waste is relatively sparse. Various authors (Kavazanjian, 2006; Dixon and Langer, 2006; Landva et al., 2000; Dixon et al., 1999; Carvalho and Vilar, 1998; Matasovic and Kavazanjian 1998; Beaven and Powrie, 1995 and Sharma et al., 1990) have measured the elastic properties of waste using various techniques. The evolution of elastic properties as a result of degradation, however, is not well understood. Knowledge of the change in the mechanical properties of MSW over time is important as it governs the deformation behaviour of the waste.
The mechanism of settlement in landfills is complex due to the heterogeneous composition of municipal waste. This complexity is further exacerbated due to the large variation in compressibility and degradation potential of waste constituents. There is significant loss of mass as a result of degradation and loss of volume due to collapse of the macro and micro-structure of the waste (McDougall and Pyrah, 2004, Stoltz and Gourc, 2008). As a result, an equilibrium void ratio is seldom reached in waste and the landfill continues to settle and deform for a very long time. Large and differential vertical settlements can damage the integrity of the landfill cover resulting in excessive infiltration of surface water and consequent increased generation of leachate. This can also lead to unwanted escape of landfill gases to the atmosphere. Lateral deformations, on the other hand, can substantially damage gas collection systems installed in landfills for mitigating greenhouse gas emissions and for implementation of waste to energy program (Singh et al., 2007). Given these facts, post-closure settlements in landfills have often been recognized as the greatest concern especially for bioreactor landfills (McDougall, 2008).

Though long-term deformations in a landfill cannot be prevented, it may be possible to mitigate adverse effects by designing its various components to withstand the anticipated deformations. In order to be able to do this, it will be necessary to understand the change in mechanical properties over time. This study explores the evolution of elastic and compressibility behaviour of MSW during accelerated degradation. The results from this study are compared with similar published results from the literature. The present study is an extension of previous work done by Singh and Fleming, 2008.
5.2 EARLIER WORK

The mechanism of compression of MSW in response to applied normal stress is somewhat different from soils and has been discussed by various authors (Van Impe and Bouazza, 1996; Gasparini et al., 1995; Wall and Zeiss, 1995; Morris and Woods, 1990 and Sowers, 1973). Broadly speaking, waste settlement is a combined outcome of mainly two phases: initial compression and delayed or secondary compression. The initial compression occurs immediately following application of external load either by dozers/compactors or due to the self weight of overlying waste. A majority of crushing, distortion, squeezing and raveling of waste constituents occurs during this stage and the initial compression can continue for the first few days of waste placement depending upon landfill operating practices. Due to short-term settlements, the initial compression is of limited interest to engineers except when considering piggy-back expansion (Kavazanjian, 2006).

Secondary compression, on the other hand, is of great interest to engineers and takes place as a combined action of two different mechanisms which occur as a result of mechanical and degradation processes. Laboratory tests conducted by Al-Khafaji and Andersland, 1981 on organic soils suggest that secondary compression produced by the degradation process exceeds that caused by simple creep. Similar behaviour might also be expected in waste but to a greater degree, given the higher proportion of organic material in waste when compared to organic soils. The two mechanisms of secondary compression are indistinguishable and it is difficult to identify their precedence over each other. It was hypothesized by McDougall et al., 2004 that these two mechanisms proceed simultaneously as an episodic process of gradual weakening of the waste structure due to degradation and its collapse at a point when the structure becomes too weak to resist overburden stresses. This...
process is then followed by the mechanical processes of raveling of constituents into the collapsed structure.

For soils, compressibility is conveniently described using compression indices expressed in terms of void ratio. However, the meaning and significance of void ratio as it applies to MSW is somewhat complicated (McDougall, 2008). Given the inadequate information regarding the void ratio of waste, the compressibility of waste has often been described in terms of primary compression ratio ($C_{ce}$) and secondary compression ratio ($C_{\alpha e}$) which are expressed in terms of axial strains rather than void ratio. The value of $C_{ce}$ is obtained from the slope of the straight line virgin compression part of the $\varepsilon_a$–$\log(\sigma')$ curve using Eq. (5.1),

$$C_{ce} = \Delta \varepsilon_a / \Delta \log(\sigma') \quad \ldots \quad \ldots \quad \ldots \quad \text{Eq. (5.1)}$$

where $\Delta \varepsilon_a$ is the change in axial strain per log cycle of change in vertical effective stress [$\Delta \log(\sigma')$]. Similarly, the secondary compression ratio ($C_{\alpha e}$) is computed as the slope of the $\varepsilon_a$–log(time) curve, expressed as:

$$C_{\alpha e} = \Delta \varepsilon_a / \Delta \log(t) \quad \ldots \quad \ldots \quad \ldots \quad \text{Eq. (5.2)}$$

