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# Shear Strength Characteristics of Municipal Solid Waste

**M.A.G.P. Perera and N.H. Priyankara**

**Abstract:** Disposal of Municipal Solid Waste (MSW) has become a serious problem all over the world which is affected by the rising population and rapid urbanization. Most of the developed countries tend to proceed with engineered landfilling or incineration of solid waste while developing countries continue with open dumping. Most of these open dump sites are located on marshy lands or low lying land areas due to the high demand for prime lands in city areas, and they are expanded in vertical direction, saving the horizontal spaces. Therefore, physical, chemical and shear strength properties of MSW are timely important to overcome the stability failures of the dump sites during the operational period and after the closure of the dump sites. In this study, engineering properties of MSW were investigated using several laboratory experiments for disturbed waste samples collected from Meethotamulla dump site. In order to represent the aging effect of MSW, samples were extracted at different depths and variation of geotechnical properties with aging was analysed. Based on the laboratory test results, it can be noted that MSW in open dump sites in wet zone of Sri Lanka mainly consists of fine residue, aggregated soil, polythene and textiles. Further, higher shear strength parameters were obtained for MSW due to presence of textiles within the waste body. As such, it can be concluded that, it is necessary to consider the influence of textiles in analyzing the stability of open dump sites.

**Keywords:** Dilatancy, Municipal solid waste, Shear strength parameters, Waste composition

## 1. Introduction

In the United State of America, 54% of solid waste is landfilled and in Japan, there is a higher tendency to incinerate solid waste using advanced technologies [1]. The best example for open dump sites in developing countries is the world's largest garbage mound in Indonesia, which is considered as a ticking time bomb. This is a clear indication that, due to absence of advanced technologies and a higher amount of cost requirement, open dumping is the most popular method of waste disposal in developing countries like Sri Lanka.

Usually, open dump sites receive all types of heterogeneous solid waste, consisting of biodegradable waste, non-biodegradable waste and residual fines from the municipal areas without sorting [2]. Due to the decomposition of biodegradable solid waste, settlement would be induced during the operational stage of the dump sites which is directly affected by the stability of the garbage mounds. In addition, due to scarcity of land and high demand for prime land around Colombo municipal area, the existing dump sites are expanded in the vertical direction. Therefore, proper planning and monitoring is essential to overcome the disasters and failures of garbage mounds.

There was a sudden failure of Meethotamulla dump site in 2017, which affected the surrounding environment, destroyed human lives, public property and several infrastructures at the South-Western side of the garbage mound [3]. Such incidents clearly illustrated that it is necessary to follow proper technical procedure to maintain the stability of solid waste dump sites. The physical, chemical and engineering characteristics of solid waste are required to assess the current stability condition, planning closure of the open dump sites and converting them to public parks. Further, these parameters are varying with time due to degradation of solid waste. As such, this research was conducted to determine the physical, chemical and shear strength properties of Municipal Solid Waste (MSW), considering the aging effect.

*Eng. (Miss.)* ***M.A.G.P. Perera,*** *AMIE (SL), B.Sc. Eng. (Hons) (Ruhuna), Department of Civil and Environmental Engineering, University of Ruhuna.*
*Email:gayanipiyumika9637@gmail.com*
*https://orcid.org/0000-0003-1072-6676*
***Eng. (Dr.) N.H. Priyankara,*** *C.Eng, MIE(SL), B.Sc.Eng.(Hons) (Moratuwa), M.Eng.(AIT), Ph.D.(Tohoku), MSLGS, Senior Lecturer, Department of Civil and Environmental Engineering, University of Ruhuna. Email:nadeej@cee.ruh.ac.lk*
*http://orcid.org/0000-0002-8775-7246*

According to Reddy et al. [4], cohesion varies in the range of 31-64 kPa and drained friction angle varies in the range of $26^0$-$30^0$ for MSW of Orchard Hills Landfill in USA. In Sri Lankan context, cohesion varies from 10-25 kPa and angle of friction varies from $18^0$-$21^0$ for MSW in Colombo Municipal Council area [2]. Based on a series of laboratory tests conducted by Balasooriya et al. [5], cohesion and angle of friction of MSW for dry region of Sri Lanka were found to vary from 14-49 kPa and $21^0$-$49^0$, respectively.

This clearly illustrates that only very limited research has been carried out related to finding engineering properties of MSW in Sri Lanka, especially variation of shear strength parameters of MSW over time. Therefore, it is very important to have a firm understanding on the variation of engineering characteristics, especially shear strength parameters of MSW with time.

## 2. Methodology

In order to determine the physical, chemical and engineering properties of MSW considering the aging effect, following procedures were carried out sequentially.

### 2.1 Sample Collection

Waste samples were extracted from the Meethotamulla dump site, which is located in Kolonnawa area, during the restoration phase. The arial image of the collapsed Meethotamulla dump site is shown in Figure 1.

Four numbers of disturbed waste samples were collected from different depths of the waste body at Meethotamulla dump site, using a long arm excavator, to represent the aging effect of MSW. Waste samples were extracted from 0 m (surface), 4.0 m, 8.0 m and 12.0 m depths as illustrated in Figure 2.

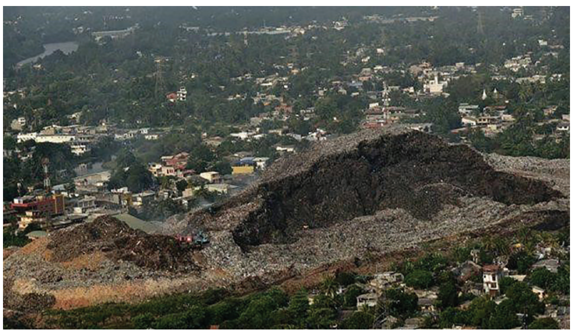

**Figure 1 – Meethotamulla Dump Site after Failure**

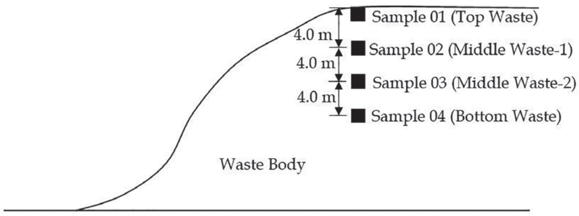


**Figure 2 – MSW Sample Collection**

### 2.2 Sample Preparation

Air-dried samples were laid on a dry concrete surface and large debris was subdivided into small parts. Then, laid waste materials were mixed well using a shovel. Mixed waste was divided into four segments diagonally, with each segment approximately same size, as shown in Figure 3. The two segments opposite to each other were removed from the mixture. Then, remaining waste was mixed again well and divided into four segments. This procedure was repeated until the remaining waste becomes 5 - 10 kg in size. This procedure of sampling is known as "quartering method" as shown in Figure 3.

