Waste Management 29 (2009) 952–959

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA

Krishna R. Reddy[a,*], Hiroshan Hettiarachchi[b], Naveen S. Parakalla[a], Janardhanan Gangathulasi[a], Jean E. Bogner[c]

[a] Department of Civil and Materials Engineering, University of Illinois at Chicago, 842 West Taylor Street, Chicago, IL 60607, USA
[b] Department of Civil Engineering, Lawrence Technological University, 21000 West Ten Mile Road, Southfield, MI 48075, USA
[c] Landfills +, Inc., 1144 N. Wheaton, IL 60187, USA

ARTICLE INFO

Article history:
Accepted 21 May 2008
Available online 23 September 2008

ABSTRACT

This paper presents the results of a laboratory investigation to determine the geotechnical properties of fresh municipal solid waste (MSW) collected from the working phase of Orchard Hills Landfill located in Davis Junction (Illinois, USA). Laboratory testing was conducted on shredded MSW to determine the compaction, hydraulic conductivity, compressibility, and shear strength properties at in-situ gravimetric moisture content of 44%. In addition, the effect of increased moisture content during leachate recirculation on compressibility and shear strength of MSW was also investigated by testing samples with variable gravimetric moisture contents ranging from 44% to 100%. Based on Standard Proctor tests, a maximum dry density of 420 kg/m^3 was observed at 70% optimum moisture content. The hydraulic conductivity varied in a wide range of 10^{-8}–10^{-4} m/s and decreased with increase in dry density. Compression ratio values varied in a close range of 0.24–0.33 with no specific trend with the increase in moisture content. Based on direct shear tests, drained cohesion varied from 31 to 64 kPa and the drained friction angle ranged from 26 to 30°. Neither cohesion nor friction angle demonstrated any correlation with the moisture content, within the range of moisture contents tested. The consolidated undrained triaxial shear tests on saturated MSW showed the total strength parameters (c and φ) to be 32 kPa and 12°, and the effective strength parameters (c' and φ') to be 38 kPa and 16°. The angle of friction (φ) decreased and cohesion (c) value increased with the increase in strain. The effective cohesion (c') increased with increase in strain; however, the effective angle of friction (φ') decreased first and then increased with the increase in strain. Such strain-dependent shear strength properties should be properly accounted in the stability analysis of bioreactor landfills.

1. Introduction

For many countries, engineered landfilling continues to be an affordable and environmentally acceptable method of solid waste disposal. In the United States, approximately 54% of the waste is being landfilled (USEPA, 2007). In recent years, there has been a shift in philosophy of landfill design from the dry storage concept towards the bioreactor approach. In the bioreactor approach, the moisture content of the municipal solid waste (MSW) is increased by recirculation of leachate to enhance biodegradation of MSW. In addition to more rapid degradation, bioreactor landfills offer a significant reduction in post-closure management time (Reddy and Bogner, 2003).

The geotechnical properties of MSW are of prime importance for the design and maintenance of any type of landfill. However, bioreactor landfills have added new challenges for design engineers and operators. Recirculation of leachate in bioreactor landfills enhances the degradation of MSW, but at the same time the additional moisture raises stability concerns (Koerner and Soong, 2000; Reddy and Bogner, 2003). Stability may be impacted by increased unit weight of MSW and potential increase in pore water pressure build-up within the landfill. The decreased hydraulic conductivity of MSW resulting from heavy compaction may hinder the leachate recirculation process. Therefore, variation in hydraulic conductivity with compacted density of MSW is also an important consideration in the design of leachate recirculation system design. Landfill settlement is another important aspect of bioreactor landfills, which is typically estimated using the compressibility characteristics of the MSW. However, it is not well understood how the compressibility of MSW is affected by dynamic changes in moisture content within the landfill.

Settlement and stability are believed to be affected by the degradation of MSW. Stability of fresh MSW during the initial leachate recirculation operations is critical due to increased pore water pressures and rapid degradation rate. Rapidly settling MSW during the initial stages of operation of a bioreactor landfill may damage landfill infrastructure components such as leachate recirculation

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* Corresponding author. Tel.: +1 312 996 4755; fax: +1 312 996 2426.
E-mail addresses: kreddy@uic.edu (K.R. Reddy), hiroshan@ltu.edu (H. Hettiarachchi), nparak2@uic.edu (N.S. Parakalla), jganga2@uic.edu (J. Gangathulasi), jbogner@landfillsplus.com (J.E. Bogner).