For soils, the compression indices and compression ratios are related by the expressions: $C_{c} = (1 + e_o)C_{ce}$ and $C_{\alpha} = (1 + e_o)C_{\alpha e}$, where $e_o$ is the initial void ratio and $C_c$ and $C_\alpha$ are compression indices expressed in terms of void ratio. While the applicability of this relationship for waste is somewhat unclear, various researchers (Vilar and Carvalho, 2004; Hossain et al., 2003 and Gabr and Valero, 1995) have made assumptions of the value of $e_o$ in arriving at the values for $C_c$ and $C_\alpha$ for waste.

A review of published data and present study shows a typical range of $C_{ce}$ and $C_{\alpha e}$ values lying between 0.1 to 0.92 and 0.0005 to 0.22 respectively (Table 5.1).
While some of the scatter in these values is expected because of the heterogeneous nature of MSW, the authors suggest that most of the observed scatter in the data may be attributed to the use of different sizes and types of equipment and samples of varying age, unit weight and moisture content.

Knowledge of the lateral stresses that will develop in waste over time is critical to anticipating lateral deformations, especially those developed alongside slopes. Lateral stresses are also an important consideration in the design of vaults and conduits, retaining walls, and deep foundations installed for post-closure development (Kavazanjian, 2006). Determination of lateral stresses requires an estimate of $K_0$, the ratio of the lateral to the vertical effective stresses under the conditions of no lateral deformation.
## Table 5.1 Compressibility Indices of MSW from Published and Present Study

<table>
<thead>
<tr>
<th>Reference</th>
<th>Primary</th>
<th>Secondary</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_c )</td>
<td>( C_{ce} )</td>
<td>( C_\alpha )</td>
</tr>
<tr>
<td>Vilar and Carvalho (2004)</td>
<td>0.18-0.23</td>
<td>0.52-0.92</td>
<td>0.012-0.016</td>
</tr>
<tr>
<td>Hossain et al.(2003) (a) With accelerated degradation</td>
<td>0.16-0.37</td>
<td>0.08-0.22</td>
<td></td>
</tr>
<tr>
<td>(b)Degradation inhibited</td>
<td>0.16-0.25</td>
<td>0.07-0.12</td>
<td></td>
</tr>
<tr>
<td>Landva et al.(2000)</td>
<td>0.17-0.24</td>
<td>0.01-0.016</td>
<td></td>
</tr>
<tr>
<td>Test Description</td>
<td>Compression Index</td>
<td>Void Ratio</td>
<td>Test Details</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Gabr and Valero (1995)</td>
<td>0.4-0.9</td>
<td>0.09-0.03</td>
<td>150mm were shredded; vertical stress 46-260kPa; loading duration 1-32 days</td>
</tr>
<tr>
<td>Test cell 63mm in diameter; particle size&lt;6.3mm; sample-auger cuttings representative of 15-30 years old waste; initial void ratio 1.0-3.0. no vertical stress and test duration.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall and Zeiss(1995) (a) with accelerated degradation</td>
<td>0.25</td>
<td>0.033-0.056</td>
<td>Test cell 570mm in diameter designed to perform as both lysimeter and consolidometer; particle size reduced by shredding; loading duration 229 days at a constant average vertical stress of 10kPa</td>
</tr>
<tr>
<td>(b) Degradation inhibited</td>
<td>0.21</td>
<td>0.037-0.049</td>
<td></td>
</tr>
<tr>
<td>Sowers (1973)</td>
<td>0.15-0.55 times $e_0$</td>
<td>0.03-0.09 times $e_0$</td>
<td>Compression indices related to initial void ratio</td>
</tr>
</tbody>
</table>
Published data on $K_0$ values for MSW are sparse. Measurements of $K_0$ from in-situ testing (e.g. Dixon et al., 1999), laboratory testing (e.g. Singh and Fleming, 2008; Kavazanjian, 2006; Towhata et al., 2004 and Landva et al., 2000) and by indirect estimation from measurement of Poisson’s ratio (e.g. Zekkos, 2005;

Table 5.1 (continued)

| Present Study | 0.42 | 0.0005-0.15 | Test cell 400mm in diameter; 1 year old waste degraded for 150 days dual purpose compression cell (Bioreactor + consolidometer); loading duration 60 days+ leachate injection; vertical stress 22-180kPa; primary compression ratio reduced from 0.58 to 0.27 under the application of incremental vertical stresses and simultaneous degradation. A best fit representing all stages of loading gave a value of 0.42. |

[167]
Matasovic and Kavazanjian, 1998 and Houston et al., 1995) suggest a range of possible $K_0$ values from 0.1 to 1.0 with values between 0.3 to 0.5 being common. However, the influence of waste degradation on $K_0$ with time has not been documented.