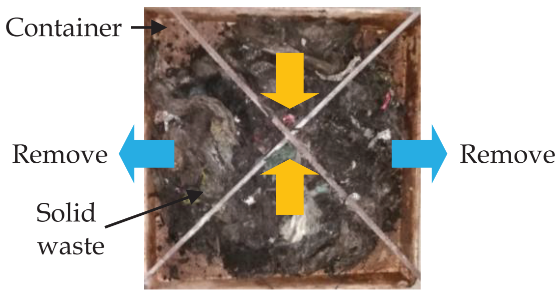


**Figure 3 – Quartering Method of Sample Preparation**

### 2.3 Physical Properties of MSW

After preparation of the samples using the quartering method, physical properties of MSW such as composition, particle size distribution, specific gravity, bulk unit weight and saturated moisture content were determined.

#### 2.3.1 Waste Composition

The composition of MSW was described in terms of 13 main categories such as kitchen waste, paper, hard plastic, soft plastic, metal, glass, ceramic, leather and rubber, textile, grass and wood, rock, cemented material, aggregated soil, and others. After sorting the MSW into above stated categories by visual observations, weight fractions were calculated to find the composition of each category.

#### 2.3.2 Particle Size Distribution

Particle size distribution of the MSW was determined using sieve analysis test. The air-dried waste samples were sieved using 63, 37.5, 19, 9.5, 4.75, 1.7 and 0.075 mm diameter sieves and passing percentages were determined.

#### 2.3.3 Specific Gravity

Specific gravity of MSW was determined for the large-size particles and small-size particles separately, by using density bottle method. Large-size particles consist of particle sizes between 2 mm to 10 mm, whereas small-size particles consist of particles having less than 2 mm diameter.

#### 2.3.4 Bulk Unit Weight

In order to determine the bulk unit weight, MSW was completely filled into a 1000 $cm^3$ capacity steel mould without any compaction and container was allowed to fall down to the ground from a 30 cm height three times [6]. Then the volume of waste within the mould was decreased and mould was again filled completely with waste and the above activity was repeated until there was no reduction in volume due to above activity. Once there is no reduction in volume of MSW, the weight of mould to compute the bulk unit weight was determined.

#### 2.3.5 Saturated Moisture Content

Saturated moisture content is the maximum water content that can be stored in the waste sample. In order to perform this test, the waste samples were placed in water, after taking the initial moisture content. Then, moisture content was checked daily until it became constant. When the moisture content was constant this value was considered as the saturated moisture content.

### 2.4 Chemical Properties of MSW

pH, Electrical Conductivity (EC) and Volatile Organic Content of MSW were determined under the chemical properties of MSW.

#### 2.4.1 pH Value

The pH value of MSW was measured using Glass-electrode pH meter at several temperatures. First, air dried waste samples were taken and particles larger than 10 mm were removed by sieving. The amount of sample required for the test was selected according to the maximum particle size of the MSW [6].

Then raw samples were placed in beakers and distilled water was added in such a way that the mass of water in the beaker was five times more than the dry mass of the sample. Finally, the samples were stirred using a glass rod and kept for 30 - 180 minutes for complete soaking. Then, by using the Glass- electrode pH meter, pH values were measured.

#### 2.4.2 Electrical Conductivity (EC)

Sample preparation method for EC test is same as the pH test. EC values of the MSW were measured using the Electrical Conductivity sensor as illustrated in Figure 4.

**Figure 4 – Measurement of Electrical Conductivity of MSW Samples**

#### 2.4.3 Volatile Organic Content

Volatile Organic Content of MSW is an important parameter which can directly affect the stability of the dump site because organic materials can decompose easily within a short period. Therefore, the Volatile organic content of MSW was measured according to the JIS A 1226 [7].

The waste samples were oven-dried at $60^0$ C without destroying the organic portion of the MSW. Then it was dried up to $800^0$ C in the Muffle furnace to remove the volatile organic components of the MSW. The loss of mass of MSW during the drying process from $60^0$ C to $800^0$ C was used to compute the Volatile Organic Content.

### 2.5 Compaction Characteristics of MSW

The Standard Proctor Compaction Test was performed according to ASTM D 698 [8], which is equivalent to JIS A1210 [9]. Compaction is a type of densification of soil or waste by removing the air from voids. Higher compaction leads to improving the density and strength characteristics of solid waste while decreasing the compressibility and permeability characteristics [10].

### 2.6 Shear Strength Characteristics of MSW

According to the results obtained from the Standard Proctor Compaction Test, samples were prepared for the direct shear test to obtain the shear strength parameters, varying the moisture content. This test was carried out using the automated direct shear apparatus as shown in Figure 5 according to the ASTM D3080 [11] which is equivalent to JGS 0561 [12].

**Figure 5 – Automated Direct Shear Apparatus**

The size of the shear box is 100 mm inner diameter and 40 mm thickness. The maximum particle size for the direct shear test was selected as 9.5 mm [13]. The direct shear tests were performed under different compaction levels on the dry side and wet side of the compaction curve (more details of test procedure are described in Section 3.4.1 and Figure 11). A constant strain rate of 0.125 mm/min was used to shear the sample at different normal stresses of 25 kPa, 50 kPa and 75 kPa. For each normal stress, variation of shear strain, shear stress and vertical displacements were recorded in the data logger attached to the direct shear apparatus.

## 3. Results and Discussion

After performing the laboratory experiments, physical, chemical and engineering properties of MSW were determined considering the aging effect. The obtained results were analyzed and presented in this section.

