3.1 GENERAL

Over the past decade, the stability of landfill slopes has received considerable attention because of a number of high-profile failures of large municipal landfills. Notable recent examples of landfill failure include: the 1997 Dona Juana landfill failure in Bogota, Colombia (Hendron et al., 1999), the 2000 Payatas landfill failure in Manilla, Philippines (Merry et al. 2005) and the Bandung landfill failure in Indonesia (Kolsch et al., 2005). The apparent increase in the number of landfill failures likely reflects the fact that present-day landfills have been created to greater heights in response to economic, social, and regulatory considerations. Landfills extending 70 to 90 m above the ground surface are becoming increasingly a common sight as municipalities worldwide are under pressure to constrain the footprints of their landfills by accepting more municipal solid waste (MSW) per unit base area of the landfill. This reduction in footprint is being achieved by designing new higher landfills or extending the heights of older landfills using “piggyback” expansions. A higher landfill puts greater demand on the shear strength of MSW for its stability because MSW is the largest structural element of a municipal landfill.

The condition of MSW inside a closed landfill changes over time because of degradation, decomposition or creep. It is, therefore, logical to expect a change in the shear strength of MSW with time, which may affect the long – term stability of a closed landfill. To ensure the stability of both the open and closed landfills, it is vital to understand how MSW mobilizes its shear strength and to obtain accurate estimates of the shear strength of MSW.

Like soils, the shear strength of MSW is evaluated using triaxial compression test or direct shear tests, or by conducting limit equilibrium back analysis of failed
landfill slopes. The shear strength of MSW is commonly described using Mohr-Coulomb failure criterion.

\[ \tau = C' + \sigma'_n \tan (\phi') \quad \ldots \quad \ldots \quad \ldots \quad \text{Eq. (3.1)} \]

where, \( \tau \) is the shear strength of MSW,
\( \sigma'_n \) is the normal effective stress
\( C' \) is the effective cohesion intercept and
\( \phi' \) is the effective angle of friction

These all are collectively termed as shear strength parameters of MSW.

Satisfactory design of an engineered municipal landfill facility requires meaningful values of \( C' \) and \( \phi' \) for MSW. Considerable research has been done till date on the estimation of \( C' \) and \( \phi' \) values for MSW using small and large direct shear tests, large triaxial tests as well as in-situ test. Consequently, an extensive data base of \( C' \) and \( \phi' \) values of MSW (Table 3.1) is available in published literatures. It is, however, difficult to interpret and use this database in practice because of the inherently heterogeneous nature of MSW, the use of non-representative MSW samples, and the absence of a universally accepted method for the estimation of MSW shear strength parameters. This has prompted some researchers (e.g. Kavazanjian, 2003) to suggest that back-analysis of case studies involving failure of landfill slopes or the use of field trials involving controlled failure by excavation are the only appropriate ways of obtaining representative \( C' \) and \( \phi' \) values for MSW. Such field trials, however, are generally quite expensive and time consuming to conduct. It is often more practical to obtain shear strength parameters through laboratory or in-situ shear testing of MSW samples.
### Table 3.1 Shear Strength Parameters of MSW from Literature

<table>
<thead>
<tr>
<th>Reference</th>
<th>Shear strength Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C'$ (kPa)</td>
<td>$\phi'$ (°)</td>
</tr>
<tr>
<td>Caicedo et al. (2002)</td>
<td>67</td>
<td>23</td>
</tr>
<tr>
<td>Eid et al. (2000)</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Gabr and Valero (1995)</td>
<td>17</td>
<td>34</td>
</tr>
<tr>
<td>Grisolia et al. (1995)</td>
<td>2-3</td>
<td>15-20</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>30-40</td>
</tr>
<tr>
<td>Houston et al. (1995)</td>
<td>5</td>
<td>33-35</td>
</tr>
<tr>
<td>Jessberger and Kockel (1995)</td>
<td>0</td>
<td>31-49</td>
</tr>
<tr>
<td>Kavazanjian et al. (1995)</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Landva and Clark (1990)</td>
<td>0-23</td>
<td>24-41</td>
</tr>
<tr>
<td>Landva and Clark (1986)</td>
<td>10-23</td>
<td>24-42</td>
</tr>
<tr>
<td>Mazzucato et al (1999)</td>
<td>43</td>
<td>31</td>
</tr>
<tr>
<td>Study</td>
<td>C'</td>
<td>Φ'</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Pelkey et al (2001)</td>
<td>0</td>
<td>26-29</td>
</tr>
<tr>
<td>Siegel et al. (1990)</td>
<td>0</td>
<td>36-53</td>
</tr>
<tr>
<td>Vilar and Carvalho (2002)</td>
<td>39.2</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>60.7</td>
<td>23</td>
</tr>
<tr>
<td>Whitian et al. (1995)</td>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

Legend: C'- Effective Cohesion; Φ'- Effective Angle of friction; DS- Direct Shear test; CU- Consolidated undrained test

Testing of intact MSW samples, which usually involves in-situ shearing of MSW using a transportable direct shear apparatus (e.g. Houston et al., 1995, Mazzucato et al., 1999), involves lot of time and effort compared to testing of recompacted MSW samples.