One-dimensional compression cell has been used to estimate the constrained modulus ($E_0'$) of MSW (e.g. Singh and Fleming, 2008; Beavan and Powrie, 1995). In situ tests have also been used to obtain estimates of the shear modulus of MSW using shear wave velocity measurements (Kavazanjian et al., 1996), pressure meter tests (Dixon et al., 1999), or high pressure dilatometer and self boring pressure meter tests (Dixon and Langer, 2006).

5.3 STATEMENT OF THE PROBLEM AND OBJECTIVES

A sincere effort is made to study the compressibility behaviour of MSW with the following objectives –

i. To investigate compressibility characteristics of MSW subjected to accelerated degradation under the application of vertical stresses.

ii. To examine primary compression ratio of some selected samples from some municipal solid waste landfill sites.

iii. To study secondary compression behaviour under accelerated degradation.

iv. To investigate void formation in MSW and subsequent collapse mechanism in MSW.

5.4 INSTRUMENTS USED AND METHODOLOGY

The experimental set-up used in this study is a dual-purpose landfill compression cell (LCC) designed and fabricated at the Assam Agricultural University,
Jorhat, Assam (Fig 5.1). The purpose of the LCC is to study changes in the mechanical behaviour of waste subjected to accelerated degradation under controlled conditions. Incremental vertical stresses were applied to simulate the staged construction of a landfill.

The LCC is a 442 mm internal diameter and 600 mm high stainless steel cell with a wall thickness of 6.8 mm. The wall thickness of the cell was chosen so as to enable measurement of lateral stresses from less than 10 kPa to approximately 100 kPa while satisfying the $K_0$ condition. The cell is mounted on a 600 mm x 600 mm x 50 mm aluminum plate bolted to the bottom rail of a 1.83 m tall steel girder frame. An air-jack manufactured by Hydro-line, Inc. having a piston diameter of 200 mm and capable of applying a maximum vertical stress of 260 kPa to the top of the waste, is attached to the top rail of the steel girder frame. The piston rod of the air jack has a diameter of 75 mm with a stroke length of 330 mm. A regulated supply of nitrogen is used in the air jack to maintain a desired vertical stress in the waste sample. The constant pressure system was able to maintain vertical stresses within ±5% of the targeted stress.

The plunger used for consolidating the waste is 442 mm in diameter and 38 mm thick, and was constructed by butting two aluminum plates each 19 mm thick together. The lower aluminum plate of the plunger has uniformly distributed holes 5 mm in diameter to facilitate biogas escape into a cavity which is provided between the two aluminum plates. An outlet is provided on the upper aluminum plate to collect the biogas from this cavity via a one-way valve. The plunger is sealed against the cell wall by two O-rings spaced vertically at 20 mm. The overall system is thus sealed and leachate may be introduced and gas collected as the system is operated.
Four leachate injection ports, each with a hollow shaft are provided on the top aluminum plate of the plunger. The hollow shafts extend 75 mm beyond the bottom plate of the plunger so as to prevent leachate back-up into the gas cavity. The injection ports are evenly spaced for providing uniform distribution of leachate inside the cell. A peristaltic pump is used to inject leachate at a desired flow rate. The rubber tubing which is used to transport leachate from peristaltic pump to injection ports was capable of withstanding liquid pressures up to 275 kPa which was deemed necessary for pumping leachate into compacted waste. An outlet is

Figure 5.1 Dual Purpose Landfill Compression Cell (LCC) used in the Present Study.
provided in the bottom aluminum plate for collecting leachate coming out of the waste.

5.4.1 Instrumentation

The instrumentation attached to the LCC comprises a load cell (to measure the vertical stress), a cable extension transducer (to measure vertical settlement of the sample), a pore pressure transducer and six strain gauges to measure the lateral stress of the consolidating waste against the sidewall of the compression cell.