### 3.1 Physical Properties of MSW

#### 3.1.1 Waste Composition

The variation of waste composition with depth is shown in Figure 6. It can be observed that, irrespective of the depth, largest portion of the waste material consisted of aggregated soil, fine residue and polythene. Aggregated soil is defined as particle size greater than 9.5 mm while fine residue is defined as particle size smaller than 9.5 mm. It can be seen that MSW comprises more fine residue than the other materials, and percentage of fine residues is increased with depth.

Soil layers used as cover to reduce animal attraction, bad odour and displeasing view of open dumps, can be easily mixed with the waste materials, during the extraction of waste materials from several depths. Further, due to the decomposition of organic waste materials, fine particles can be accumulated at the bottom of the garbage mound and these are the possible reasons for having larger amounts of fine residue within the MSW.

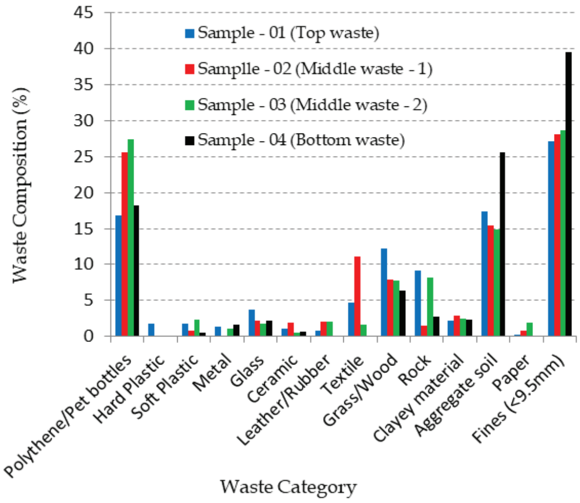


**Figure 6 – Composition of the Municipal Solid Waste**

#### 3.1.2 Particle Size Distribution

The particle size distribution of MSW samples is illustrated in Figure 7. Based on the results, it can be observed that more than 40% of the particle sizes are greater than 63 mm and they include most of the elongated and large debris such as polythene, pet bottles, hard plastics, metal, glass, ceramic, leather, textile, yard waste, wood, clayey materials and rock, etc.

The comparison of the particle size distribution of MSW in this study with literature is shown in Figure 8. It can be seen that the particle size distribution curves obtained from the Meethotamulla garbage dump (this study) are in the range of particle size distribution behaviour of Bloemendhal and Kolonnawa waste dumps [2]. However, larger particles exist in the Meethotamulla dump site than in Bloemendhal and Kolonnawa dump sites.

During the restoration work at Meethotamulla dump site, larger particles placed at higher elevation of the garbage mount may be the reason for this deviation. Further, particle size distribution curves of Hambantota dump site [5] clearly deviated from that of Meethotamulla dump site. The climatic differences of different regions would be a reason for this deviation because Meethotamulla, Kolonnawa and

Bloemendhal waste dump sites are located in Colombo region which belongs to the wet zone of Sri Lanka while Hambantota belongs to the dry zone of Sri Lanka.

Further, urbanization of the region may be another factor for this difference where more industrial wastes are developed in the Colombo Municipal Council than Hambantota.