It is therefore not surprising that shear strength parameters for MSW have traditionally been obtained using the more easily obtainable recompacted samples (e.g. Landva et al., 1984; Landva and Clark, 1990; Grisolia et al., 1995; Kavazanjian et al., 1999). It is also worth noting that recompacted or artificial MSW samples have been used in almost all published cases of the use of large triaxial tests to obtain C' and Φ' values for MSW (e.g. Gabr and Valero, 1995; Grisolia et al., 1995; Jessberger et al., 1995; Caicedo et al., 2002; Vilar and Carvalho, 2002).

A systematic study of the available literatures have revealed that some authors while quoting a strength parameters, have failed to provide the test drainage conditions and also the measurement of pore water pressure. It is felt that
there exists a need for a critical review of the practice of interpreting MSW shear strength results using the principle of effective stress.

Available literature on the shear strength variation of MSW with progress in the degradation process is not very clear. Mobilization of shear strength with degradation needs clear understanding for predicting a behaviour of imposed loads on MSW landfills. In this chapter sincere effort is made to investigate the following points-

- Consolidated undrained Triaxial tests on MSW.
- Direct shear test on MSW.
- Stress-strain behaviour of MSW from Direct Shear test.
- Stress-strain response of MSW in Triaxial tests.
- Shear strength of MSW from Triaxial tests.
- Shear strength of MSW from Direct Shear test.
- Shear strength of recompacted MSW.
- Shear strength of intact MSW.

3.2 EARLIER WORK

The characterization of shear strength of MSW is important for the design of slopes, interfaces with soils and geosynthetics, vertical or piggy back expansion of landfills and seismic stability evaluations.

Direct shear tests have been the preferred method for measuring the shear strength of MSW likely because of the ease in handling the large size waste particles. Various shapes (square, rectangular and circular) and sizes (varying from 63.5 mm diameter to 1.5m x 1.5m square) of direct shear apparatus have been
used for characterizing shear strength of MSW. Both, in-situ Direct shear test (Houston et al., 1995; Withiam et al., 1995; Mazzucato et al., 1999; Thomas et al., 1999; Caicedo et al., 2002) and tests on recompacted samples (Landva et al., 1984; Landva and Clark, 1990; Siegel et al., 1990; Howland and Landva, 1992; Gabr and Valero, 1995; Kavazanjian et al., 1999; Sadek et al., 1999; Pelkey et al., 2001; Caicedo et al., 2002; Harris et al., 2006; Dixon and Langer, 2008; Reddy et al., 2008) have been conducted for characterizing shear strength of MSW.

Some authors (Kolsh, 1995; Athanasopoulos et al., 2008) have also tried to explain the analogy between MSW and reinforced earth. The study conducted by Kolsh, 1995 is much like a tensile test and was intended to measure fibrous cohesion in waste. Athanasopoulos et al., 2008 studied the effect of orientation and the stiffness of fibrous material on mobilized shear stress. These authors suggested that the shear strength of waste is highly anisotropic and the mobilized shear stress depends on the fibre orientation and the stiffness of the fibrous material. Direct shear tests have also been conducted on large compacted waste bales (900 mm x 800 mm x 1600 mm, 400 mm x 500 mm x 600 mm) to evaluate shear resistance behaviour at the contact surfaces of different coupled materials found in MSW (Del Greco and Oggeri, 1993; Van Impe and Bouazza, 1998).

Triaxial compression tests have not been as common as direct shear tests. Some authors (Jessberger et al., 1995; Gabr and Valero, 1995; Grisolia et al., 1995; Caicedo et al., 2002; Vilar and Carvalho, 2004; Chen et al., 2008) have measured shear strength of recompacted samples of MSW from triaxial compression tests. Samples have been prepared at different unit weights, moisture contents and composition. However, the effect of these quantities on the observed mechanical behaviour of MSW has not been systematically documented. Since the deviator stress observed in these tests showed an increase without reaching any peak
strength, these authors have interpreted shear strength at different values of axial strains with 20% being the common maximum value (Grisolia, 1995; Jessberger et al., 1995; Chen et al., 2008). Similar to direct shear tests, both small and large size recompacted samples (75 mm to 300 mm diameter) have been used with triaxial tests conducted under drained as well as undrained conditions with pore pressure measurements. The unit weight of sample was observed to have minor influence on the measured shear strength (Vilar and Carvalho, 2004).

Little data is available in the literature on the evolution of shear strength of MSW with time. Landva et al., 1984 observed a slight decrease in the angle of shearing resistance ($\phi'$) in a one-year-old MSW sample, which was soaked in leachate and sheared in a direct shear apparatus. Kavazanjian, 1995 has also reported a decrease in the apparent cohesion ($C'$) and $\phi'$ of MSW after its accelerated degradation in the laboratory. However, Van Impe, 1998 contradicts these observations and reports higher shear strength parameters for old refuse samples compared to freshly deposited refuse.

A wide variation in shear strength parameter of MSW has been reported by various researchers from various tests and is presented in Table 3.1. These variations are primarily attributed to variations in the test methods, sample age, composition and unit weight, and the assumptions made in interpretations of test data. The results of direct shear tests do not clearly indicate, whether the measured shear strength parameters are representative of peak shear stress conditions or that they represent mobilized shear stress at some pre-defined value of shear displacement. The shear strength interpreted from small size direct shear apparatus and shredded/screened waste (Gabr and Valero, 1995; Caicedo et al., 2002), and their use in design and stability analysis is still being debated. In-situ direct shear tests on undisturbed samples undoubtedly can provide more realistic shear
strength over that measured from recompacted samples since a large sample can be tested under actual conditions (composition, matrix structure and unit weight). However, such tests are difficult to perform at great depths and might not be suitable (in terms of time and cost) for conducting a large no. of tests to obtain representative shear strength of MSW.