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doi:10.1016/j.wasman.2008.05.011

piping and gas extraction wells. Within this context, it is important to understand the properties of fresh landfilled MSW as it is subjected to increased moisture content. Numerous studies have been previously conducted on the geotechnical properties of landfilled MSW, so that settlement and stability of landfills can be evaluated (Landva and Clark, 1990; Fassett et al., 1994; Gabr and Valero, 1995; Kavazanjian, 2001; Hossain, 2002; Sharma and Reddy, 2004; Dixon et al., 2005; Zekkos, 2005). However, limited research has been conducted to investigate the geotechnical properties of fresh MSW under the increased moisture content expected under bioreactor landfill conditions.

This paper describes a comprehensive laboratory study conducted on fresh MSW collected from a MSW landfill to investigate the variation of geotechnical properties with increased moisture content and density. Compaction characteristics, hydraulic conductivity, compressibility and shear strength properties of fresh MSW were determined. It should be noted that moisture content can be defined in the literature in three different ways: dry gravimetric moisture content, wet gravimetric moisture content, and volumetric moisture content (Sharma and Reddy, 2004); however, in this study moisture content is defined as dry gravimetric moisture content: $w_d = \frac{M_w}{M_s} \times 100$; where M_w is the mass of water and M_s is the mass of dry MSW. All the experiments were carried out as per the standard procedures established by the American Society of Testing and Materials (ASTM) for soils (ASTM, 2006).

2. MSW sample collection and characterization

Fresh MSW samples were collected from the working phase of Orchard Hills Landfill located in Davis Junction (Illinois, USA), which is owned and operated by Veolia Environmental Services. The landfill commenced its operation in 1988 and expects to complete by 2018. Composition of the MSW was determined according to a protocol developed by the French Environmental Protection Agency as referenced in Grellier et al. (2007). MSW components were grouped into different fractions (easily degradable, moderately degradable, hardly degradable, and inert) depending on their biodegradability. The typical composition of MSW is shown in Table 1. It can be seen that the MSW consists of approximately 29% inert (non-biodegradable) components. The residual fines (less than 20 mm in size) may contain some inert fraction, but it is difficult to quantify this by visual observations.

Based on testing of four representative bulk samples (greater than 5 kg each), the in-situ dry gravimetric moisture content of the MSW was found to be 44 ± 1%. During the moisture content determinations, the temperature was maintained at 60 °C to avoid combustion of volatile materials. Four dry samples were heated in large porcelain dishes to 440 °C to determine the organic content (loss-on-ignition) of the fresh MSW in accordance with ASTM D2974. The organic content of the MSW was found to be 76–84%.

The gradation of the moist MSW samples was determined in the field using a set of three large sieves with opening diameters of 100, 50 and 20 mm (Grellier et al., 2007). The size distribution of field MSW samples indicated that approximately 53%, 16% and 11% (wet weight basis) of the MSW was retained on 100, 50 and 20 mm sieves, respectively. The percent fines passing through the 20 mm sieve was 20%. Most of the traditional laboratory geotechnical testing equipment cannot accommodate field MSW samples with large particle sizes. Therefore, in order to facilitate standard laboratory testing, but with representative field composition, the bulk field MSW samples were shredded using a slow-speed, high torque shredder (Shred Pax Corp., AZ-7H, Wood Dale, IL, USA). The shredded MSW was dried and its gradation was determined using sieve analysis in accordance with ASTM D422. Fig. 1 shows

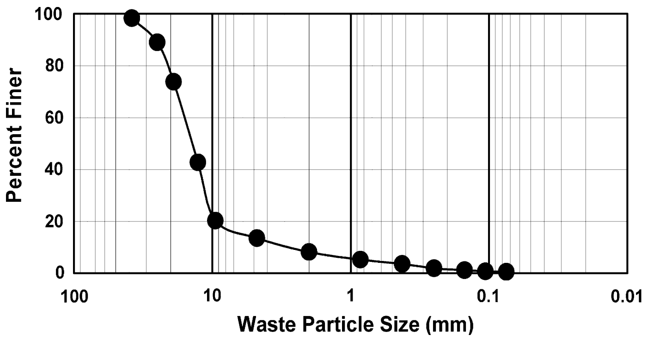

Fig. 1. Gradation of fresh MSW after shredding.

