Krishna R. Reddy,[1] Hiroshan Hettiarachchi,[2] Janardhanan Gangathulasi,[3]*
Jean E. Bogner,[4] and Thomas Lagier[5]

Geotechnical properties of synthetic municipal solid waste

ABSTRACT: This paper presents the results of laboratory investigation performed to determine the geotechnical properties of synthetic municipal solid waste (SMSW) simulating typical composition of municipal solid waste (MSW) generated in the United States. Initial characterization of SMSW was performed through the determination of particle size distribution, moisture content, and organic content. Hydraulic conductivity, compression ratio, and shear strength were studied for their variation and significance through replicate testing. Hydraulic conductivity ranged between 1.2 x 10^{-5} to 7.62 x 10^{-8} cm/s which is lower than that of field MSW, mainly due to the use of low-permeable glacial till soil to represent inert fraction of SMSW. Compression ratio ranged between 0.16 and 0.31 which is within the range reported for fresh MSW. Drained direct shear tests resulted in cohesion 16-19 kPa and friction angle 27-29°; these results are within the range reported in the literature for fresh MSW. Based on the results from triaxial consolidated undrained (CU) shear tests, SMSW exhibited cohesive behavior with 22 kPa cohesion and 7° friction angle as the total stress parameters. This study showed that the compressibility and direct shear behavior of SMSW tested during this research were similar to fresh MSW, but hydraulic conductivity and triaxial CU shear strength were different. Replicate testing and statistical analyses demonstrated that the test results did not vary significantly hence repeatability was assured.

KEYWORDS: Synthetic municipal solid waste, geotechnical properties, compressibility, hydraulic conductivity, shear strength, variability.

1. INTRODUCTION

Landfilling is found to be economical way of disposing municipal solid waste (MSW) compared to other waste management techniques such as incineration and composting. Although the waste management advocates recycling and reuse of the waste materials, many countries worldwide prefer landfilling of MSW as an economic option. About 54% of MSW generated in the United States is disposed in landfills (USEPA 2006). MSW typically consists of food waste, garden waste, paper products, plastics, textiles, wood, metals, construction demolition waste and soils. However, the composition of MSW varies from region to region and it depends upon the lifestyle, demographic features and legislation.

Integrity of landfills depends upon the geotechnical properties of the MSW and that in turn depend upon its specific composition. For instance, leachate flow in landfills, settlement and slope stability of landfills depend on the geotechnical properties such as hydraulic conductivity, compressibility and shear strength of the MSW. Geotechnical properties of MSW are difficult to determine because of the heterogeneity, wide variation in particle size distribution, and time dependent degradation. Geotechnical properties of MSW are determined through in-situ and laboratory tests and/or back analysis of field performance data. Published studies on properties of MSW are generally difficult to compare because of the difference in compositions, level of degradation and testing methods. In most cases, such specific information is often unavailable.

In order to evaluate the engineering properties of MSW, few previous studies have used synthetic MSW (SMSW) with selected components in specific proportions (Dixon et al.,

---

*Corresponding Author

[1] Professor, Department of Civil and Materials Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, Illinois 60607, USA; kreddy@uic.edu

[2] Assistant Professor, Department of Civil Engineering, Lawrence Technological University, 21000 West Ten Mile Road, Southfield, Michigan 48075, USA; hiroshan@ltu.edu

[3] Graduate Research Assistant, Department of Civil and Materials Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, Illinois 60607, USA; jganga2@uic.edu

[4] President, Landfills +, Inc., 1144 N. Wheaton, Illinois 60187, USA; jbogner@landfillsplus.com

[5] Veolia Environmental Services Research Center, Limay, France; Thomas.Lagier@veolia.com

International Journal of Geotechnical Engineering (2009) 3: (429-438)
DOI 10.3328/IJGE.2009.03.03.429-438

2008; Hettiarachchi 2005; Langer 2005; Landva et al., 1998; Chen and Chynoweth 1995). These studies focused on the mechanical behavior of the mixtures prepared from selected fresh products and utilized conventional geotechnical testing techniques. Complete control on composition and particle size and ability to identify the influence on properties from different components are among the advantages offered by SMSW, in the determination of geotechnical properties.

Based on the previous studies on SMSW, there is a need to systematically evaluate the reproducibility of test results for identical SMSW composition. This paper presents a laboratory study to investigate the engineering properties of SMSW that represents typical fresh MSW composition in the United States and to assess the variability of the properties through repeated testing. In addition, a comparison of engineering properties of SMSW from the current study and fresh MSW from published literature is also presented in this paper. To assess the repeatability of the tests, the results were subjected to a statistical analysis as per the procedures described by Montgomery et al. (2007). Mean, standard deviation, and coefficient of variation (COV) were calculated for all tests. To determine if the mean values from each set of samples were significantly different from the average of all the samples, one-way analysis of variance (ANOVA) was conducted on some tests.