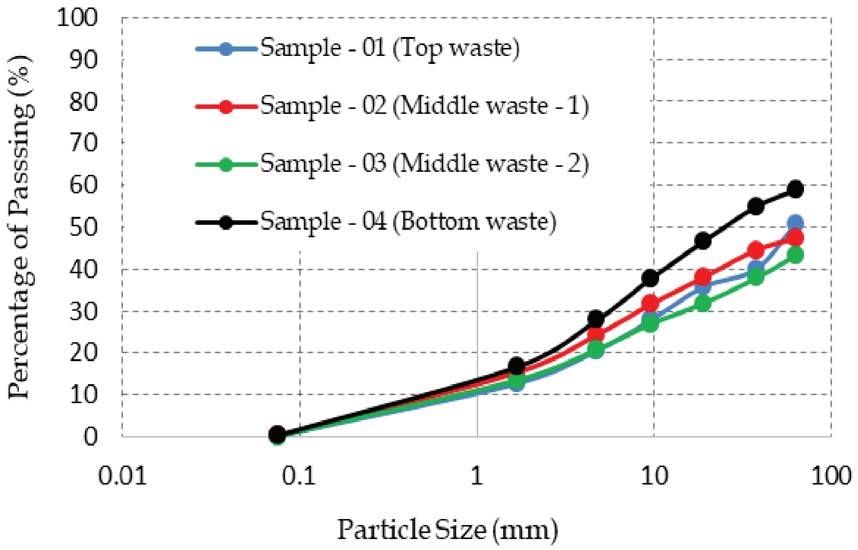


**Figure 7 – Particle Size Distribution of MSW**

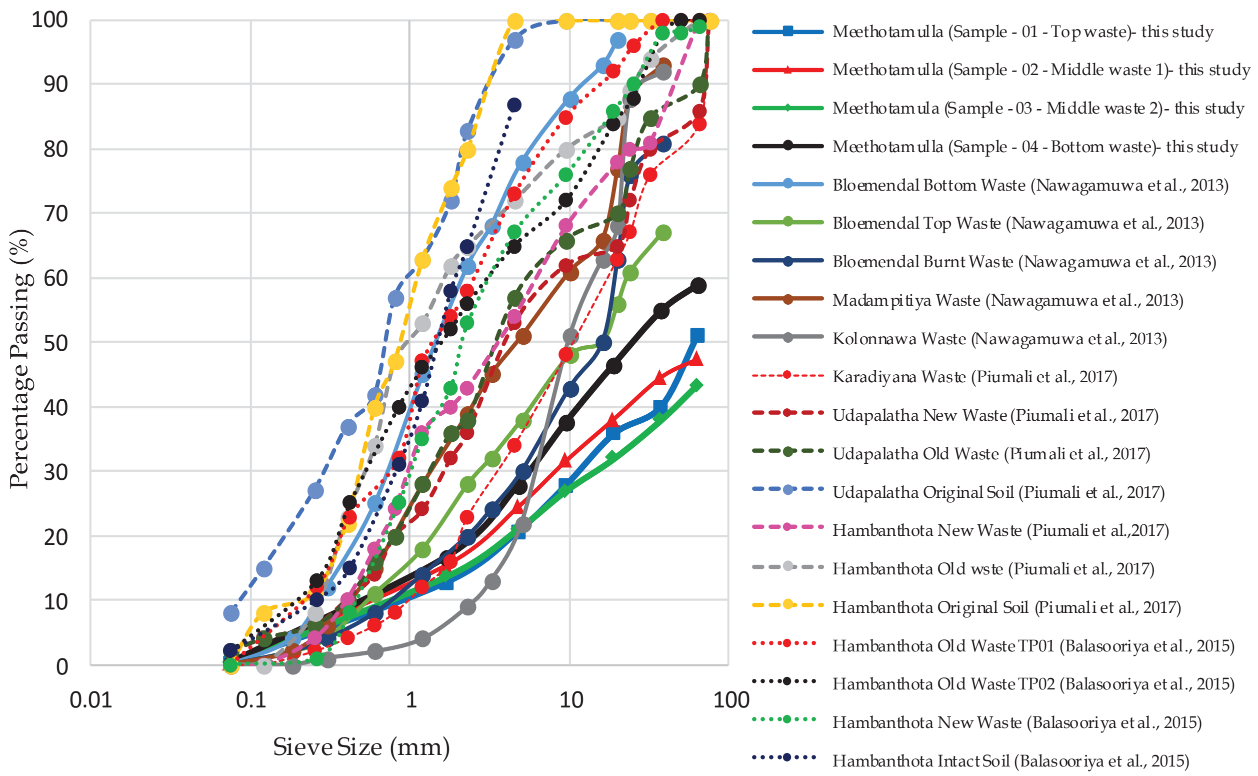


**Figure 8 – Comparison of the Particle Size Distribution of Municipal Solid Waste in this Study with Literature**

#### 3.1.3 Specific Gravity

Table 1 illustrates the specific gravity of MSW according to the particle size. It can be noted that specific gravity values are greater than 2.0 irrespective of the particle size and they are considerably high as most of the waste materials were mixed with soil. Also, it is a noticeable factor that specific gravity values are increasing with depth and this was proven through by other existing research [5].

#### 3.1.4 Bulk Unit Weight

The variation of bulk unit weight of MSW is illustrated in Table 1. It can be seen that the average bulk unit weight of the MSW of Meethotamulla dump site is about 5.1 $kN/m^3$.

#### 3.1.5 Saturated Moisture Content

Irrespective of the depth, the saturated moisture content of MSW was found to be 350-400%.

### 3.2 Chemical Properties of MSW

#### 3.2.1 pH Value

The results obtained from the pH meter for all the samples are indicated in Table 1. It can be observed that pH values of all samples are greater than 7.0. It means that these waste materials show the behaviour of a Base. However, generally, fresh MSW shows acidic behaviour due to the higher number of acidic components such as chemicals, electric equipment and spoiled kitchen matter, etc. When separating waste into different categories at the initial stage, there were only decomposed waste materials and most of the waste portion could be visualized as aggregated soil, gravel and fine residue. Hence, the reason for Base behaviour of MSW is due to presence of fully and partially decomposed waste materials.

#### 3.2.2 Electrical Conductivity (EC)

The results of the Electrical Conductivity tests are shown in Table 1. It can be seen that obtained EC values were greater than 2.0 mS/cm in the top waste layers and they are considerably high. This indicates that MSW shows electric conduction properties. Also, the values obtained from the Electrical Conductivity test for MSW decrease with the depth of the dump site.

To verify these higher EC values of MSW, total ion concentration was determined. When preparing samples using volumetric flasks as shown in Figure 9, change of colour could be identified, hence it is clear that the MSW samples consist of a considerable amount of ions. Based on the total ion concentration test, it can be concluded that MSW samples consist of metallic concentration to some extent. As a result, the higher value of EC was observed.

**Figure 9 – Total Ion Concentration Test**

#### 3.2.3 Volatile Organic Content

Results of the Volatile Organic Content are shown in Table 1. It can be observed that all samples show same volatile organic content irrespective of the depth and they were around 38-39%. However, the topmost waste has relatively higher organic content than the

**Table 1 – Physical and Chemical Properties of MSW**

| Sample | Specific gravity (Particles < 2 mm) | Specific gravity (Particles > 2 mm) | Bulk unit weight ($kN/m^3$) | pH | Electrical Conductivity EC (mS/cm) | Volatile Organic Content (%) |
|---|---|---|---|---|---|---|
| Sample - 01 (Top waste) | 2.10 | 2.17 | 6.22 | 7.54 | 2.96 | 39.17 |
| Sample - 02 (Middle waste-1) | 2.16 | 2.21 | 4.78 | 7.60 | 2.03 | 39.04 |
| Sample – 03 (Middle waste-2) | 2.21 | 2.24 | 4.28 | 7.39 | 1.81 | 38.84 |
| Sample – 04 (Bottom waste) | 2.24 | 2.25 | 8.19 | 7.61 | 1.17 | 38.79 |

bottom waste. This has occurred because of the fresh waste materials are in the topmost layer of the garbage mound and they are consisted with most of the organic compound.

### 3.3 Compaction Characteristics of MSW

The variation of dry unit weight of MSW over moisture content is illustrated in Figure 10. Based on the results, it can be noted that the maximum dry unit weight of MSW is 11.2 kN/m³ and the optimum moisture content is 38 %. The results obtained in this study agree well with the data presented by Nawagamuwa et al. [2] where dry unit weight and optimum moisture content of MSW at Kolonnawa garbage mound were found to be 13 kN/m³ and 24.2%, respectively. However, the maximum dry unit weight and optimum moisture content of MSW in Hambantota were found to be 16 kN/m³ and 15%, respectively, due to climatic difference [5].

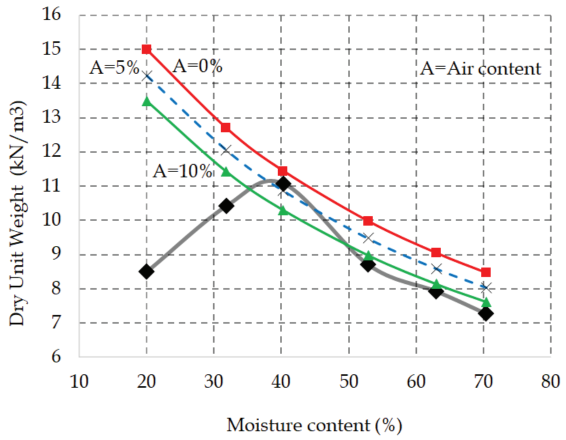


**Figure 10 – Proctor Compaction Curve (Sample - 01)**

### 3.4 Shear Strength Characteristics of MSW

Due to biodegradation of MSW, shear strength properties can vary with time and highly affect the stability of a garbage mound. Therefore, it is important to obtain the shear strength parameters of the MSW, considering the effect of aging.