The published literature on shear strength does not systematically document the effect of degradation. However, based on mechanical response to degradation in organic soils (Andersland and Al-Khafaji, 1980 Wadwell and Nelson, 1981; Al-Khafaji and Andersland, 1981), it is likely that MSW containing high percentage of organic matter might show a decrease in shear strength in time. These changes in shear strength may affect the stability of the land fill significantly. Given the limited data on MSW shear strength and the wide scatter in these values, researchers (e.g Kavazanjian et al., 1995 Manassero et al., 1996, Van Impe, 1998 and Eid et al., 2000) relied on field performance, and observed slope failures to back calculate shear strength of failed waste mass. Kavazanjian et al., 1995 proposed lower bound drained shear strength envelope (Fig 3.1) based on back analysis of existing landfill slopes and published laboratory data for recompacted samples which can be stated as:

i) For an applied normal effective stress \( (\sigma_n') \) less than 30 kPa, MSW behaves like a purely cohesive material with an apparent cohesion \( (C') \) of 24 kPa and ;

ii) For \( \sigma_n' \) more than 30 kPa, MSW behaves like a purely frictional material with an angle of shearing resistance\( (\phi') \) of 33\(^0\).
A similar shear strength envelope proposed by Manassero et al., 1996, shown in Fig3.2 suggests that:

(i) For $\sigma_{n}'$ less than 26 kPa, MSW behaves like purely cohesive material, with $C'$ of 20 kPa;
(ii) For $\sigma_{n}'$ between 26 kPa to 60 kPa, MSW is considered to be a purely frictional material with $\phi'$ of 38° and;
For $\sigma_\prime_n$ greater than 60 kPa MSW can be characterized by $C'$ of 20 kPa and $\phi'$ of 24$^\circ$.

Figure 3.2 Shear Strength Envelope Proposed by Manassero et al., 1996
Eid et al., 2000, proposed a similar linear failure envelope (Fig. 3.3) based on the results of large scale direct shear tests and back analysis of failed slopes, which is given by $C'$ of 40 kPa and $\phi'$ of $35^0$.

![Figure 3.3 Shear Strength Envelopes Proposed by Eid et al., 2000](image-url)
3.3 STATEMENT OF THE PROBLEM AND OBJECTIVES

3.3.1 Statement of the Problem

To characterize shear strength behaviour of MSW from –

- Large Triaxial compression test.
- Direct shear box test.

On-

- Intact samples, and,
- Recompacted samples.

3.3.2 Objectives

From the test mentioned in Clause 3.3.1 following objectives are desired to be achieved-

- Stress-strain response of MSW from CU- triaxial test.
- Shear strength of Intact specimen of MSW from CU- Triaxial Test based on effective stress path approach.
- Shear strength of Recompacted specimen of MSW from Direct Shear Test.
3.4 SAMPLE PREPARATION

3.4.1 Intact Samples

The gravimetric moisture content and the average unit weight of each of the forty five intact samples were determined prior to extrusion and preparation for triaxial testing. Approximately 250gm of MSW was removed from the top end of each sample for moisture content determination using the oven drying method. The average bulk unit weight was determined by recording the gross weight and the dimensions of the sample.

After determining the gravimetric moisture content and the average unit weight, the MSW sample with each sampler was saturated and the volume of water needed for full saturation was recorded.

A sampler containing MSW was removed and the ends of the MSW sample were trimmed so that these ends were flat and orthogonal to the vertical axis of the sample. Any big pieces of MSW sticking out of the ends were removed and the void left by their removal was filled with moist silty soil.

3.4.2 Recompacted Samples

Recompacted samples were prepared in the laboratory using the material from the intact samples after their triaxial testing. In this way, the same material was used for both an intact and a recompacted sample in order that the results could be compared. For recompaction the waste was placed inside a steel sampler and compacted in four lifts to achieve the desired bulk unit weight. Fragments of MSW that were too large to fit inside the sampler were either discarded or, where possible, were broken by hand to make them fit inside the sampler. Recompacted
samples were saturated and the volume of water needed for full saturation was recorded.

3.5 INSTRUMENTS USED AND METHODOLOGY

3.5.1 Instruments Used

3.5.1.1 Triaxial Compression Apparatus

Figure 3.4 shows the triaxial compression apparatus used in the present study for the testing of intact and recompacted MSW samples. The plexiglass triaxial cell, which is reinforced using stainless steel straps, is capable of accommodating cylindrical samples of MSW upto 20mm in diameter and upto 450 mm in height. The triaxial cell is connected to conventional systems for the application of cell pressure and back pressure and is equipped with a pore-water pressure transducer to record changes in pore-water pressure during shearing. The apparatus is strain-controlled, in that it is possible to achieve a user-specified rate of axial displacement of the pedestal on which the sample sits. Axial load is mobilized using a reaction frame and is recorded using a load cell. The axial displacement of the sample is recorded using a linear variable differential transformer (LVDT) as well as a mechanical dial gauge. The pore-water pressure transducer, the load cell, and the LVDT are connected to a data logger and a stabilized D.C. power supply unit. The data logger is connected to personal computer for automated acquisition of instrument readings.
3.5.1.2 Direct Shear Apparatus