A pancake-type load cell (45 kN capacity) was placed at the centre of the top aluminum plate of the plunger and rigidly fastened to the piston rod and the plunger by means of a bracket assembly. The cable extension transducer is attached to a hook on the top plate of the plunger to record waste settlement. Six quick-connect ports in two tiers, horizontally spaced at 120° on the lower middle outer surface of the cell, are provided for pore pressure measurements. The six strain gauges are mounted on the outer surface of the LCC in two levels (75 mm and 150 mm from the base of the cell) and are spaced 120° apart horizontally. They are 3.0 mm foil type strain gauges (Tokyo Sokki Kenkyudo Co., Ltd.; Type: FCA-3-350-17-3L) built as a single unit of orthogonally placed two strain gauges. Two such built-in units of strains gauges, one at each level are connected so as to provide a full bridge circuit. Such assembly of strain gauges increases the accuracy in the determining lateral stresses. The data acquisition was accomplished with a USB-based DAQ module with 8 channels of 12-bit analog input using Lab View v.8.0 software (National Instruments Inc. Ltd, Texas USA).
5.4.2 Calibration

The calibration of the load cell, cable extension transducer, and pore pressure transducer was carried out using the procedure followed in geotechnical engineering. A different procedure was followed for calibration of the strain gauges which was required for inferring lateral stresses.

Lateral stresses ($K_0$) in waste have been measured using different methods such as self-boring pressuremeters (Dixon et al., 1999), split ring consolidometers (Landva et al., 2000), vertical and horizontal stress cells (Dixon et al., 2004); and ultra thin tactile pressure sensors (Kavazanjian, 2006). However, the technique used in the present study allows for continuous measurements of lateral stresses while the MSW is degrading, and is adapted from a method used by Edil and Dhowian, 1981 to measure lateral stresses in peat soils. The calibration of strain gauges for inferring lateral stresses was done for three different sample heights. For each sample height, the compression cell was filled with de-aired water and increments of vertical stresses were applied. The response of the strain gauges to each increment of vertical stresses for each of the three sample heights was recorded in terms of change in strain gauge resistance. A linear relationship was obtained between the change in strain gauge resistance and the change in applied vertical stress for each sample height. The calibration constant for each of the three sample heights were not significantly different and, therefore, an average calibration constant was used for inferring the lateral stresses.

The measurement of hydrostatic pressure discussed above was also used for determining the actual vertical stresses transferred to the waste sample. A calibration curve was plotted between theoretical vertical stress (obtained from load cell reading) and the hydrostatic pressure measured by pressure transducers in
order to account for the sidewall friction generated between the plunger O-rings and the LCC wall. During calibration, piston friction on the sidewall was a constant value of 1.5 kN and an excellent linear fit was found between theoretical vertical stress and actual vertical stress. This work, serves to verify the vertical stress applied only at the top of the sample. The vertical stress at the bottom may be somewhat less because of sidewall friction between the waste and the vertical cylindrical walls of the compression cell.

5.4.3 Methodology

The MSW sample used in the present study is slightly different from that reported by Singh and Fleming, 2008 and is obtained from an excavation near the surface of the Cremation Ground Landfill in Jorhat, Assam(India). The waste is less than one year old as clearly evident from the presence of recovered newspaper. The overall composition is dominated by food waste, diapers, papers, newspaper, demolition wastes, wood pieces, market refuses and plastic. Metals and aluminum constituted less than 5% by weight, perhaps reflecting recycling practice in the city. The waste is highly odorous typical of very young waste. Approximately 150 kg of waste was collected in pails, sealed and brought to the laboratory. Large chunks of demolition waste, wood and metals (approximately greater than 75 mm) are discarded during sampling.

A representative sample of waste, approximately 100 kg, was prepared by thoroughly mixing and subdividing the bulk sample many times. Representative triplicate sub samples, each 2.0 to 2.5 kg, were analyzed separately for moisture content and volatile solids. The compression cell was filled with the representative MSW in layers to achieve a total height of 580 mm, equivalent to an initial bulk unit
weight of 9 kN/m$^3$. The initial compacted average unit weight (12.76 kN/m$^3$) considered in the present study is typical of most landfills where good initial compaction of waste is practiced (Zekkos et al., 2006).

The LCC was placed in a temperature controlled room maintained at 35°±2°C. A geotextile filter overlying a layer of 20 mm nominal size gravel was placed at the base of the LCC to prevent clogging of the drainage line. Similarly, a 20 mm thick gravel layer overlying a wire mesh was placed on top of the waste to provide a headspace for gas collection. The plunger was mounted on the top of the cell and a small vertical stress (approximately 10 kPa) was applied to the plunger to bring the bottom of the plunger in direct contact with the sample without actually applying any vertical stress to the sample. As discussed above, this is the minimum pressure required to move the plunger inside the cell due to sidewall friction. The compression cell, filled with waste, was allowed to sit in this state for 24 hours. During this period, the baseline instrumentation response was recorded and thereafter, the increments of vertical stresses were applied by raising the pressure in the air-jack. The response of strain gauges, pore pressure transducer, cable extension transducers, and load cell were logged continuously. For each instrument, the average of all the values logged each day was computed. Five different data sets were recorded to document the complete stress history of the waste sample: time, lateral stresses, vertical stress, vertical displacement and pore water pressure.