2. PREPARATION AND CHARACTERIZATION OF SMSW

MSW in the United States is approximately 60% biodegradable and 40% non-biodegradable by weight as shown in Table 1. Biodegradable fraction consist of paper and paper board, food scraps, yard trimmings, wood and other materials, and nonbiodegradable fraction include metals, plastics, textiles, rubble, glass and miscellaneous inorganic waste. Table 2 shows the different types of materials and their proportions selected to prepare SMSW to simulate typical MSW in the United States. Glacial till was used to represent the non-biodegradable fraction (40%): metals, plastics, textiles, rubble, glass and miscellaneous inorganic materials. Biodegradable fraction (60%) was represented by selected fresh biodegradable material: grass; vegetables, ground beef, white wheat bread, and plain paper. The sizes of the components were selected so that they will not over influence the test results obtained from the conventional laboratory testing equipment. The preparation of SMSW involved weighing required amounts of fresh individual components and then mixing them in a large plastic container. Then deionized water of volume equal to 40% of SMSW (by total weight) was added to the container. Deionized water was selected in this study to simulate consistent liquid phase composition in waste samples. Components and water were mixed by hand until the moisture distribution and the material appeared homogeneous. Five sets of SMSW samples, with each weighing approximately 2.5 kg, were prepared at different time periods during the course of this study.

Figure 1 shows the particle size distribution of the SMSW obtained through sieve analysis conducted as per ASTM D422 (ASTM, 2007). Maximum particle size was 15–20 mm. Finer fraction (<0.075 mm) was approximately

Table 1. Typical composition of MSW in the United States (USEPA 2006).

MSW Components		% by Weight
Biodegradable	Paper and paper board	25.2
	Food scraps	17.1
	Yard trimmings	7.3
	Wood	7.6
	Other	2.0
	Total	**59.2**
Nonbiodegradable	Total Metals	7.1
	Plastics	16.4
	Rubber and Leather	3.4
	Textiles	5.7
	Glass	6.0
	Miscellaneous inorganic waste	2.2
	Total	**40.8**

Table 2. Composition of SMSW prepared for this study

Components		% by Weight	Material Used
Nonbiodegradable		40	Glacial till
Biodegradable	Garden Waste	20	Grass clippings (size less than 1 mm wide and 12 mm long)
	Vegetable Waste	10	Greens (approximately cut into 6.3 mm size)
	Meat	5	Ground beef
	Cellulose Non-paper Material	5	White wheat bread (size less than 7-10 mm)
	Paper Waste	20	Plain paper shredded (approximately less than 3 mm wide by 25 mm long)

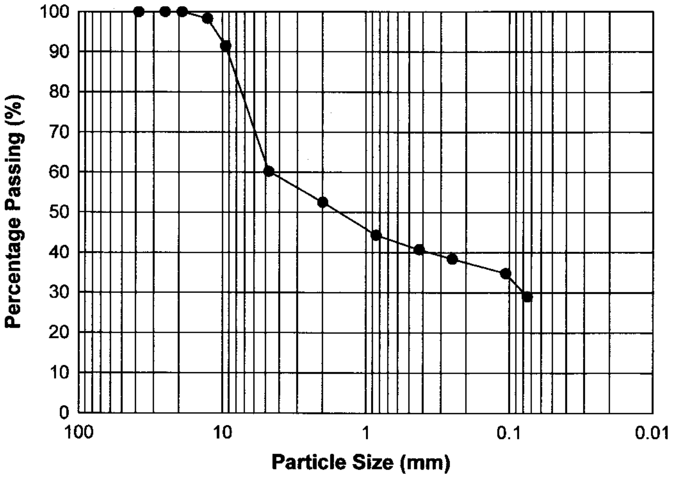

Figure 1. Particle size distribution of synthetic MSW

30%. Approximately 10% of the particles were greater than 10 mm and 50% of the particles were greater than 2 mm. With 90% of the particles having less than 10 mm diameter, the SMSW used in this research is not expected to over influence the test results obtained from the conventional testing equipment in a soil mechanics laboratory.

Moisture content of SMSW was determined in accordance with the standard procedure ASTM D2216 (ASTM, 2007). However, the temperature was maintained at 60°C to avoid combustion of volatile materials. Moisture contents measured were ranged from 93.9% to 145.1% on dry weight basis, equivalent to 48.4% to 59.2% on wet weight basis. This range agrees with the typical moisture content of the field fresh waste of 25% to 70% on wet basis reported in the literature (Landva and Clark 1990; Gomes et al 2005; Reddy et al. 2008). Based on the data of 24 specimens from five sets, the mean, standard deviation and COV of dry gravimetric moisture content were found to be 116%, 11.85 and 10.17%, respectively. ANOVA was applied to study whether there is any variability in the moisture content of five sets of samples. At 95% confidence level, critical value is 2.9 whereas the calculated value is 2.564, showing that there is no significant difference in the average moisture content of SMSW specimen obtained from different sets. Therefore, it can be stated that the method adopted to prepare SMSW has resulted in a reproducible uniform moisture distribution in the samples.

The organic content of the SMSW was measured as per ASTM D2974 (ASTM, 2007). SMSW was prepared to achieve a 60% organic content (Table 2). But tests conducted on 20 replicate samples from five sets resulted in organic content varying from 50.9% to 63.8% with an average value of 55.9% and standard deviation of 3.04%. To ensure all the samples represent fresh SMSW, statistical variation of the 20 samples of five sets was conducted. COV for the tested samples was 5.44% and it clearly shows there was not much variation in the tested values. Significance among mean value of five sets was determined using ANOVA. At 95% confidence level, calculated value was found to be lower than the critical value and hence it can be stated there is no significant difference in the average organic content.