In order to study the effect of aging on shear strength parameters, MSW samples were extracted from four different depths of the garbage mound. Greater depth represents the older waste while sample collected from the surface represents the fresh waste. Since physical properties of the MSW samples do not significantly vary with depth, direct shear tests were carried out only on top (Sample – 01) and bottom (Sample -04) MSW specimens to determine the shear strength parameters.

#### 3.4.1 Sample Preparation

The samples were prepared based on the compaction curve developed using Standard Proctor compaction test. For each sample, a direct shear test was performed under corresponding moisture content and dry unit weight as shown in Figure 11.

Initially MSW samples were air dried and shredded. Using the compaction curves developed which represent the different depths, samples for direct shear tests were prepared with moisture content of OMC - 6%, OMC - 3%, OMC, OMC + 3% and OMC + 6%, where OMC is the Optimum Moisture Content. An increments of 3% were chosen, because it is an ideal value to obtain samples for direct shear test varying across the entire compaction curve. Once the required dry unit weights were decided, the corresponding bulk unit weights were calculated by adjusting the moisture content. After the bulk mass calculation, the sample was prepared in the direct shear box by compacting the waste in three layers using a light weight manual compactor.

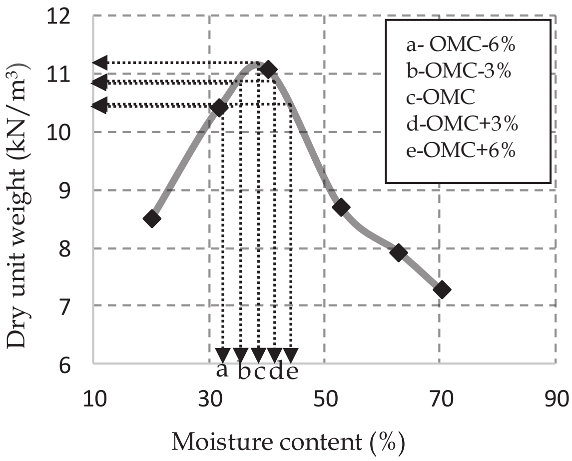


**Figure 11 – Sample Selection Procedure for Direct Shear Test**

#### 3.4.2 Effect of Sample Preparation Method

Waste is a heterogeneous material and it includes several types of waste materials. When using different samples for the direct shear tests for different normal stresses under a particular moisture content, properties of the samples could vary due to change of composition of MSW. As a result, the level of compaction could change in preparing the samples.

Bray et al. [14] conducted a series of direct shear tests at several levels of increasing normal stress on the same waste specimen to reduce the specimen variability effects and to improve the testing efficiency. This method provides conservative estimates of shear strength parameters than use of separate samples. Further, Bray et al. [14] reported that shearing in stages at higher normal stresses yields lower shear strength due to the effects of pre-shearing in the previous loading stage.

To verify the argument of staged testing in MSW [14], direct shear tests were carried out for two different cases: using same sample and using different samples for shearing under different normal stresses. After testing under the lower normal stress, the same sample was re-sheared while increasing the normal stress. In this case, properties of the waste materials would not be changed. Then the second scenario was carried out using separate samples for the shearing. In this case, properties of waste would be changed due to the heterogeneous natures of the waste. Figure 12 shows the comparison of shear stress versus shear strain behaviour for Sample - 01 (top waste) at OMC – 6 % of moisture content.

It can be seen that both scenarios depict the similar stress-strain behaviour at a particular normal stress as depicted in Figure 12. Based on the stress-strain diagram, Mohr-Coulomb failure envelops were developed for the same and separate samples as shown in Figure 13, and it can be seen that both failure envelops are almost identical. Hence, same sample was used to determine the shear strength parameters of MSW under different normal stresses.

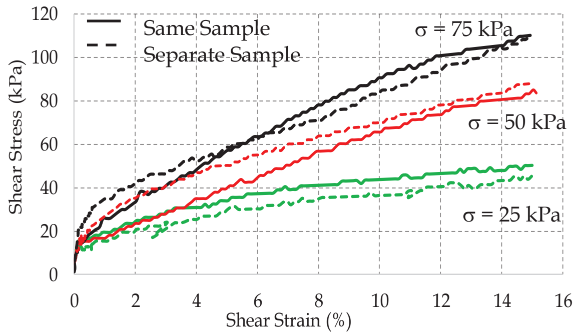


**Figure 12 – Shear Stress Versus Shear Strain Behaviour of Same and Separate Samples**

Further, in all the tests, shear stress did not reach the peak during the shearing. It is unlikely that a significant shear band developed in the waste specimen at the end of each loading stage. Thus, it can be assumed that waste was not significantly pre-sheared before the next loading stage. And the shear surface that may have partially developed previously, is compressed downwards due to recompression of the specimen under the higher normal stress. Therefore, new shear surface of the next stage of the test is created above the level of shearing impost in the previous stage of the test, which resulted in a shear surface that is different than the previously formed and is sheared during the next stage of the test. As such, pre-shearing effects would not be expected in this case [14]. Therefore, in this research study, stage testing method was used to obtain the shear strength parameters.

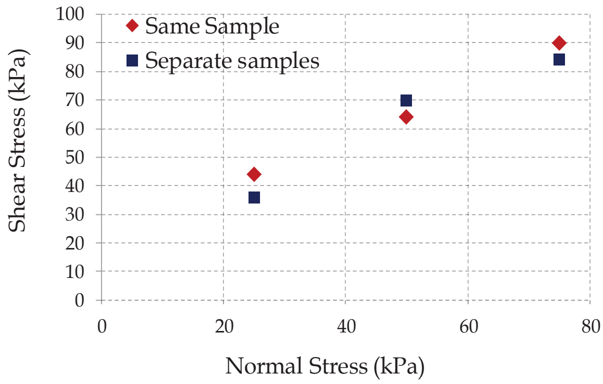


**Figure 13 – Mohr-Coulomb Failure Envelops for Same and Separate Samples (at 10% Strain)**

### 3.4.3 Initial Settlement

Before applying the shear, MSW samples were subjected to vertical (normal) stresses until settlement reaches a constant as shown in Figure 14. It can be noted that, irrespective of the normal stress, initial settlement reaches constant after a period of about 1.6 hours. It can be observed that there is a considerable initial settlement in the MSW specimens due to presence of biodegradable materials.