The biodegradation of waste in the LCC was enhanced by leachate recirculation. The leachate injection rate for the first seven days, was approximately 700 ml-day$^{-1}$ after which it was reduced to 160 ml-day$^{-1}$ injected every alternate day. It took eight days for the waste to reach its field capacity, assuming that the liquid was distributed uniformly and there were no preferential flow paths inside.
the sample. No seeding was done in this experiment and the characteristics of the leachate and biogas, therefore, represents solely the biochemical properties of waste present inside the LCC. The overall composition of the waste was evaluated in terms of its volatile solid content for comparison with the composition of the sample after several months of accelerated degradation in the LCC.

The moisture content of the sample, both before and after incubation, was determined by drying the sample at 60°C until the weight became constant. For determining volatile solids (VS), the residue left after moisture content determination was ignited at 550°C until the weight became constant. Because of the sample size, the time taken for both moisture and volatile solids determination was more than 24 and 12 hours respectively. Leachate samples were analyzed intermittently. Biogas samples were collected using tedlar bags for analysis of the gas composition. The gas production rate was estimated using the water displacement method.
5.5 RESULTS AND INTERPRETATION

The experiment commenced with a first increment of vertical stress equal to 22 kPa. The subsequent increments of vertical stresses were 44, 84 and 180 kPa. Each increment of vertical stress was maintained for at least 30 days except for $\sigma_v = 180$ kPa, for which the duration was 60 days. The time-settlement profile for the entire duration of experiment (Fig 5.2) represents the combined effect of degradation and increments of vertical stresses on the overall settlement behaviour of waste.

![Time-settlement profile](image)

**Figure 5.2** Time-Settlement Curve for the Entire Duration of the Experiment

(Present Study)

[176]
5.5.1 Degree of Degradation of the Waste Sample during the Experiment

The degree of degradation of the waste sample was assessed from cumulative methane production, leachate quality and the volatile solids remaining after degradation. Biochemical Methane Potential (BMP) values for MSW typically lie between 54-108 L·kg\(^{-1}\) of waste (Themelis and Ulloa, 2007). In an earlier study by Singh and Fleming, 2004, the Biochemical Methane Potential (BMP) of the waste from the Cremation Ground landfill was estimated to be 60 L·CH\(_4\)·kg\(^{-1}\) of waste and the volatile content of the waste was estimated as 55%. The cumulative CH\(_4\) production over the entire testing was 30 L·CH\(_4\)·kg\(^{-1}\) of waste (Fig.5.3). This represents approximately 30-50% degradation of the waste sample, consistent with the estimate of loss of volatile solids during this study (Table 5.2). The volatile solids decreased from 56.6% before incubation to 27.2% after incubation. As a result of degradation, an estimated 3.5 kg of solids were removed from the system (in the form of gas, condensate and dissolved solids in leachate) representing approximately 6% of initial total solids. The cumulative gas production (Fig 5.3) and biogas composition (Figure 5.4) were stable during the period monitored.
Figure 5.3 Cumulative Gas Production for the Entire Duration of Experiment.
Table 5.2 Biochemical characterization of waste used in this study

<table>
<thead>
<tr>
<th></th>
<th>Before incubation</th>
<th>After incubation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet wt (kg)</td>
<td>82.4</td>
<td>86.9</td>
</tr>
<tr>
<td>Average Water Content(%)</td>
<td>30.6</td>
<td>38.3</td>
</tr>
<tr>
<td>Average VSS Content(%)</td>
<td>56.6</td>
<td>27.2</td>
</tr>
<tr>
<td>Weight of dry solids (kg)</td>
<td>57.1</td>
<td>53.6</td>
</tr>
<tr>
<td>Loss of solids during degradation</td>
<td>3.5 kg which corresponds to 6% of initial total solids</td>
<td></td>
</tr>
</tbody>
</table>

The leachate quality was assessed in terms of pH, chemical oxygen demand (COD) and ammonia. The pH of the leachate fluctuated between 6.5 and 8.5 during the first week of the controlled experiment, and was then stable around 7.5 indicative of favourable conditions for methanogenesis. Fig 5.5 shows the removal of COD and ammonia during various stages of degradation. More than 90% of COD and ammonia were removed from the system during the experiment.
Figure 5.4 Biogas Composition Measured During the Entire Duration of Experiment.