Table 1
Typical composition of fresh municipal solid waste at Orchard Hills Landfill

Category	Waste type	Waste composition (% by wet mass*)	
Easily biodegradable	Cooking waste	6.6	6.9
	Garden waste	0.3	
Medium biodegradable	Paper	8.2	24.6
	Cardboard	13.3	
	Food carton	0.0	
	Sanitary waste	3.1	
Hardly biodegradable	Textiles	5.8	19.2
	Nappies	1.7	
	Wood	11.7	
Inert waste	Metal	4.4	29.2
	Plastic bottles	5.7	
	Other plastics	5.3	
	Special waste	0.0	
	Medical waste	0.1	
	Other waste	3.5	
	Inert waste	5.8	
	Glass	4.4	
Residual fines**	Fines (<20 mm)	20.1	20.1

* Average gravimetric moisture content=44%.

** May include some inert fraction which is hard to visually identify and separate.

the typical gradation of shredded MSW, and it can be seen that the shredded samples consisted of particles with sizes ranging from 0.75 to 40 mm, but approximately 80% (by dry weight basis) of MSW consisted of particles with sizes less than 20 mm.

3. Testing methods

Although MSW samples were obtained from landfills, many previous studies have focused on testing of either individual MSW components or reconstituted MSW samples with predefined proportions (Landva and Clark, 1990; Grisolia et al., 1991; Gabr and Valero, 1995; Wall and Zeiss, 1995). In this study, the MSW samples collected from the field were shredded without any pre-sorting, and the geotechnical testing was conducted using these samples. Compaction, hydraulic conductivity, compressibility, and shear strength tests were conducted. During testing, every attempt was made to prevent biodegradation, so that the test results reflect the properties of the fresh MSW.

3.1. Compaction

Shredded oven-dried fresh MSW samples were used to evaluate compaction characteristics. Standard Proctor compaction tests were conducted in accordance with ASTM D698 using a 102 mm diameter mold. However, when it was needed to increase the moisture content during testing to simulate the field conditions, leachate (collected from Orchard Hill Landfill) was used instead of water. The testing was performed on samples with four different initial target moisture contents: 44%, 60%, 80%, and 100%.

3.2. Hydraulic conductivity

Constant head hydraulic conductivity tests were performed in accordance to ASTM D2434. For these tests, fresh MSW was compacted in the rigid-wall permeameter (with sample dimensions of 64 mm inside diameter and 160 mm height) using a tamping device. Flow rate under constant hydraulic gradient was measured. Darcy's law was used to calculate hydraulic conductivity. Hydraulic conductivity of MSW was also determined by flexi-wall triaxial testing which was performed in accordance with ASTM D5084. In this testing, cylindrical MSW samples (70 mm diameter and 140 mm height) were first subjected to a low initial confining pressure and then saturated by flushing deionized water from bottom up under a low hydraulic gradient. Once the sample was saturated, hydraulic conductivity was determined by measuring flow rate under constant gradient conditions. The sample was then consolidated under desired confining pressure, and the total volume change was measured by measuring the outflow from the sample based on which the increased density of the sample was calculated. The sample was checked for saturation and then hydraulic conductivity was determined under confined condition by measuring flow rate under constant gradient conditions and applying Darcy's law.

3.3. Compressibility

Confined compressibility testing was carried out in a floating ring oedometer to determine the compressibility characteristics of fresh MSW with varying moisture content. In this testing, the MSW sample was placed in the oedometer with one porous stone on the top and another on the bottom of the sample. Fresh MSW was compacted into 63 mm inside diameter and 27 mm thick circular oedometer rings with a tamping device. Leachate was added to MSW to prepare samples at 44%, 60%, 80%, and 100% moisture contents. For each load increment, strain vs. time readings were recorded until the primary compression process was complete. Long-term compressibility testing to assess secondary compression and biodegradation was beyond the scope of this study.