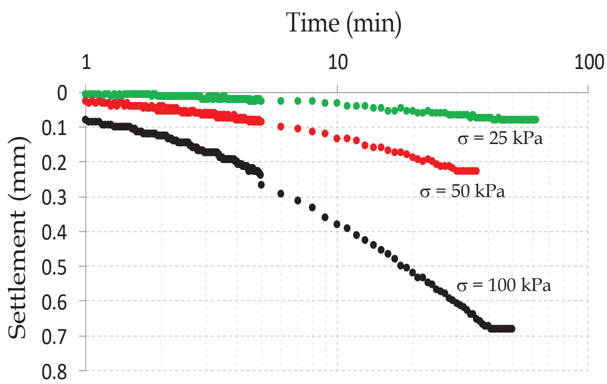


**Figure 14 – Variation of Vertical Displacement Versus Time for Top Waste (Sample – 01)**

### 3.4.4 Effect of Shear Strain Levels on Shear Strength Parameters

After performing direct shear tests on the waste materials, only strain hardening behaviour could be observed In other words, there is no clear peak points in the stress-strain curves. The comparison between strain hardening and strain softening behaviour is illustrated in Figure 15. Hence, it can be concluded that MSW failure conditions cannot be clearly defined.

Based on the above analysis, the shear strength parameters for MSW are usually determined by the Mohr-Coulomb criterion related to a certain acceptable strain level for landfill, unlike for soil. Usually, in soil, in most of the situations, the strain softening behaviour can be clearly identified. Therefore, the maximum shear stress can be obtained at a certain shear stain level. But, in the case of waste, only the strain hardening behaviour was observed and hence it was decided to define different strain levels to develop the Mohr-Coulomb failure envelop. These strain levels are established based on the compatibility of acceptable deformations for other strain softening landfill materials such as liners and drainage system, etc. According to Zekkos [15], the critical shear strain levels to develop Mohr-Coulomb failure envelops to define shear strength parameters of MSW are generally between 10% to 20%. As such, shear stress at 5%, 10% and 15% strain levels was studied in this research study.

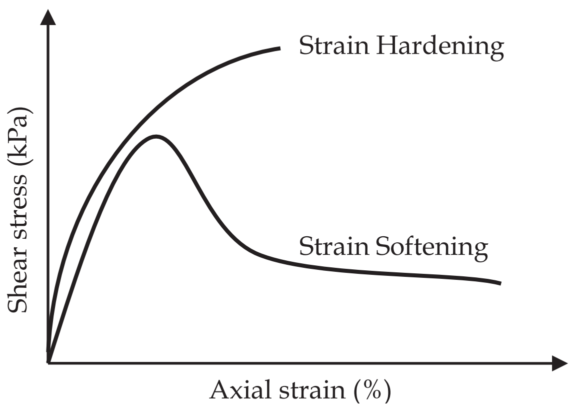


**Figure 15 – Comparison of Strain Hardening and Strain Softening Behaviour**

### 3.4.5 Shear Strength Parameters

After obtaining the shear stress values at the three different strain levels, failure envelopes were developed as illustrated in Figure 16. The effective shear strength parameters obtained for different strain levels for the same and separate samples are depicted in Table 2.

When the results obtained from two different sample preparation methods are compared, there is no significant variation between the shear strength parameters corresponding to relevant strain levels. As such, it can be concluded that the use of same sample to determine the shear strength parameters of MSW will not make any significant difference to the results. Accordingly, in this research study, same MSW sample at different normal stresses were used to determine the shear strength parameters.

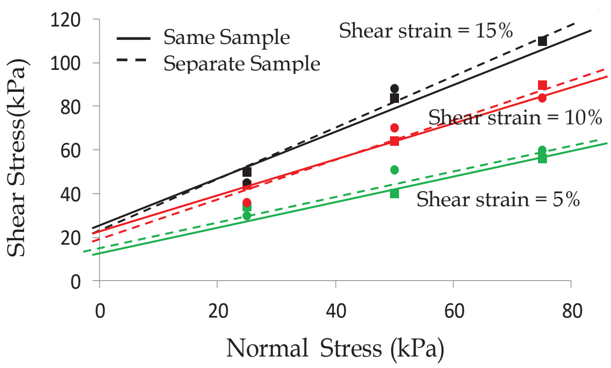


**Figure 16 – Failure Envelop at Different Strain Levels**

**Table 2 – Effective Shear Strength Parameters at Different Strain Levels (OMC- 6%; Moisture Content = 32 %) – Top Waste (Sample 1)**

| | Same sample | | | Separate samples | | |
|---|---|---|---|---|---|---|
| Strain level (%) | 5 | 10 | 15 | 5 | 10 | 15 |
| Cohesion $c'$ (kPa) | 16 | 20 | 23 | 17 | 18 | 21 |
| Friction angle $\phi'(^0)$ | 26 | 41 | 49 | 30 | 44 | 49 |

Based on the results presented in Figure 16, and Table 2, the lowest strength of MSW corresponds to the lower shear strain level of 5% whereas highest strength of MSW corresponds to the higher shear strain level of 15%. Grisolia et al. [16] reported that even at 20 - 30 % strain, the peak shear stress was not mobilized in MSW. As such, they presented the shear strength parameters as mobilize values. Vilar and Carvalho [17] presented that frictional resistance of MSW tends to fully mobilize when strain ≤ 20% while the cohesion started to mobilized when strain ≥ 10%. As such, many researchers [16], [17], [18] and [19] stated that shear strength parameters of MSW are strain dependent. Most of the MSW shear strength parameters reported in the literature correspond to the measured shear stress at displacement or strain at test termination [20]. As such, there is an incompatibility in the reported shear strength parameters of MSW.