Figure 5.5 Depletion of Leachate COD and Ammonia During Degradation.
5.5.2 At-Rest Lateral Earth Pressure

Figure 5.6 shows the variation in effective stresses measured during the entire duration of the experiment. Drainage continued without any problem of clogging during the entire test run. During the first two months of loading, the observed pore water pressures were insignificant, possibly due to the low vertical stress and high void ratio. A temporary localized high pore pressure on day-90 can be seen in Fig 5.6 and corresponds to the start of last increment of vertical stress (= 180kPa). This high pore pressure however, soon dissipated.

Four increments of vertical stresses were used to investigate the long-term effect of degradation on $K_0$. At each increment of vertical stress, $K_0$ was estimated as the ratio of the average daily horizontal effective stress to the average daily vertical effective stress. The daily average value of $K_0$ was observed to have some fluctuation during each stage of loading. However, the moving average of $K_0$ was found to be stable and close to 0.40 for the entire duration of the experiment.

Figure 5.7 shows the change in horizontal effective stress ($\Delta \sigma'_h$) vs. change in vertical effective stress ($\Delta \sigma'_v$) for each load step obtained from the present study as well as from Singh and Fleming, 2008. The values of $\sigma'_h$ and $\sigma'_v$ used here are the average value of stresses for the entire duration of each load step and thus accounts for degradation as well. The at-rest earth pressure coefficient ($K_0$) is obtained as the slope of the regression line fitted to experimental data from this study. The value of $K_0$ obtained in Fig 5.7 is very close to that obtained from moving average method. The moving average of $K_0$ was obtained from the ratio of daily average values of $\sigma'_h$ and $\sigma'_v$ and is in good agreement with published studies by Landva et al., 2000 and Singh and Fleming, 2008.
Figure 5.6 Variation of Effective Stresses During the Test Duration.
A $K_0$ of 0.40 corresponds to a Poisson’s ratio of 0.29, which is also consistent with values of Poisson’s ratio obtained by Matasovic and Kavazanjian, 1998. Lateral stress measurement using a pressure-meter (Dixon et al. 1999) provided a varying $K_0$ from 0.2 to 1.0. Towhata et al., 2004 measured $K_0$ from triaxial compression tests and obtained a value of 0.25 to 0.35 for vertical stresses of 250 kPa. Kavazanjian, 2006 used ultra-thin tactile pressure sensors in estimating $K_0$ of waste and reported values of 0.3 for a moderately-compacted sample ($\gamma = 9.6$ kN/m$^3$) and 0.2 for densely compacted sample ($\gamma = 11$ kN/m$^3$).

In geo-technical engineering, $K_0$ is widely accepted as a unique elastic constant. The present study suggests that it is also a unique elastic constant for MSW regardless of applied stresses and age.

5.5.3 Constrained Modulus

In this study, the stiffness of the refuse has been quantified in terms of the constrained modulus which is defined as:

$$E_0' = \frac{\Delta \sigma_v}{\Delta \varepsilon_a} \quad \cdots \quad \cdots \quad \cdots \quad \text{Eq. (5.3)}$$

Figure 5.8 presents the values of the constrained modulus obtained from the present study. The values shown in Fig 5.8 are the values of $E_0'$ measured at the end of each 30 to 60 day load step and therefore these values incorporate the effect of degradation. The data from previous short-term tests by Singh and Fleming, 2008 are also plotted in Fig 5.8. The results from this study are consistent with the findings of Beaven and Powrie, 1995 for the selected range of vertical stress used in this study. Table 5.3 shows the constrained modulus when vertical effective stress is being applied. A closer look at Figure 5.8 suggests that, though there is a general increase in $E_0'$ with increasing vertical stress, the value of


\(E_0'\) shows some decrease when compared with values obtained in short-term tests by Singh and Fleming, 2008 and this may be a result of degradation. However, at this stage this cannot be conclusively explained.

**Figure 5.7** Estimation of \(K_0\).

\[K_0 = 0.4\]
\[R^2 = 0.99\]
Table 5.3 Observation of Vertical Effective Stress and Constrained Modulus

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Vertical Effective Stress (kPa)</th>
<th>Constrained Modulus (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>330</td>
</tr>
<tr>
<td>2</td>
<td>42</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>84</td>
<td>460</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>1200</td>
</tr>
</tbody>
</table>

5.5.4 Compressibility

The primary compression, as discussed earlier, takes place immediately at the instance of load application and continues for some time. The primary compression is accompanied by significant changes in axial strains and this was observed in this study to occur during the first twenty four hours of load increment. The commencement of secondary compression was assumed to take place after primary compression has occurred. This was also evidenced from the record of axial strain which did not change by more than 1% after primary compression has occurred. Similar assumptions have also been made by other researchers such as Landva et al., 2000.