3. GEOTECHNICAL TESTING

SMSW was tested for hydraulic conductivity, compressibility and shear strength properties. In order to determine the variability in the test results, several replicate samples were tested. Five sets of results were available for hydraulic conductivity and compression ratio. Triplicate test results were available for direct shear and triaxial shear tests.

3.1 Hydraulic Conductivity Testing

Flexible wall permeameter was used to measure the hydraulic conductivity of SMSW in general accordance with ASTM D5084 (ASTM, 2007). SMSW was compacted in a cylindrical mold of diameter 50 mm and height 100 mm, using a tamper to achieve the target initial wet unit weight of 10.7 to 13.7 kN/m^3. Each specimen was then extruded and encased in a latex membrane before placing in the triaxial cell. Sample was first saturated by applying an initial confining pressure of 35 kPa and flushing deionized water under a constant hydraulic gradient. SMSW samples were tested at confining pressures 69, 138 and 276 kPa. Rigid-wall permeameter tests were also conducted on the waste samples in accordance with ASTM D2434 (ASTM, 2007) to provide hydraulic conductivity under no confining pressure conditions.

3.2 Compressibility Testing

Compressibility of SMSW was tested in general accordance with ASTM D2435 (ASTM, 2007). The oedometer used in this study was floating ring type with a 63 mm diameter - 25 mm thick circular brass ring. SMSW specimen was compacted in layers with the tamper to achieve initial wet unit weight ranging from 7.8-11.8 kN/m^3. The specimen was placed in the brass ring with one porous stone on the top and another one at the bottom of the sample. The specimen was subjected to a constant vertical stress range of 48-766 kPa.

3.3 Drained Direct Shear Testing

Drained shear strength properties of the SMSW were determined by performing direct shear testing as per ASTM D3080 (ASTM, 2007). For this testing, SMSW was compacted into a circular shear box with 63 mm inside diameter and 34 mm depth. SMSW specimens were tested under different normal

Table 3. Hydraulic conductivity of SMSW and fresh MSW

Source	Unit weight (kN/m³)	Hydraulic conductivity (cm/s)
Current research (50 mm diameter and 100mm height sample, flexiwall test, SMSW particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm)	4.7 – 6.0	1.20 x 10^{-5} to 7.62 x 10^{-8}
Reddy et al. (2008) (50 mm diameter and 100 mm height sample, flexiwall test and 63 mm diameter and 100 mm height rigid wall test with shredded fresh MSW, maximum particle size 40 mm)	5.78 – 10.0	10^{-4} to 10^{-8}
Powrie and Beaven (1999) (2000 mm diameter and 2500 mm height Pitsea compression cell, constant head test, unshredded fresh MSW collected from tipping face of a landfill)	3.8 – 7.1	3.7 x 10^{-6} to 1.5 x 10^{-2}
Landva et al. (1998) (440 mm diameter, constant head, SMSW)	8.6 - 9.5	3 x 10^{-6} to 3 x 10^{-5}
Chen and Chynoweth (1995) (375 mm diameter and 1220 mm height column, constant head test, nominal size of particle 12.7mm, SMSW consisted paper, plastics and yard waste)	1.5 – 4.7 (dry)	2.3 x 10^{-5} to 2.5 x 10^{-1}
Korfiatis et al. (1984) (constant head permeameter, unprocessed six months old MSW)	–	8.0 x 10^{-3} to 1.3 x 10^{-2}

stress conditions. Initial wet unit weight of SMSW ranged from 7.35 to 12.75 kN/m³ with a moisture content 54% on dry basis (35% on wet basis). Porous stones were placed on the top and the bottom of the sample. Pre-selected constant vertical stress was applied to the sample and then sheared at a constant strain rate of 0.035 mm/min.

3.4 Consolidated Undrained (CU) Triaxial Testing

CU triaxial testing was conducted in accordance with ASTM D4767 (ASTM, 2007). Three identical SMSW specimens with a 50 mm diameter and 100 mm height with initial wet unit weight ranging from 10.8 to 13.7 kN/m³ were tested. All specimens were initially subjected to confining pressure of 35 kPa and back pressure of 21 kPa. The specimen were then consolidated under different effective confining pressures of 69, 138, and 276 kPa and the total volume change was measured by amount of outflow for over 24 hours. Waste samples were finally subjected to shear under undrained condition. Shearing was done at a constant strain rate of 2.1 mm/min, to ensure approximate equalization of pore pressures throughout the specimen.