3.4. Drained shear strength

Direct shear tests were conducted to determine the drained shear strength parameters (cohesion and the angle of internal friction) of fresh MSW at different moisture contents. Tests were performed in accordance with ASTM D3080. Leachate was added to MSW to prepare samples at four different moisture contents (44%, 60%, 80%, and 100%). The samples were compacted in the circular shear box with 63 mm inside diameter and 49 mm height and then sheared at a constant strain rate under four different normal stress conditions: 176, 266, 538 and 630 kPa for 44% moisture content tests, and 176, 266, 538 and 774 kPa for other moisture content tests.

3.5. Consolidated undrained shear strength

In order to perform consolidated undrained (CU) triaxial testing, the fresh MSW at in-situ moisture content was compacted in a cell. Tests were performed according to ASTM D4767. Samples were compacted in a mold, extruded and then inserted into latex membranes. The samples were then set up in the triaxial shear setup. The average diameter and height of the samples were 70 mm and 140 mm, respectively. All samples were initially subjected to a confining pressure of 35 kPa and a back pressure of 21 kPa and were saturated. The samples were then consolidated under different confining pressures of 69, 138, and 276 kPa and volume change was measured. The MSW samples were finally subjected to shear under undrained condition. Shearing was done at low constant strain rate (approximately 1.0–1.2% per min) so that pore pressure generated was uniform throughout the specimen. The tests were repeated with samples with three different increased initial moisture contents.

4. Results and discussion

4.1. Compaction characteristics

Standard Proctor compaction tests conducted on shredded MSW resulted in a maximum dry density of 420 kg/m^3 at 70% optimum moisture content (see Fig. 2). However, under confined conditions (in triaxial hydraulic conductivity/shear tests), the dry density of MSW was found to increase to 600–620 kg/m^3. Hetti-

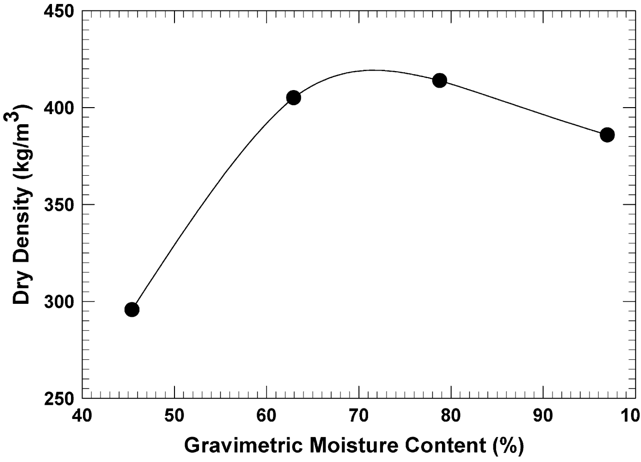

Fig. 2. Variation of dry density of fresh shredded MSW with gravimetric moisture content.

arachchi (2005) reported a maximum dry density of 525 kg/m^3 at 62% optimum moisture content for a MSW sample generated in the laboratory. The mix proportion for this lab-prepared MSW was selected to simulate the average MSW composition in the US and the average specific gravity was reported as 1.6, but the maximum particle size was limited to 12.5 mm as opposed to 40 mm in this study. The difference in the maximum particle sizes is believed to be one of the reasons responsible for the difference between the two maximum dry density values reported by these two studies. Another major reason could be the difference in the average specific gravity. Fresh MSW collected at Orchard Hills Landfill had an average specific gravity of 0.85, which is considerably lower than the specific gravity of the lab-prepared MSW reported by Hettiarachchi (2005). Therefore, the maximum size and size distribution should be taken into account when laboratory results are interpreted or compared.

4.2. Hydraulic conductivity

The hydraulic conductivity values obtained from flexi-wall triaxial equipment under different confinement pressures are presented in Fig. 3. Assuming a zero confinement, results obtained from the rigid-wall permeameter tests are also included in Fig. 3. Fig. 3 demonstrates how hydraulic conductivity varies with dry density of fresh MSW. The hydraulic conductivity values vary in a range of 10^{-8}–10^{-4} m/s when the dry densities vary in an approximate range of 300–650 kg/m^3. The general trend is that the hydraulic conductivity decreases with increase in dry density of fresh MSW. The results are in agreement with the data published by Blieker et al. (1993). For a similar dry density range, Blieker et al. (1993) obtained an average hydraulic conductivity value of 10^{-6} m/s for the laboratory tested MSW samples from Keele Valley Landfill in Ontario, Canada. Information on the age or the state of degradation of the MSW was not available; however, the depth of sampling as deep as 37 m indicates that it may be at least a few years old.