Figure 5.9 shows a plot of $\varepsilon_a - \log \sigma'_v$ obtained from this study. The value of $\varepsilon_a$ and $\sigma'_v$ are the average of the values measured during first twenty four hours of load increments. The value of primary compression ratio obtained in this way also incorporates the effect of degradation. A best-fit line drawn through the data points gives an overall value of $C_{ce}$ as 0.48. The present study is of the view that the value of $C_{ce}$ estimated in this manner is more representative of waste since the processes of degradation (in lower lifts) and initial settlement due to overburden (in upper lifts) cannot be distinguished in a landfill.
Figure 5.8 Constrained Modulus Measured in Present Study and from Published Literature.

Figure 5.9 Primary Compression Ratio ($C_{ce}$) Measured in this Study
Hossain et al., 2003 observed an increase in the value of $C_c$ from 0.16 to 0.37 as a result of degradation. It is worth mentioning here that these authors used shredded waste sample(s) with a maximum particle size of approximately 10 mm x 20 mm, tested in a 63.5 mm diameter oedometer. Vilar and Carvalho, 2004 obtained values of $C_c$ between 0.52 and 0.92 for 15 year old auger cuttings of degraded waste. Some researchers opine that size reduction or shredding of waste may exhibit increased biodegradation due to large available surface area and increased nutrient access for biological activity (Wall and Zeiss, 1995).

Figure 5.10 through Fig 5.13 shows $\mathbf{\epsilon_a-log(t)}$ curves for different stages of loading obtained from this study. The data for the first 24 hours of load increment, representing initial compression, have been demarcated clearly in these figures to elaborate the two-stage compression behaviour of MSW that was observed. It is evident from Fig 5.10 through Fig 5.13 that, there does not appear to be a smooth transition from initial compression to the onset of secondary compression and is thus consistent with the hypothesis that the mechanism of initial compression is a combined effect of distortion, bending, crushing and reorientation of waste constituents.
Figure 5.10 Secondary Compression for $\sigma_v = 22$ kPa.
The secondary compression begins after 24 hours of load application and therefore in Fig 5.10 through Fig 5.13, for times beyond 24 hours up to the next increment of loading, the recorded data has been smoothed by presenting the daily average value. It appears from Fig 5.10 and Fig 5.11 that at small vertical loads (representing near surface waste); the secondary compression is not very significant except for an abrupt “collapse” observed near the end of the 42 kPa load step which is further discussed below. However, as the vertical stress is increased (as a result of placement of successive lifts of waste) and with the progression of degradation, the secondary compression becomes more prominent.
Figure 5.11 Secondary Compression for $\sigma_v = 42$ kPa.
The values of $C_{\alpha e}$ as shown in Table 5.3 for various stages of loading and degradation were obtained by drawing a best fit line to secondary compression data (beyond 24 hours up to the next load increment). The pattern suggests a general increase in the value of $C_{\alpha e}$ with an increase in vertical stress and degradation, though not in a linear fashion. Such a change in $C_{\alpha e}$ as a result of degradation has also been reported by Manassero et al., 1997 from their observations of landfill settlement in Spain and Greece. However, these observations are not in agreement with the results of Wall and Zeiss, 1995 and Landva et al., 1984 who suggested that there is no significant difference between secondary compression rates in older and more recent landfills. Contrary to a suggestion by Sowers, 1973; Gabr and Valero, 1995 suggested that secondary compression is less dependent on initial void ratio and depends more on conditions favorable for degradation.
Figure 5.12 Secondary compression for $\sigma_v = 84$ kPa.
Table 5.4 Secondary compression ratio ‘$C_{ae}$’ estimated in this study

<table>
<thead>
<tr>
<th>Vertical stress (kPa)</th>
<th>Duration of loading (days)</th>
<th>$C_{ae}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>30</td>
<td>0.0005</td>
</tr>
<tr>
<td>44</td>
<td>30</td>
<td>0.150</td>
</tr>
<tr>
<td>84</td>
<td>30</td>
<td>0.104</td>
</tr>
<tr>
<td>180</td>
<td>60</td>
<td>0.131</td>
</tr>
</tbody>
</table>

A brief overview of the testing details and results of compressibility of waste from published studies is shown in Table 5.1. A general observation from Table 5.1 reveals that these studies were conducted either as short term studies with vertical stress increasing over a very short period of time, or as long term studies at a constant vertical stress. In either case, the waste settlement behaviour as simulated and observed in the present study is somewhat different from published studies.