A direct shear apparatus (Fig 3.5) with ancillary hydraulics and computer control/data acquisition was used at two landfill sites at Jorhat, Assam (India) to obtain shear strength parameters of recompacted MSW. In this direct shear apparatus, a rigid steel loading plate connected to a hydraulic actuator was used to apply a constant vertical stress to the MSW sample (60mm x 60mm x 55mm). The shearing of the sample was achieved by applying a horizontal load to the lower shear box, which is seated on a set of rollers, while restraining the upper shear box in the horizontal direction. The surfaces of the steel plates sliding against each other
at the interface between the top and bottom boxes are treated with a specially formulated industrial coating to minimize friction and abrasion. The apparatus is instrumented to record displacements of the vertical loading plate and horizontal (shear) displacement of the lower box. Vertical and horizontal loads are recorded using load cells mounted at the ends of the hydraulic actuators.

*Figure 3.5 Direct Shear Apparatus Used in the Present Study*
3.5.2 Methodology

3.5.2.1 Collection of intact MSW samples

The MSW samples for the present study is obtained from the two landfill sites of Jorhat Town, Assam (India), located near the bank of river Bhogdoi on the edge of a rural/residential area in the Engineering College Road of Jorhat town, Assam, approximately 3 km south-east of Jorhat main town. This 32 hectare landfill, which is owned by the Jorhat Municipality Board, began accepting waste in 1974 and was closed in 1996 after accepting 10 million metric tonnes of wastes. It is the first landfill in this region to be converted into a Cremation Ground and Daily Market Place after its closure.

A typical cross-section of the samplers used for the collection of intact MSW samples is shown in Fig 3.6. An adapter is also shown in Fig 3.6 which is designed and fabricated to obtain samples from greater depths in bore holes. Two different samplers (internal diameters 150mm and 200mm), each 750mm long are used. These samplers are similar to Shelby tube except that each sampler has ribs machined on its inside over a length of 300mm from the cutting edge in order to prevent the MSW sample from slipping out of the sampler during its retraction.

Sampling of MSW has been carried out at the bottom of a pit that was excavated on the south slope of the landfill. Samplers are pushed approximately 450mm into the waste using a hydraulic powered excavator bucket. Samplers with MSW inside them are retrieved by pulling the steel cables attached to the top of each sampler.
Figure 3.6 Details of Sampler and Adaptor used in the present study
In cases where pulling of samplers proved difficult, they are retrieved by excavating around the sampler. The ends of the retrieved samplers are packed with soil and sealed. The sealed samplers are then sent to the Assam Agricultural University, Jorhat (Assam) to the Soil Science Laboratory. A total of six intact samples were collected from two different sites of Jorhat municipal solid waste dumping site.

3.6 RESULTS

3.6.1 Consolidated Undrained Triaxial Tests on MSW

Consolidated undrained triaxial tests were conducted on intact and recompacted MSW samples using the triaxial compression apparatus as described in Clause 3.5.1.1. Five tests were conducted using intact samples and nine tests were conducted using recompacted samples. One intact sample disintegrated upon extrusion because of the presence of a large piece of wood in it; therefore, it was not possible to conduct a triaxial test on this sample. Details of these tests are given in Table 3.2. The procedure for conducting these tests was very similar to that prescribed by I.S 2720 for conducting consolidated undrained triaxial tests on fine-grained soils.
Table 3.2 Details of Triaxial Tests on Intact and Recompacted MSW

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Type</th>
<th>Diameter 'D' (mm)</th>
<th>Moisture Content 'w' (%)</th>
<th>Bulk unit weight 'γ' (kN/m³)</th>
<th>Cell pressure σ′₃ (kPa)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-1</td>
<td>Intact</td>
<td>150</td>
<td>25</td>
<td>13.7</td>
<td>150</td>
<td>Plastics, paper, textile, wood soil and humus</td>
</tr>
<tr>
<td>U-2</td>
<td>Intact</td>
<td>150</td>
<td>17</td>
<td>11.3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>U-3</td>
<td>Intact</td>
<td>150</td>
<td>21</td>
<td>13.2</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>U-4</td>
<td>Intact</td>
<td>200</td>
<td>19</td>
<td>13.0</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>U-6</td>
<td>Intact</td>
<td>200</td>
<td>27</td>
<td>11.5</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>R-1</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>14.8</td>
<td>50</td>
<td>Plastics, paper, textile, wood soil and humus</td>
</tr>
<tr>
<td>R-2</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>15.3</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>R-3</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>14.6</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>R-4</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>15.8</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>R-5</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>15.7</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>R-6</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>15.9</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>R-7</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>12.6</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>R-8</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>13.0</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>R-9</td>
<td>Recompacted</td>
<td>150</td>
<td>-</td>
<td>13.7</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