The higher confinement increases the density; therefore, hydraulic conductivity decreases with the increase in the confinement pressure. Zero confinement simulates fresh MSW located near the top surface of a landfill. To explain the practical meaning of confining pressure and the corresponding hydraulic conductivity of MSW, the confining pressures were converted to approximate equivalent MSW heights, assuming average dry densities and an average gravimetric moisture content of 70% (Table 2). This provided a relatively fair basis to compare results with a second set of data published by Blieker et al. (1993), who conducted constant head hydraulic conductivity tests on core samples obtained from Brock West Landfill in Ontario. The MSW samples varied in depth from 18–30 m from the surface and were estimated to be a minimum of 10 years old. The approximate hydraulic conductivity value of 10^{-8} m/s that they reported for 27.4 m compares well with the value predicted for the same depth in Table 2. It should be noted that the tests were conducted using saturated fresh MSW; therefore, the hydraulic conductivity values represent the saturated hydraulic conductivity of fresh MSW. If the MSW is unsaturated, then unsaturated hydraulic properties should be determined.

Table 2
Variation of hydraulic conductivity of fresh MSW with confining pressure

Confining pressure (kPa)	Average dry density (kg/m^3)	Average bulk density* (kg/m^3)	Equivalent average depth (m)	Hydraulic conductivity (m/s)
0	350	595	0	10^{-5}–10^{-4}
67	500	850	8	10^{-7}–10^{-6}
137	550	935	15	10^{-7}
275	600	1020	27	10^{-8}–10^{-7}

* Based on 70% average dry gravimetric moisture content.

4.3. Compression ratio

An instantaneous compression, followed by gradual time differed compression (characterizing a process of mechanical compression), was observed during loading. The results of the compressibility tests are presented in Fig. 4. Compression ratios obtained from each graph in Fig. 4 are given in Table 3. Samples tested had varying moisture contents from 44% to 100%. However the results did not exhibit any specific increase or decrease in compressibility with the increase in moisture content. All four compression ratio values fall into a very close range of 0.24–0.33 (with an average of 0.27 and 0.04 standard deviation).

Table 3 also summarizes compression ratio values reported in the literature for fresh MSW. All but Hunte et al. (2007) are laboratory efforts. Hunte et al. (2007) back calculated compression ratio using stress strain data collected during the filling phase of Calgary Biocell Landfill in Canada. Their compression index is comparable to what Hettiarachchi (2005) reported for saturated synthetic MSW. The compression ratio values published by Hossain (2002) are distributed in a wide range of 0.16–0.25. However, the average value is also comparable to the values reported by Hunte et al.

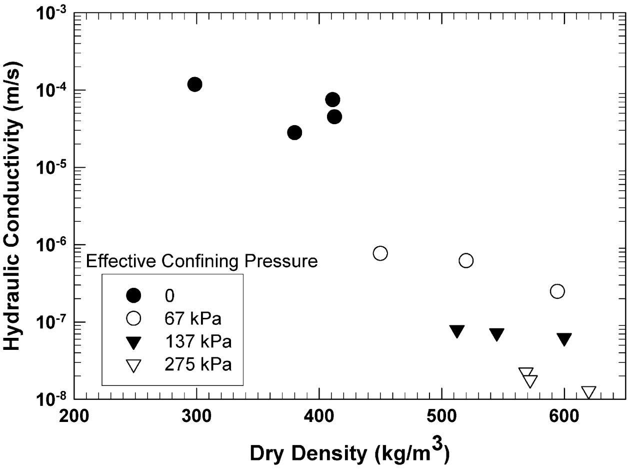

Fig. 3. Variation of hydraulic conductivity of fresh shredded MSW with dry density under different confinement pressures.