Eid et al. [21] recommended to use 10% strain level to define the shear strength parameters, because these values are compatible with the stress-strain behaviour of interface between geosynthetics and foundation soil. Based on series of triaxial tests, Zekkos et al. [22] reported that better regression coefficients can be obtained when the failure criterion of 10% strain is used. This agrees well with the recommendations of Eid et al. [21]. Further, Zekkos et al. [22] reported that the use of 5% strain to determine the shear strength parameters appear to be more conservative for MSW slope stability analysis. The data presented in Table 2 illustrated that when strain of 15% is used to define the failure criterion, fiction angle of MSW appears to be significantly high. As such, 10% shear strain was used to define the failure criterion in this research study. A summary of the shear strength parameters of MSW with respect to moisture content, obtained based on 10% strain criterion, is illustrated in Table 3.

The variation of friction angle and cohesion of MSW over moisture content is illustrated in Figure 17 and Figure 18, respectively. It can be clearly seen that minimum friction angle was achieved at the optimum moisture content of the MSW. Conversely, maximum cohesion occurred on the dry side of optimum, which is slightly less than the optimum moisture content. Similar trend of shear strength parameters over moisture content were reported by Balasooriya et al. [5] for MSW samples collected from the dry zone of Sri Lanka.

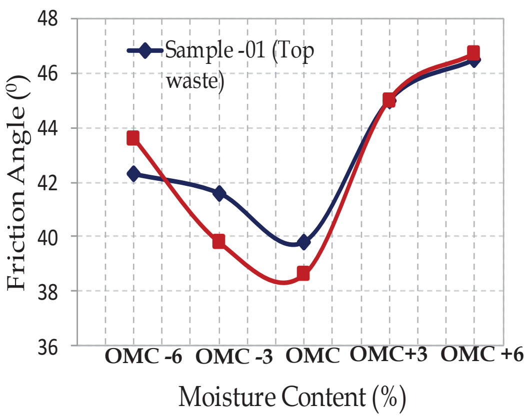


**Figure 17 – Variation of Friction Angle Over Moisture Content**

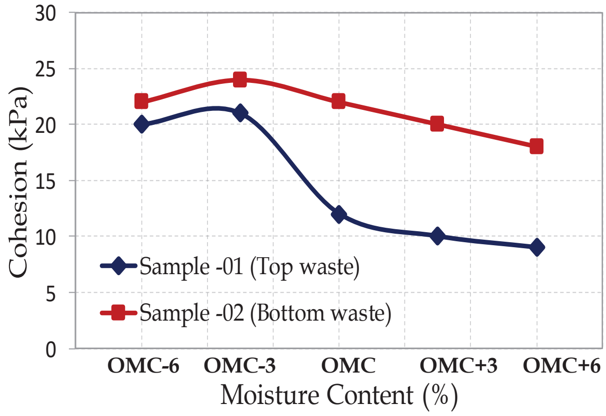


**Figure 18 – Variation of Cohesion over Moisture Content**

Based on 181 shear strength data sets, Jaime et al. [23] presented the overall range of cohesion and friction angle of MSW to be 0 – 108 kPa and $5^0$-$53^0$, respectively, reflecting significant dispersion. These data represent two regions according to Singh and Murphy [24] and Sanchez-Alciturri et al. [25], as depicted in Figure 19.

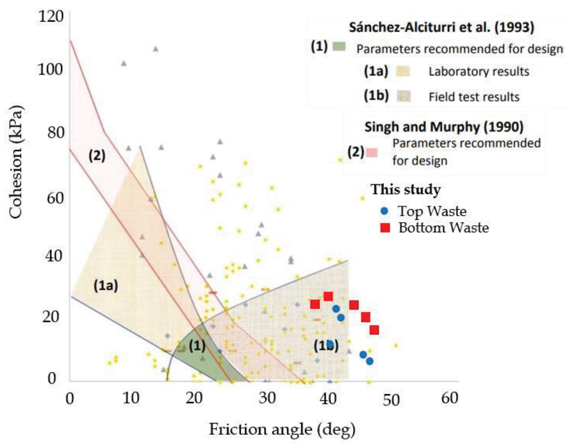


**Figure 19 – Relationship Between Cohesion and Friction Angle (after Jaime et al., 2016)**

**Table 3 – Shear Strength Parameters of MSW**

| Moisture Content (%) | Sample – 01 (Top waste) | | Sample – 04 (Bottom waste) | |
|---|---|---|---|---|
| | Cohesion $c'$ (kPa) | Friction Angle $\phi'$ ($^0$) | Cohesion $c'$ (kPa) | Friction Angle $\phi'$ ($^0$) |
| OMC - 6 | 20 | 42.3 | 22 | 43.6 |
| OMC - 3 | 21 | 41.6 | 24 | 39.8 |
| OMC | 12 | 39.8 | 22 | 38.6 |
| OMC + 3 | 10 | 45.0 | 20 | 45.0 |
| OMC +6 | 9 | 46.5 | 18 | 46.7 |

The shear strength parameters obtained from this study are also indicated in Figure 19. It is very clear that all the test data presented in this study are within the field test results region according to Sanchez- Alciturri et al. [25]. However, none of the test data are within the region proposed by Singh and Murphy [24]. By analysing the shear strength parameters obtained in this research study and literature, they can be considered as statistically independent; there is no direct correlation between cohesion and friction angle.

Jaime et al. [23] reported that the mean cohesion of MSW is around 15 kPa based on the developed cohesion histogram while the mean friction angle of MSW is around $27^0$ based on the developed friction angle histogram. Even though cohesion of MSW in this research study well agrees with the findings of Jaime et al. [23], friction angle of MSW in this research study is well above the given average value. The main reason for this higher friction angle of MSW is the waste composition.

### 3.4.6 Effect of the Fabric on Shear Strength Parameters

Even though MSW in this study mainly consists of fine residue and aggregated soil, the main factor for higher friction angle is the presence of considerable amount of textile in MSW in the Meethotamulla dump site. It can be seen that 5 - 10% of textile exists within the MSW in the Meethotamulla dump site on weight basis. This implies, huge volume of textile exists within the MSW as unit weight of the textile is small. Same behaviour was reported by Yamawaki et al. [26] based on the field direct shear tests, where friction angle of MSW in illegal dump sites which contain considerable amount of fibrous materials in Japan was $46^0$-$51^0$. As such, it can be concluded that there is a tensile strength of MSW other than the shear strength. This is the main factor on the stability of most of the illegal open dump sites in the developing countries. According to the conventional slope stability analysis, most of the open dump sites are unstable. However, there is no collapse or even any displacements occurring in these dump sites.