[LEGEND: D-Diameter of the sample; w- In-situ moisture content of the sample; γ-bulk unit weight of the sample; σ′₃- Effective confining pressure at the start of the triaxial test]
A trimmed sample of MSW was placed on the pedestal of the triaxial cell and an end cap was placed over its top end. After ensuring that the axis of the sample was vertical and coinciding with the axis of the loading ram, a rubber membrane was stretched over the sample and its ends were sealed using O-rings. The triaxial cell was then assembled and gradually filled with water while allowing the air to escape from the top. The sample was then allowed to ‘consolidate’ for 24 hours under a chosen value of effective confining pressure. Back pressure was applied during consolidation to ensure full saturation of the sample. The sample was sheared at an axial displacement rate of 0.4 mm/min. Shearing was stopped when: (a) the axial load did not increase appreciably with increasing axial displacement; (b) the axial load decreased with increasing axial displacement; (c) excessive deformation of the sample (e.g. bulging or buckling) was observed; or (d) when the maximum permissible axial displacement of the sample pedestal was reached. At the end of each test, the sample was dismantled from the triaxial cell and was examined for the presence of large chunks (bigger than about 80 mm) of rigid materials such as wood, stone, metal, etc. The results from a sample containing one or more of such large chunks were discarded. The data for each test were downloaded from the data logging computer for subsequent processing and analysis.

3.6.2 Direct Shear Test on MSW

A direct shear test is a laboratory test used by geotechnical engineers to find the shear strength parameters of soil. Test is performed as per IS 2720 part XIII. The test is performed on three or four specimens from a relatively undisturbed soil sample. A specimen is placed in a shear box which has two stacked rings to hold the sample; the contact between the two rings is at approximately the mid-height of the sample. A confining stress is applied vertically to the specimen, and the upper
ring is pulled laterally until the sample fails, or through a specified strain. In a direct shear test, the failure of the soil sample in shear is caused along a predetermined plane. The load applied and the strain induced is recorded at frequent intervals to determine a stress-strain curve for the confining stress. The normal load, strain and shearing force are measured directly during the test. It is also used to estimate residual stress of soil.

Direct Shear tests can be performed under several conditions. The sample is normally saturated before the test is run, but can be run at the in-situ moisture content. The rate of strain can be varied to create a test of undrained or drained conditions, depending whether the strain is applied slowly enough for water in the sample to prevent pore-water pressure buildup.

Several specimens are tested at varying confining stresses to determine the shear strength parameters, the soil cohesion (C) and the angle of internal friction (commonly friction angle) (φ). The results of the tests on each specimen are plotted on a graph with the peak (or residual) stress on the x-axis and the confining stress on the y-axis. The y-intercept of the curve which fits the test results is the cohesion, and the slope of the line or curve is the friction angle.

The horizontal displacement rate for each direct shear test was 5 mm/min. In order to maintain a constant effective normal stress on the test specimen, the normal load on the test specimen was reduced in proportion to the reduction in the area of the shear plane with increasing horizontal displacement. Real-time recording of the horizontal load, the vertical load, the horizontal displacement of the lower shear box, and the vertical displacement of the top loading plate was done using a data acquisition system. The recorded horizontal load data were
corrected to account for the small frictional resistance generated by the rollers supporting the lower shear box.

### Table 3.3 Details of Direct Shear tests on MSW samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Water Content ‘w’ (%)</th>
<th>Bulk unit weight ‘γ’ (kN/m³)</th>
<th>Normal effective Stress ‘σ’ (kPa)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>9.7</td>
<td>9.5</td>
<td>150</td>
<td>Plastics, paper, metal, wood and soil.</td>
</tr>
<tr>
<td>D-2</td>
<td>14.8</td>
<td>10.1</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>D-3</td>
<td>11.2</td>
<td>8.9</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>D-4</td>
<td>8.5</td>
<td>8.8</td>
<td>135</td>
<td></td>
</tr>
</tbody>
</table>

[LEGEND: w- In-situ moisture content of the sample; γ- Bulk unit weight of the sample; σ_n- Normal effective stress during the direct shear test]
3.7 INTERPRETATION

3.7.1 Composition of MSW

Post-test visual examination of the intact samples revealed that the MSW was slightly degraded, blackish brown and slightly odourous, which indicated a relatively low level of organic matter decomposition. It contains cardboard, paper, wood, textiles and thin plastic sheets along with small fractions of inorganic/ inert materials like metals, glass, ceramic and gravel, which is typical of domestic waste. Pieces of textile could be torn easily.

3.7.2 Stress-Strain Response of MSW in Triaxial Tests

The stress strain response of MSW is presented in terms of cumulative axial strain \( \varepsilon_a = \Delta L/L_0 \) (where \( \Delta L \) is the change in the length of sample and \( L_0 \) is the length of the sample prior to shearing) and deviatoric stress \( q = \Delta \sigma_1 = \sigma_1 - \sigma_3 \) (where \( \sigma_3 \) is the total cell pressure, and \( \sigma_1 = \sigma_3 + \Delta \sigma_1 \), i.e. \( \sigma_1 \) the total axial stress applied to the sample).