4. RESULTS AND DISCUSSION

4.1 Hydraulic Conductivity

Hydraulic conductivity of SMSW tested in this research ranged from 1.20 x 10^{-5} to 7.62 x 10^{-8} cm/s (Table 3). Even though the dry unit weight of SMSW did not vary in a wide range (4.7 – 6.0 kN/m³), the hydraulic conductivity varied by as much as three orders of magnitude. Variation of these values with dry unit weight is compared in Figure 2 with the other laboratory measured hydraulic conductivity values of SMSW and fresh MSW reported in literature. The hydraulic conductivity determined in this research is among the lowest found in Table 3 and Figure 2. It may be attributed to the

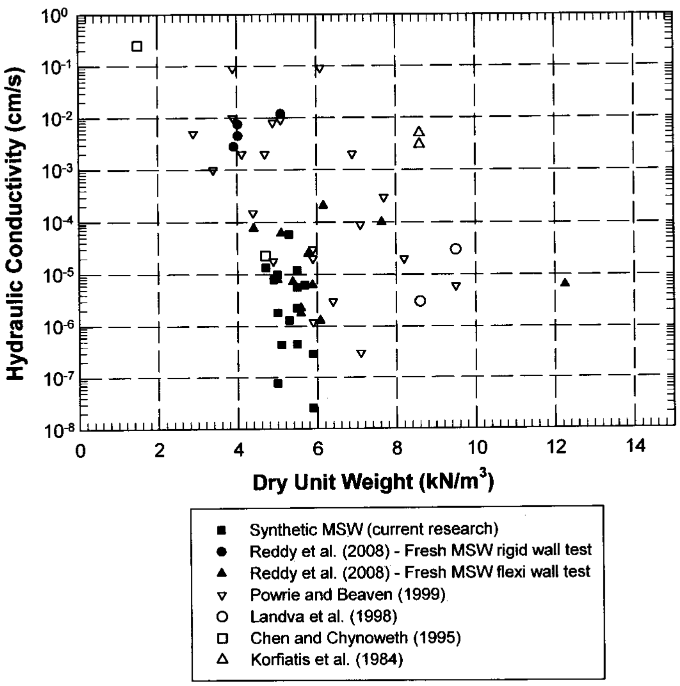

Figure 2. Hydraulic conductivity of synthetic MSW and field MSW

presence of 40% glacial till, which is a low permeable material. No particular trend was observed between the hydraulic conductivity and the particle size distribution of the SMSW or fresh MSW considered in this comparison.

To determine the variation in hydraulic conductivity among the five sets of SMSW samples, mean, standard deviation and COV were determined. COV of the 15 samples was found to be 17.7% with a mean of 8.0 x 10^{-6} cm/s and a standard deviation of 1.4 x 10^{-6} cm/s. ANOVA testing was performed for the five sets of samples tested. At 95% confidence level critical value was less than the calculated value, showing a significant difference between the average values of the samples. Observed variation was significant due to the change in density of the samples.

4.2 Compression Ratio

Compressibility tests were performed on samples with density of 8.9 – 11.7 kN/m^3 and moisture content of 51.7% to 63.3% on wet weight basis (107% to 172% on dry weight basis). Compression ratio (slope of the strain vs. log pressure curve) calculated from this study are summarized in Figure 3 and Table 4. Compression ratio of the SMSW varied in the range of 0.16 to 0.31. Initial compression of the SMSW upon the first loading of 96 kPa varied from 3% to 15% whereas the final total compression under pressure of 766 kPa was in the range of 29% to 33%. These differences can be attributed due to variation in initial density and moisture content of the tested samples. Repeatability of the test results was assessed by performing tests on five replicate specimens. Average, standard deviation and COV of compression ratio were found to be 0.22, 0.05 and 25.17%, respectively.

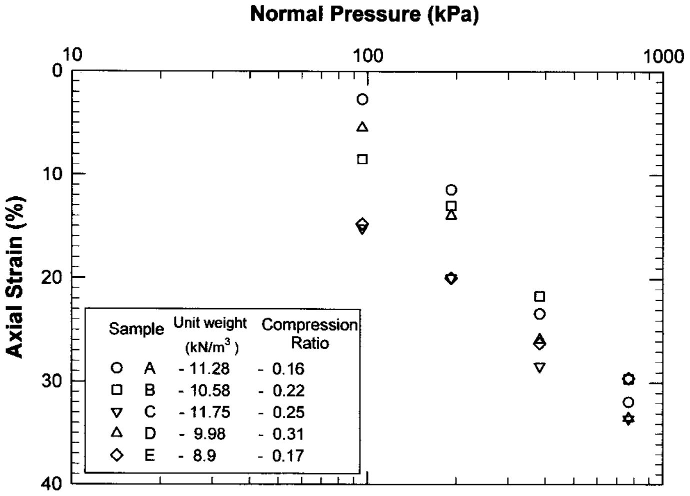

Figure 3. Variation of compressibility of synthetic MSW

As shown in Table 4, compression ratio of SMSW ranged from 0.18 to 0.35 in published studies (Dixon et al. 2008; Hettiarachchi 2005; Langer 2005). In a recent study by the authors, compression ratio of shredded fresh MSW was found to vary from 0.24 to 0.33 with total compression between 46% and 58% under a maximum pressure of 766 kPa