A possible mechanism for the degradation-induced compression of MSW is associated with ‘phase change’ of materials during the process of degradation (McDougall et al., 2004 and McDougall and Pyrah, 2004). These authors suggested that the solid decomposition results in an enlarged void space without significant overall volumetric reduction. The solid skeleton progressively weakens due to degradation and reaches a point where it can no longer support the overburden and a collapse occurs. Densification due to collapse temporarily improves the material strength and become able to resist further deformation. Continued decomposition will produce further episodes of void enlargement and collapse.
The development and collapse of voids during degradation is likely to be a major contributory factor to secondary compression in MSW. The settlement mechanism suggested by McDougall et al., 2004 and McDougall and Pyrah, 2004 has been well demonstrated in Fig 5.10 through Fig 5.13. Referring to Fig 5.11 and Fig 5.12, from points (a) to (b), the waste skeleton seems to be getting weaker as a result of degradation, however with minor distortion and raveling. At point ‘b’ the waste structure becomes sufficiently weak to sustain vertical stresses and the voids developed due to degradation collapses which is marked by an abrupt increase in axial strain at point ‘b’. It is expected that additional such episodes of void collapse might have been observed, had the waste been allowed to degrade at each vertical stress for a longer period of time.

**Figure 5.13** Secondary Compression for $\sigma_v = 180$ kPa.
From the pattern in $C_{ae}$ values obtained from this study and based on Fig 5.10 through Fig 5.13, some important observations can be made regarding the settlement behaviour of MSW with particular emphasis to bioreactor landfills. It is likely that significant differential settlements may be expected during the early phases of the landfill operation (typically 10-15 years). During this period, the majority of the readily-degradable waste constituents will be volatilized, thereby creating a collapsible structure. The collapse of these voids will result into an uneven settlement of the waste surface. Further degradation will gradually reduce the size of constituents available for collapse and the secondary settlement will become uniform and linear in the later phase of degradation. The use of a single value of $C_{ae}$ for settlement calculation may thus provide unrealistic estimates of settlement in waste.

5.6 CRITICAL COMMENTS

A dual-purpose compression cell has been used to study the evolution of compressibility and elastic properties of municipal solid waste subjected to accelerated degradation under the application of incremental vertical stresses. Approximately 30-50% degradation of the waste sample was achieved during the experiment which was quantified from the estimates of volatile solids removed and cumulative methane produced.

The evolution of at-rest lateral earth pressure of MSW was quantified from the estimates of lateral stresses developed during the course of degradation. It is proposed that $K_0$ of waste is a unique elastic parameter and is not influenced by applied stresses and degradation. The constrained modulus was estimated to lie between 300 kPa and 1200 kPa.
The cumulative settlement during this study was estimated as 255 mm under an applied vertical stress of 180 kPa, constituting approximately 44% of the initial height of the sample. The experiment yielded a value for the primary compression ratio which is high compared to published values in which degradation had not been considered. This observation suggests that degradation increases the compressibility of waste. The primary compression ratio ($C_{ce}$) was observed to decrease from 0.58 to 0.27 for successive increments of vertical stresses.

The secondary compression is significantly affected by degradation and accounted for approximately 21.5% (50 mm) of the overall settlement observed in this study. The contributions of secondary settlement at individual load steps were 0.2% (22 kPa); 10.7% (44 kPa); 4.2% (84 kPa) and 6.5% (180 kPa). The secondary compression ratio ($C_{ae}$) was observed to increase from 0.0005 to 0.15 for various load increments. Use of a single value of $C_{ae}$ may therefore result in unrealistic settlement estimates of landfills. Given these observations, it is suggested that enhancing waste degradation may result in an increase in the compressibility of waste.

A significant finding is that the data from this study tend to confirm that the mechanism of secondary compression in MSW occurs as an episodic process of void formation and later collapse of these voids. The differential settlements observed in landfills are an outcome of the mechanism as discussed above. The overall settlement will depend upon the constituent size; its degradation potential; and the existence of favourable conditions for its degradation. Long-term laboratory or field studies on a larger scale are required to substantiate these observations and to understand the influence of pre-compression, re-compaction, and lateral stresses (three-dimensional compression) on the compression indices and on the mechanism of settlement.
REFERENCES


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