Fig 3.7(a) shows the test results on intact and Fig 3.7(b) shows the same for recompacted MSW samples. Non-linear stress strain behaviour was exhibited by both the intact and recompacted samples. Several recompacted samples (e.g. R-5, R-6, R-7 and R-9) showed a distinct peak in their stress-strain response whereas no distinct peak was observed in the stress-strain responses of the intact samples. Post peak behaviour of several recompacted samples exhibit hardening phenomenon.
Figure 3.7(a) Deviatoric Stress vs Axial Strain Plots Obtained from Triaxial Compression Tests on Intact MSW Samples
Figure 3.7(b) Deviatoric Stress vs Axial Strain Plots Obtained from Triaxial Compression Tests on Recompacted MSW Samples.
3.7.3 Shear Strength of MSW from Triaxial Tests

For the purpose of obtaining shear strength parameters of MSW, the results of the triaxial tests are presented in terms of stress paths of deviatoric stress \( q \) vs mean effective stress \( p' \) (where \( p'=\left(\sigma'_3+2\sigma'_1\right)/3 \); \( \sigma'_3 \) is effective confining stress and \( \sigma'_1 \) is the effective axial stress). This approach has also been used by Caicedo et al., 2002 for the presentation of results from consolidated undrained triaxial tests on recompacted MSW samples. The effective confining pressure and effective axial stress were obtained by subtracting the pore water pressure \( u \) from the total cell pressure \( \sigma_3 \) and total axial stress \( \sigma_1 \) respectively. At the beginning of the undrained shearing, the mean effective stress \( p' \) was equal to effective confining pressure \( \sigma'_3 \) (equal to total cell pressure minus the back pressure) and the deviatoric stress \( q \) was equal to zero. The effective confining pressure value at the beginning of undrained shearing for each of the 14 triaxial tests is given in Table 3.2.

3.7.3.1 Shear Strength of Recompacted MSW

Figure 3.8(a) shows the stress paths in \( q-p' \) stress space for the nine recompacted MSW samples. There is striking similarity between these stress paths and those typically experienced by a horizontally layered or cross-anisotropic soil sample (e.g. Graham and Houlsby, 1983; Wood, 1990). As mentioned above, all the recompacted samples were prepared by compacting MSW in four horizontal lifts. Such ‘one dimensional’ deposition and stress history has imparted cross anisotropy in recompacted MSW samples.

During the initial stage of undrained shearing each stress path appeared to have followed a straight line with a slope of 3:1 (i.e. incremental stress ratio \( \Delta q/\Delta p'=3:1 \) w.r.t the \( p' \)-axis. Since the total stress paths for a conventional (constant cell pressure) triaxial tests are also inclined at a slope of 3:1 w.r.t \( p' \)-axis,
Figure 3.8(a) Stress Paths and Failure Envelops in Deviatoric Stress vs Mean Effective Stress Space from Triaxial Tests on Recompacted MSW Samples.
it can be inferred that there was hardly any excess pore water pressure induced in
the sample during the initial stage of undrained shearing. This could be attributed
to the compressible structure of MSW. It is hypothesized that during this stage of
the test, the application of axial stress resulted in compression of various
components of MSW, but not the compression of the inner component voids.

As the undrained shearing continued, the stress path began to curve
towards the q-axis, signifying a reduction of $p'$ due to increase in pore water
pressures inside the sample. During this stage of undrained shearing, the
incremental stress ratio $\Delta q/\Delta p'$ was negative. The stress paths for several samples
[e.g. sample R-3 in Fig 3.8(a)] appeared to have reversed their trend of negative $\Delta q/\Delta p'$
after achieving a certain critical value of $q/ p'$. From this point onwards the
stress paths had positive $\Delta q/\Delta p'$ and appeared to be heading along a straight line
irrespective of their initial $p'$ values.

Stress paths for samples R-1, R-2, R-3, R -5 and R-8 end up in a straight line with a
slope of 1.95 and a q-intercept of 15kPa [solid line in Fig 3.8(a)] while the stress
paths for samples R-4, R-6 and R-7 end up on another straight line with a slope of
1.43 and a q-intercept of zero [dashed line in Fig.3.8(a)]. Stress paths for sample R-9
terminates in a zone bound by the two straight lines, however, it is likely that this
stress path would have ended up on the upper straight line if the sample could have
been sheared further.
As mentioned in the previous section, the linear increase in $q$ and $p'$ along a failure envelope is likely associated with the development of a shear band (or a failure plane) inside a sample soon after the sample achieves a critical value of $q/p'$. Once the shear band forms, the mechanism of shearing changes from undrained to drained shearing because of dilation and localized draining of pore-water along the failure plane. Shearing on the failure plane now continues at a constant positive incremental stress ratio, i.e. the stress path moves along a straight line. The upper solid black and the lower dashed black straight line [Fig 3.8(a)] on which the stress paths for all recompacted samples end up, therefore, represent the upper bound.
and the lower bound failure envelopes for the recompacted MSW. Whether a sample would end up on the upper bound failure envelope or the lower bound failure envelope probably depends on the extent of dilation occurring at the failure plane. It is hypothesized that a sample that has better interlocking between its constituent elements would experience greater dilation at the failure plane, and therefore, it would mobilize higher shear strength and end up on the upper bound failure envelope.