Table 4. Compressibility of SMSW and fresh MSW

Source	Compression Ratio
Current research (63 mm diameter oedometer test, SMSW particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm)	0.16 – 0.31
Reddy et al. (2008) (63 mm diameter oedometer test, shredded fresh MSW, maximum particle size 40 mm)	0.24 – 0.33
Dixon et al. (2008) (Large scale test of size 500 x 500 x 750 mm, SMSW, maximum particle size 120 – 500mm)	0.30
Hettiarachchi (2005) (63 mm Teflon cell, SMSW, maximum particle size approximately 5mm)	0.18 – 0.21
Langer (2005) (0.5 x 0.5 x 0.75 m compression box, shredded SMSW control samples, maximum particle size 10 mm x 40 mm)	0.30
Hossain (2002) (63.5 mm diameter Oedometer tests, shredded relatively fresh MSW in control samples, maximum particle size 120 – 500 mm, majority was 40 – 120 mm)	0.16 – 0.25
Wall and Zeiss (1995) (570 mm diameter cell, shredded fresh MSW, maximum size 4.7 cm)	0.21 – 0.25
Landva and Clark (1990) (470 mm diameter consolidometer, shredded fresh MSW samples from Edmonton, Canada)	0.35

(Reddy et al. 2008). From the studies compared in Table 4, no significant difference or any particular trend in the compression ratio is observed in spite of different specimen size and/or particle size. Compression ratio of SMSW determined in the current research is approximately within the range of values reported in the published literature. As a general trend, the total compression of the SMSW was less than that of fresh MSW.

4.3 Drained Shear Strength Properties

Figure 4 shows the horizontal displacement versus shear stress response obtained from three sets of experiments conducted on SMSW. The initial moisture content of the specimen ranged from 44% to 61% with an average of 47% based on wet weight (79% to 156% with an average of 89% based on dry weight) and bulk unit weight ranged from 8.7 kN/m^3 to 11.1 kN/m^3 (average unit weight of 10.32 kN/m^3). Similar to what has been observed for MSW in previous research during drained direct shear testing (Reddy et al. 2008; Dixon et al. 2008; Hossain 2002; Jones et al. 1997), SMSW exhibited continuous strength gain with increase in horizontal deformation. In the absence of samples reaching any peak strength, it is common in geotechnical testing to assume 10 to 20% strain level as a failure condition. In this research shear stress at 15% horizontal deformation was selected to determine the shear strength parameters.

Cohesion of SMSW varied from 16 to 19 kPa and the friction angle varied from 27 to 29° (Figure 5). Combined data from all triplicates resulted in cohesion of 18 kPa and friction angle of 28°. Based on the statistical analysis of results from three sets of samples, average, standard deviation and COV of cohesion and friction angle were 17.43 kPa, 1.27 kPa and 7.27% and 28.34°, 0.52° and 1.81%, respectively. Low values of COV for cohesion and friction angle from the direct shear test results indicates that the values did not differ significantly, hence assures reproducibility of test results.

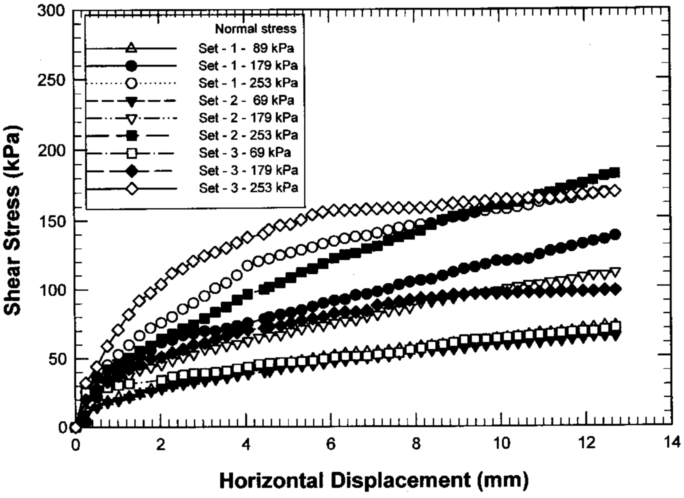

Figure 4. Shear stress vs horizontal displacement for SMSW

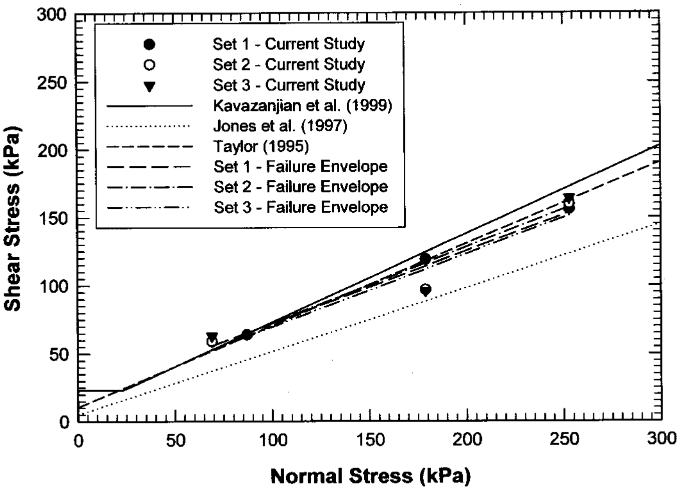

Figure 5. Shear strength failure envelopes for SMSW and field MSW

Table 5 compares the results from this study with the direct shear strength properties of fresh MSW and SMSW reported in the literature. The friction angles determined in this study falls within the range reported for the fresh MSW, whereas cohesion values were less than the values reported in the literature. Although SMSW samples had 40% glacial till, the overall composite behavior was frictional in nature, perhaps due to the presence of 40% reinforcing material (paper and grass). In the case of fresh MSW, cohesion varies from 10.5-78 kPa and the friction angle is 23-34° (Reddy et al. 2008; Hossain 2002; Caicedo et al. 2002; Kavazanjian et al. 1999; Jones et al. 1997; Landva and Clark 1990). Shear strength tests conducted on fresh MSW in large scale direct shear testing machines has yielded friction angle between 23 and 32° and cohesion between 10.5 and 78 kPa (Caicedo et al. 2002; Kavazanjian et al. 1999; Jones et al. 1997; Landva and Clark 1990). Figure 5 shows that the shear strength curve of the SMSW lies within the failure envelopes reported in the literature (Kavazanjian 1999; Jones et al. 1997).