The stability behaviour of these MSW open dump sites can be explained with respect to Figure 20. As illustrated in Figure 20, there is a tensile resistance caused by the fibrous materials across the slip surface, which enhance the stability against sliding. According to Perera [27], average tension at failure of fresh fabric is around 343 N(35 kg). Hence, due to the

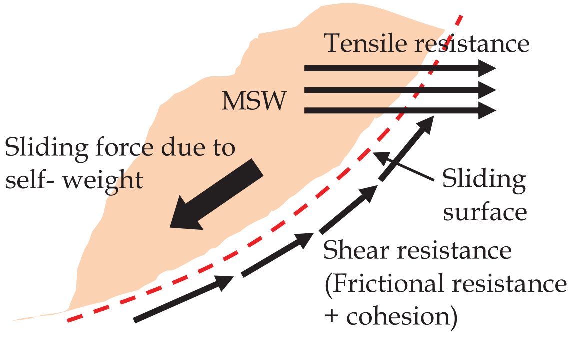


**Figure 20 – Failure Mechanism of MSW Dump Sites**

availability of higher textile composition in MSW, causes higher shear strength parameters.

### 3.4.7 Dilatancy Behaviour of MSW

The relationship between vertical displacement and shear strain of MSW under different normal stresses during the direct shear test is shown in Figure 21.

The expansion behaviour of MSW during shearing under higher normal stresses can be clearly seen. Due to presence of fibrous materials in MSW, stretched fibrous materials hold other materials up during shearing, and appear as an expansion As such, it can be concluded that, due to presence of textiles (fibrous materials), MSW illustrates dilatancy behaviour. The dilatancy angle of MSW in this research study is about $5^0$-$10^0$.

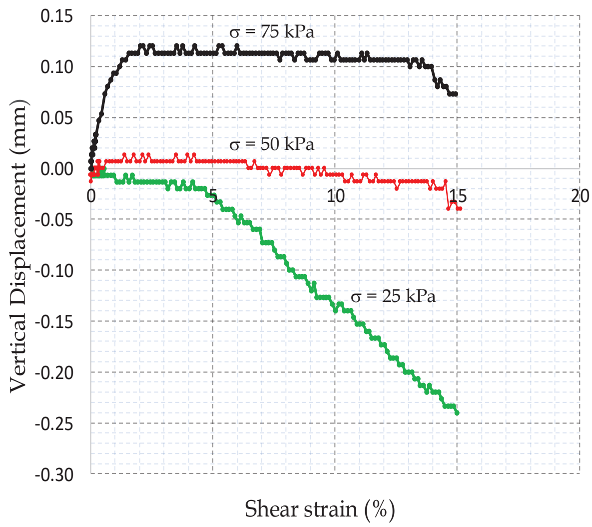


**Figure 21 – Vertical Displacement Versus Shear Strain – Sample 01 (Top waste): OMC – 6%**

To present this behaviour in detail, normalized shear stress with respect to normal stress (Stress Ratio = $\tau/\sigma$) was plotted against normalized vertical settlement with respect to shear displacement (Displacement Ratio = $h/\delta$) as depicted in Figure 22.

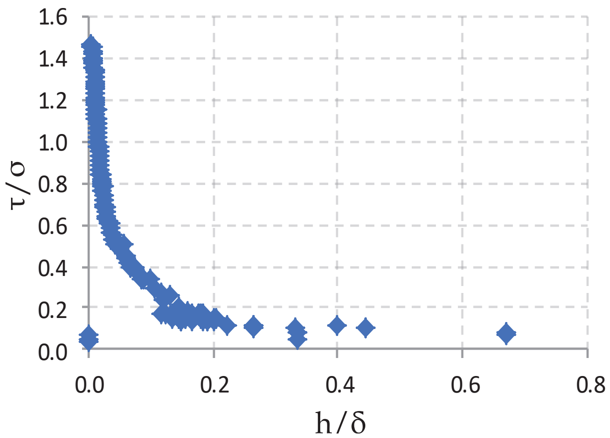

**Figure 22 – Dilatancy Characteristics of MSW**

It can be seen that deformation ratio decreases with increase of stress ratio. Further, it can be noted that at larger stress ranges, deformation ratio indicates a constant value. This implies that small deformation ratio is within the plastic range of MSW while elastic property becomes prominent at the large deformation ratios. As such, it can be concluded that, depending on the stretching behaviour of textiles (fibrous materials) during shearing, waste materials exhibit elastic and ductility characteristics.

## 4. Conclusions

The conclusions of this research study can be summarized as follows:

1. MSW in open dump sites in the wet zone of Sri Lanka mainly consists of fine residue, aggregated soil, polythene and textiles. Since cover soil is mixed with waste materials, more than 40% of the particles in MSW are larger than 63 mm. This phenomenon is very common for almost all the open dump sites in Colombo area.

2. According to the laboratory test results, it was noted that MSW samples consist of considerable amount of metallic concentration, as a result there is a possibility to contaminate the groundwater during the rainy season.

3. Since waste materials show the strain hardening behaviour, it is recommended to use 10% strain level to define the failure criterion.

4. Shear strength parameters vary with the moisture content under the same compaction. The minimum friction angle was achieved at the optimum moisture content of the MSW whereas maximum cohesion occurred in the dry side of optimum, near the optimum moisture content.

5. The average cohesion of the MSW in Meethotamulla dump site is about 15 kPa whereas average friction angle is about $43^0$. The higher friction angle of MSW is mainly due to the presence of textiles (fibrous materials) within the waste body.

6. The textiles in the MSW behave as reinforcements against sliding which enhance the stability.

7. Similar to dense sand, MSW in open dump sites shows the dilatancy behaviour due to presence of textiles in the waste body.

8. The slope stability of open dump sites is underestimated in the conventional geotechnical analysis. Hence, it is recommended to consider the influence of textiles (fibrous materials) in computing the stability of MSW.

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