The Mohr-Coulomb shear strength parameter cohesion intercept $C'$ and the angle of friction $\Phi'$-associated with these two failure envelopes can be obtained using the following two equations:

\[
\phi' = \sin^{-1} \left( \frac{3M}{6 + M} \right) \quad \text{...} \quad \text{...} \quad \text{Eq. (3.2)}
\]

\[
c' = k \frac{3 - \sin(\Phi')}{6 \cos(\Phi')} \quad \text{...} \quad \text{...} \quad \text{Eq. (3.3)}
\]

Where, $M$ is the slope of failure envelope and $k$ is the q-intercept of the failure envelope in q-p' stress space. The upper bound and the lower bound values of $C'$ and $\Phi'$ associated with these two failure envelopes are given in Table 3.4.
Table 3.4 Shear Strength Parameter of MSW obtained from Triaxial Tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>From Triaxial Tests</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Bound</td>
<td>Upper bound</td>
<td></td>
</tr>
<tr>
<td>$C'$ (kPa)</td>
<td>0</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>$\Phi'$ (°)</td>
<td>35</td>
<td>47</td>
<td></td>
</tr>
</tbody>
</table>

3.7.3.2 Shear Strength of Intact MSW

Figure 3.8(b) shows the stress paths in q-p’ stress space for five intact MSW samples. Comparing Fig 3.8(b) with Fig 3.8(a), it is evident that the stress paths followed by the intact MSW samples are not as curved as those obtained from recompacted MSW samples. This suggests that the structures of the intact samples are less anisotropic than that of the recompacted samples. The intact samples for the present study were obtained from a relatively shallow depth. It is possible that intact samples of MSW taken from greater depths would be cross-anisotropic to a greater extent by virtue of having experienced predominantly one dimensional compression under overburden stress.

The upper bound and the lower bound failure envelopes obtained for the recompacted samples are shown superimposed on the stress paths for intact samples in Fig 3.8 (b). The stress paths for three intact samples (U-2, U-3, U-4) end up either on or close to the upper bound failure envelope while the stress path for sample U-6 ends up close to the lower bound failure envelope. The stress path for sample U-1 terminates below the lower bound failure envelope. The triaxial test on sample U-1 was terminated prematurely because the sample buckled excessively.
and came in contact with the inner wall of the triaxial cell. As such, sample U-1 could not be tested to failure. An attempt was made to extend the stress path of sample U-1 by extrapolating the deviatoric stress vs axial strain an excess pore water pressure vs. axial strain curves. Such extrapolation was achieved by fitting hyperbolic curves through the measured data points as shown in Fig 3.9. The fitted hyperbolic curves were then used to extend the stress path for sample U-1 in q-p’ stress space as indicated by the dotted curve in Fig 3.8(b). It is likely that if further shearing of sample U-1 could be achieved, the stress path for sample U-1 would have ended up close to the upper bound failure envelope.

The stress path for intact sample U-2, which was tested at zero effective confining pressure, is along a straight line with a slope of 3:1 with respect to the p-axis. It is suggested that failure was achieved in sample U-2 along a ‘tension cut-off’ line, which for triaxial test has a slope of 3:1 with respect to the p-axis. Admittedly, the existence of a tension cutoff line for saturated MSW cannot be confirmed on the basis of just one triaxial test, more triaxial tests on saturated MSW samples at a low value of effective confining pressure would be needed.
Figure 3.9 Extrapolation of Measured Deviatoric Stress vs. Axial Strain and Excess Pore Water Pressure vs. Axial Strain Curves Using a Non Linear Hyperbolic Model to Obtain Deviatoric Stress at Failure for Intact Sample U-1.

Only a limited number of triaxial tests could be conducted on intact MSW samples, however, it is evident from the results of these tests that although the pre-
failure deformation behaviour of the intact samples is different from that of the recompacted samples, they both appear to be mobilizing fairly similar shear strength values.

3.7.4 Stress-Strain Behaviour of MSW from Direct Shear Test

Figure 3.10 shows the measured shear stress vs. shear strain curves of the four direct shear tests. The shear stress vs. shear strain response of MSW in direct shear tests is nonlinear and it varies similar to the deviatoric stress vs. axial strain response of MSW in triaxial tests [Fig 3.7 (a) & (b)]. The value of initial tangent shear modulus of MSW appears to increase with increasing effective normal stress. It can also be seen from Fig 3.10 that no distinct peak in shear stress could be achieved within the maximum permissible horizontal displacement of the shear box. This is consistent with the experience of other researchers (e.g. Kolsch, 1995, Kavazanjian et al., 1999) who have conducted large direct shear tests on recompacted MSW samples. It was, therefore, decided to extrapolate the shear stress vs. shear strain curve for each test by fitting hyperbolic curve through measured data points and values of ‘ultimate’ shear stress were obtained as asymptotes to the fitted hyperbolic curves.
Figure 3.10 Measured and Extrapolated Shear Stress vs. Shear Strain Plots for the Direct Shear Tests.