4.4 Triaxial CU Shear Strength Properties

Many have observed strain hardening behavior (continuous increase in the deviator stress without exhibiting any peak or failure) during triaxial tests on both fresh and aged MSW (Jessenberger and Kockel 1993; Gabr and Valero 1995; Grisolia et al. 1995; Kavazanjian 2001; Caicedo et al. 2002; Vilar and Carvalho 2004). Therefore, the shear strength prop-

Table 5. Drained shear strength properties of SMSW and fresh MSW

Source	Friction Angle (degrees)	Cohesion (kPa)
Current research (63.5 mm diameter shear box, SMSW particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm, shear strength defined at 15% strain)	27-29	16 – 19
Reddy et al. (2008) (63.5 mm diameter shear box, shredded fresh MSW, maximum particle size 40 mm, shear strength defined at 15% strain)	26-30	31-64
Dixon et al. (2008) (1.0 x 1.0 m shear box, SMSW, maximum particle size 120–500 mm, shear strength defined at 240 -260 mm)	34	0
Hossain (2002) (100 mm diameter shear box, Shredded field MSW, maximum particle size 50 mm)	24-32	–
Caicedo et al. (2002) (900 mm diameter sample, 1 year old unshredded MSW, shear strength defined at 6.7% strain)	23	78
Taylor (1995), Jones et al. (1997) (Wykeham 300 mm×300 mm shear apparatus, disturbed bulk sample, large particles were removed, 3 months old MSW, shear strength defined at 10% stress)	31	10.5
Landva and Clark (1990) (434 mm×287 mm sample dimensions, shredded fresh MSW from Edmonton, Canada, shear strength defined at peak stress)	24	23

erties of MSW are believed to be strain dependent. A similar behavior was observed during the triaxial CU tests conducted on SMSW during this research. Samples were sheared to the maximum axial strain in excess of 30% as there was no peak shear response observed. To compare the results with direct shear test results, shear strength parameters were defined at 15% strain in this study (Figure 6). Table 6 summarizes the shear strength parameters obtained from triaxial tests.

Figure 6 shows the characteristic stress-strain behavior observed during CU triaxial tests conducted on saturated SMSW. Since pore water pressures were not measured during the shearing, the shear strength parameters from CU tests represent the total strength parameters (TSP). Variation of shear strength parameters was studied through replicate testing under CU conditions. During CU tests, cohesion varied between 19 and 23 kPa and friction angle varied from 6° to 8°. The results from CU tests are also included in Figure 7 to compare with the results from the direct shear tests and other types of triaxial tests. In general, the angle of friction resulted by CU tests on SMSW were approximately 50% of those found from direct shear testing. Based on the statistical analysis of results from five sets of samples, average, standard deviation and COV of cohesion and friction angle were 21.6 kPa, 1.8 kPa and 8.7% and 7.0°, 0.82° and 11.66%, respectively.

Triaxial shear strength properties obtained for SMSW during this research are compared with the shear strength of fresh MSW reported in other studies (Table 6). Shredded fresh MSW tested using the same testing procedures and same sample dimensions yielded average (total strength parameters), cohesion of 32 kPa and friction angle of 12° (Reddy et al. 2008). Values obtained from the SMSW through CU testing produced cohesion within the range of the values obtained from the fresh MSW, where as friction angle was lower. Differences in the structure and size of the particles

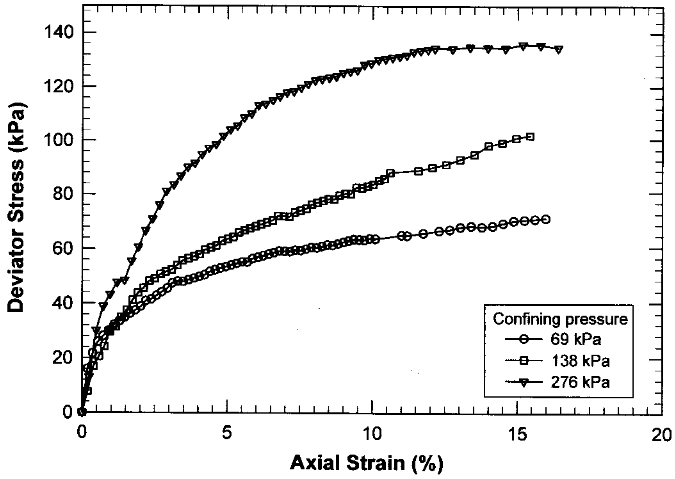

Figure 6. Axial strain vs deviatoric stress during CU testing on SMSW

Table 6. Triaxial consolidated undrained (CU) shear strength properties of SMSW and fresh MSW

Source	Friction Angle (degrees)	Cohesion (kPa)
Current research (50 mm diameter 100 mm height sample, SMSW particles were of average size 1.5 mm, 10% particles were greater than 10 mm and 35% particles were finer than 0.1 mm shear strength defined at 15% strain)	6-8 (TSP)	19-23 (TSP)
Reddy et al. (2008) – CU test (50 mm diameter 100 mm height sample, Shredded field fresh MSW, maximum particle size 15 - 20 mm, shear strength defined at 15% strain)	12 (TSP) 16 (ESP)	32 (TSP) 38 (ESP)
Caicedo et al. (2002) – CU test (1 year old unshredded MSW, sample dimensions: diameter 300 mm, height 600 mm, shear strength defined at 15% strain)	45 (ESP)	14 (ESP)

TSP = Total stress parameters; ESP = Effective stress parameters

could be the reason for this lower friction angle of SMSW. The effective angle of friction (14°) and effective cohesion (45 kPa) reported by Caicedo et al. (2002) for relatively fresh MSW from Dona Juana landfill is slightly higher than what was found for SMSW, which may be due to the higher percent of organic matter in the MSW from Don Juana landfill. Figure 7 shows the friction and cohesion values of SMSW with the values reported in the literature. The cohesion value of SMSW was in range with the values reported in literature, whereas the friction angle was relatively lower. In general, the shear strength behavior of SMSW tested in this research was highly cohesive in nature compared to typical fresh MSW.

5. SUMMARY AND CONCLUSIONS

During this research the geotechnical properties of SMSW representing the composition of MSW in the United States were determined through laboratory testing and the test results were compared with the relevant published studies. Variability of the tests results was also studied by testing replicate samples. Approximately 40% of the particles in the SMSW samples used in this research was in the range between 2 to10 mm and the maximum particle size was limited to 15 to 20 mm. Finer fractions with size less than 0.075 mm was approximately 30%. Initial moisture content of the SMSW was in the range from 49% to 59% on wet basis and organic content varied from 51% to 64%.

Hydraulic conductivity of SMSW samples ranged from 1.20 x 10^{-5} to 7.62 x 10^{-8} cm/s. Due to the presence of 40% fines, hydraulic conductivity of the SMSW was lower than reported hydraulic conductivity of field and SMSW in the literature. Compression ratio of the SMSW varied from 0.16 to 0.31 and was in agreement with reported compression ratio values of the field and SMSW. Drained cohesion of SMSW varied from 16-19 kPa and the drained friction angle ranged from 27-29° at higher moisture content and exhibited increase in cohesion with decrease in moisture content. Results from direct shear testing shows the SMSW replicates field fresh MSW frictional behavior, whereas cohesion parameter was far less than the reported values. Composite behavior of the material was frictional in nature similar to field MSW. The average total strength parameters (TSP) from triaxial consolidated undrained tests were found to be 22 kPa and 7°. The angle of friction resulted by CU tests on SMSW are approximately 50% of what was produced by the

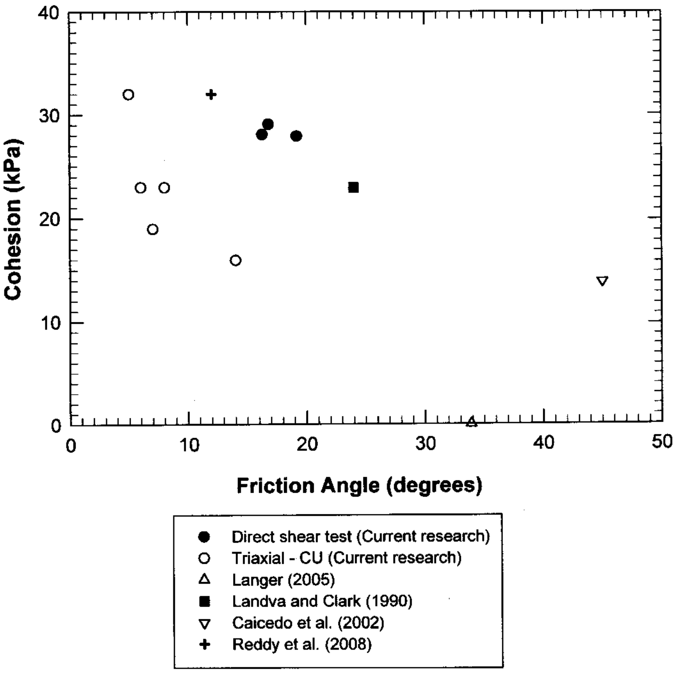

Figure 7. Distribution of shear strength parameters for SMSW and fresh MSW (CU- triaxial consolidated undrained test)

direct shear tests. In the case of triaxial shear testing SMSW exhibited cohesive behavior rather than frictional behavior. Overall, compressibility and direct shear behavior of SMSW replicated fresh MSW; triaxial testing yielded lower shear strength of SMSW than that of field MSW.

During this study, reproducibility of test results was also investigated by replicate testing of SMSW samples. Based on COV and ANOVA, the moisture content and the organic content did not vary significantly hence repeatability was assured. In the case of hydraulic conductivity variation was observed due to the differences in the unit weight. Compressibility testing also produced a behavior similar to the fresh MSW and COV was within the acceptable limit, and the variation was possibly due to the difference in initial unit weight. Reproducibility of results was also assured in direct shear and triaxial CU testing.