The range of values of $C'$ and $\phi'$ obtained from the four direct shear tests together with that obtained from triaxial tests (Table 3.4) are presented in Table 3.5.
Table 3.5 Shear Strength Parameters from Direct Shear Test and Triaxial Test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>From Triaxial Tests</th>
<th>From Direct Shear Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower Bound</td>
<td>Upper bound</td>
</tr>
<tr>
<td>$C'$ (kPa)</td>
<td>0</td>
<td>8.4</td>
</tr>
<tr>
<td>$\Phi'$ (°)</td>
<td>35</td>
<td>47</td>
</tr>
</tbody>
</table>

3.7.5 Shear Strength of MSW from Direct Shear Test

Plots of shear stress at failure vs. effective normal stress for the four direct shear stress are shown in Fig 3.11. The asymptotic ‘ultimate’ shear stress value (as explained in previous section) was taken as the shear stress at failure for the hyperbolic extrapolations. Mohr-Coulomb (M-C) failure envelopes were fitted through the measured and extrapolated results (Fig 3.11) and shear strength parameters ($c'$ and $\Phi'$) were obtained using the slopes and the y-intercepts of these failure envelopes. The M-C failure envelope denoted by the solid line was fitted using all four measured data points whereas the M-C failure envelope denoted by the dashed line was fitted by ignoring the results for test D-1 (conducted at 150 kPa effective normal stress). Similarly the M-C failure envelope for the extrapolated results was obtained by considering all four tests or by ignoring the results for the test D-1.
The MSW failure envelopes obtained from the present study, i.e. upper bound and lower bound failure envelopes obtained from triaxial tests [Fig 3.8 (a)& (b)] and the four failure envelopes obtained from direct shear tests (Fig 3.11) are plotted together in Fig 3.12(a). In Fig 3.12(a) the upper bound and the lower bound failure envelopes for MSW inferred from the values of $C'$ and $\Phi'$ for MSW obtained from the literature (Table 3.1) are presented. It can be seen from Fig 3.12(a) that the
Figure 3.12(a) Shear Strength Envelopes for MSW from Present Study and the Literature
MSW failure envelopes obtained from the present study lie in between the upper bound and the lower bound MSW failure envelopes obtained from the literature.

Figure 3.12(b) Upper Bound and Lower Bound Failure Envelope from this Study and from Literature.
Figure 3.12(b) shows a comparison between the upper bound and the lower bound failure envelopes obtained from the triaxial tests with the bilinear failure envelope proposed by Kavazanjian et al., 1995 and the trilinear failure envelope proposed by Manassero et al., 1996, which are widely used in practice for the assessment of stability of landfill slopes. The lower bound failure envelope obtained from the triaxial tests plots fairly close to the ‘frictional’ portion of the bilinear failure envelope. It also plots fairly close to the middle portion of the tri-linear failure envelope; however, at higher effective normal stresses, it plots higher than the tri-linear failure envelope.

An effective normal stresses less than 30 kPa, the bilinear failure envelope becomes ‘cohesive’ whereas the lower bound failure envelope continues to be ‘frictional’. This difference in the two failure envelopes may be caused by the fact that the bilinear failure envelope is based on the back-analysis of landfill failures (Kavazanjian et al., 1995) where MSW was only partially saturated. The lower bound failure envelope, on the other hand, is based on the results of fully saturated MSW samples. It is therefore likely that the ‘cohesive’ portion of the bilinear failure envelopes includes some effect of apparent cohesion associated with negative pore-water pressures in the MSW under conditions of partial saturation.
3.8 CRITICAL COMMENTS

Results from a program of shear strength testing of intact and recompacted samples of municipal solid waste (MSW) have been presented in this study. A method of taking intact samples from landfill sites using a push-in sampler has been developed and used successfully to obtain intact samples of MSW from Jorhat municipal landfill site near river Bhogdoi, Jorhat, Assam (India). Consolidated undrained triaxial tests were conducted on MSW samples using a triaxial compression apparatus. A direct shear apparatus was used for shear strength testing of MSW samples. The results of shear strength testing were presented in terms of Mohr-Coulomb shear strength parameters, i.e. cohesion intercept ($C'$) and angle of friction ($\Phi'$), and compared with those available in the literature.

Based on these results and their favourable comparison with the published literature, it can be concluded that it is feasible to obtain meaningful shear strength parameters for MSW using consolidated undrained triaxial tests on large-diameter intact and recompacted MSW samples. Values of $C'$ and $\Phi'$ for MSW obtained from these triaxial tests were comparable with those obtained from direct shear tests.

Using a triaxial compression apparatus, it is possible to shear saturated samples of MSW and to measure their pore-water pressure response during shearing. It is difficult, if not impossible, to achieve this in a direct shear apparatus. Consequently, the results of a triaxial test can be analyzed in terms of effective stresses and the effective stress paths followed by the MSW samples during shearing can be plotted. On the basis of the fairly coherent picture of shear behaviour of MSW presented by these effective stress paths [Fig 3.8 (a) & (b)], it is reasonable to conclude that the mechanical behaviour of saturated MSW samples can be explained using the principle of effective stress.
It was found that the intact and recompacted saturated samples of MSW mobilize fairly similar values of shear strength when sheared in a triaxial compression test [Fig 3.8 (a) & (b)]. It can, therefore, be suggested that reasonable values of $C'$ and $\Phi'$ for MSW can be obtained using recompacted samples.

Although the intact and the recompacted saturated samples mobilized similar values of shear strength, their pre-failure response was quite different. As shown in [Fig 3.8 (a) & (b)], recompacted samples behave in a fairly ductile manner and generates higher excess pore-water pressures, whereas intact samples shows a stiffer response and generates lower pore-water pressures. This observation is important from the viewpoint of evaluating deformation and serviceability conditions within a landfill. It appears to support the use of intact samples for establishing deformation characteristics of MSW. More triaxial tests on intact as well as recompacted samples are required to confirm this observation.
REFERENCES


[124]