ACKNOWLEDGEMENTS

This project was funded by Veolia Environmental Services Research Center and the U.S. National Science Foundation (CMMI #0600441).

REFERENCES

ASTM (American Society of Testing and Materials). (2007). Annual Book of Standards, West Conshohocken, PA.

Caicedo, B., Yamin, L., Giraldo, E., and Coronado, O. (2002). "Geomechanical properties of municipal solid waste in Dona Juana sanitary landfill," *Proc. of Int. Conf. Environmental Geotechnics (4th ICEG)*, Lisse, The Netherlands, 177-182.

Chen, T., and Chynoweth, D.P. (1995). "Hydraulic conductivity of compacted municipal solid waste." *Bioresour. Technol.*, 51(2-3), 205-212.

Dixon, N., Langer, U., and Gotteland, P. (2008). "Classification and mechanical behavior relationships for Municipal Solid Waste: study using synthetic waste." *J. Geotech. Geoenviron. Eng.*, ASCE, 134 (1), 79-90.

Gabr, M.A., and Valero, S.N. (1995). "Geotechnical properties of municipal solid waste." *Geotechnical Testing Journal*, ASTM, 18(2), 241-251.

Gomes, C., Lopes. M.L., and Lopes, M.G. (2005). "A study of MSW properties of a Portuguese landfill." *Proc., of Int'l workshop on Hydro-Physico Mechanics of landfills*, LIRIGM, France.

Grisolia, M., Napoleoni, Q., and Tangredi, G., (1995). "The use of triaxial tests for the mechanical characterization of municipal solid waste," *Proc., Sardinia '95, Fifth International Landfill Symposium*, Cagliari, Italy, V.2, 761-767.

Hettiarachchi, C.H. (2005). "Mechanics of biocell Landfill settlement." *Dissertation*, Doctor of Philosophy, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, USA

Hossain, M.S. (2002). "Mechanics of Compressibility and Strength of Solid Waste in Bioreactor Landfills" *Dissertation*, Doctor of Philosophy, Department of Civil Engineering, North Carolina State University at Raleigh, USA.

Jessberger, H. L., and Kockel, R. (1993). "Determination and Assessment of the Mechanical Properties of Waste Materials." *Proc., Sardinia '93, Fourth International Landfill Symposium*, S. Margherita di Pula, Cagliari, Italy, 1383-1392.

Jones, D.R.V., Taylor, D.P., and Dixon, N. (1997). "Shear strength of waste and its use in landfill stability." *Proc. Geoenvironmental Engineering conference*, Thomas Telford, 343-350.

Kavazanjian, E. (1999). "Seismic Design of Solid Waste Containment Facilities", *Proc. of the Eight Canadian Conference on Earthquake Engineering*, Vancouver, BC, 51-89.

Kavazanjian, E., (2001). "Mechanical Properties of Municipal Solid Waste," *Proc., Sardinia '2001, Eighth International Landfill Symposium*, S. Margherita di Pula, Cagliari, Italy, V.3, 415-424.

Korfiatis, G.P., Demetracopoulos, A.C., Bourodimos, E.L., and Nawy, E.G. (1984). "Moisture transport in a solid waste column." *J. Envi. Eng., ASCE*, 110 (4), 780-796.

Landva, A.O., Pelkey, S.G., and Valsangkar, A.J., (1998). "Coefficient of permeability of municipal refuse." Proc., of the Third International Congress on Environmental Geotechnics, Lisboa, Portugal, A.A.Balkema, V.1, 63-67.

Landva.A.O and Clark.J.I (1990), "Geotechnics of waste fill", *Geotechnics of waste fills—theory and practice, ASTM* STP 1070, Philadelphia, 86-113.

Langer, U. (2005). "Shear and compression behaviour of undegraded municipal solid waste." *Dissertation*, Doctor of Philosophy, Loughborough University.

Montgomery, C.D., Ronger, G.C., and Hubele, N.F. (2007). *Engineering Statistics, Fourth Edition*, John Wiley & Sons, Inc.

Powrie, W. and Beaven, R.P. (1999). "Hydraulic Properties of Household Waste and Applications for Landfills." *Proc. Institution of Civil Engineers, Geotechnical Engineering*, 137, 235-247.

Reddy, K.R., Hettiarachchi, H., Parakalla, N.S., Gangathulasi, J., and Bogner, J.E. (2008). "Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill." *Waste Management Journal,* In Print.

Taylor, D.P. (1995). "Strength testing of domestic waste by plate bearing and shear box tests" *MSc. Dissertation,* University of Durham School of Engineering.

USEPA (2006). "Municipal Solid Waste in the United States: 2005 Facts and Figures," <www.epa.gov>.

Vilar, O. and Carvalho, M. (2004). "Mechanical Properties of Municipal Solid Waste," *ASTM Journal of Testing and Evaluation,* 32 (6),1-12.

Wall, D.K., and Zeiss, C. (1995). "Municipal landfill biodegradation and settlement." *J. Envi. Eng.,* ASCE, 121(3), 214-224.