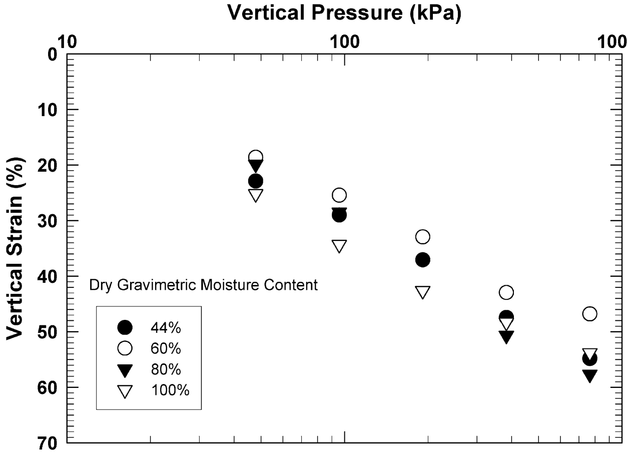

Fig. 4. Variation of compressibility of fresh shredded MSW with moisture content.

Table 3
Compressibility of fresh MSW at different moisture contents

Source	Compression ratio (%)	Gravimetric moisture content (%)
Current research (Oedometer test, fresh shredded MSW, maximum particle size approximately 40 mm)	0.28	44
	0.25	60
	0.33	80
	0.24	100
Hunte et al. (2007) (Calculated from field data, Calgary Biocell Landfill, Canada, relatively fresh MSW)	0.21	55 (Average)
Hettiarachchi (2005) (Special loading frame and a teflon cell, synthetic waste to simulate fresh MSW, maximum particle size approximately 12.5 mm)	0.18	60
	0.21	128 (Saturated)
Hossain (2002) (Oedometer tests, relatively fresh, shredded MSW from control samples, maximum particle size 10 mm × 40 mm, saturated with 6% acetic acid)	0.16–0.25	Saturated
Landva and Clark (1990) (470 mm diameter consolidometer, fresh shredded MSW samples from Edmonton, Canada)	0.35	Relatively dry

(2007) and Hettiarachchi (2005). Landva and Clark (1990) reported a 0.35 value for fresh MSW from Edmonton tested in a large consolidometer. The compressibility data summarized in Table 3 does not show any correlation to the moisture content. This supports the observations made by Vilar and Carvalho (2004) for aged MSW. Vilar and Carvalho (2004) studied the compressibility of 15 year old MSW recovered from Bandeirantes sanitary landfill in Brazil. The compressibility of this aged MSW was found to be 0.21, but it was not influenced by saturation.

4.4. Drained shear strength parameters

Fig. 5 shows the direct shear test results for MSW at an in-situ moisture content of 44%. Similar trends were observed in the results for samples tested at increased moisture contents. The fresh MSW samples exhibited continuous strength gain at horizontal deformation well in excess of 10% of the diameter of the sample. In the absence of samples reaching any peak strength, shear strength at 15% horizontal deformation was used to establish the Mohr-Coulomb shear strength envelopes (see Fig. 6). Shear strength parameters estimated from Fig. 6 for fresh MSW at 44%, 60%, 80% and 100% moisture contents are presented in Table 4. It is observed that the cohesion of fresh MSW varied around from 31–64 kPa and the drained friction angle ranged from 26–30°. Neither the cohesion nor the friction angle demonstrated any correlation with the moisture content. Landva and Clark (1990) conducted direct shear tests on large samples of shredded fresh MSW from Edmonton, Canada. They reported 23 kPa and 24° as the shear strength properties (see Table 4). Kavazanjian (1999) presented results of direct shear tests performed on samples collected from the OII landfill in California and found cohesion of 43 kPa and friction angle of 31°. Caicedo et al. (2002) also used large samples to conduct direct shear tests on relatively new (1 year aged) unshredded MSW from Don Juana landfill in Bogota, Colombia. Moisture contents of these samples were comparable to what was used in the current research and the shear strength properties were found to be 78 kPa and 23° (Table 4). It is evident from Table 4 that the drained angle of friction varies in a narrow range of 23–30°. However the range for cohesion, 23–78 kPa, is much wider. The wide variation in cohesion may be attributed to the composition of MSW.

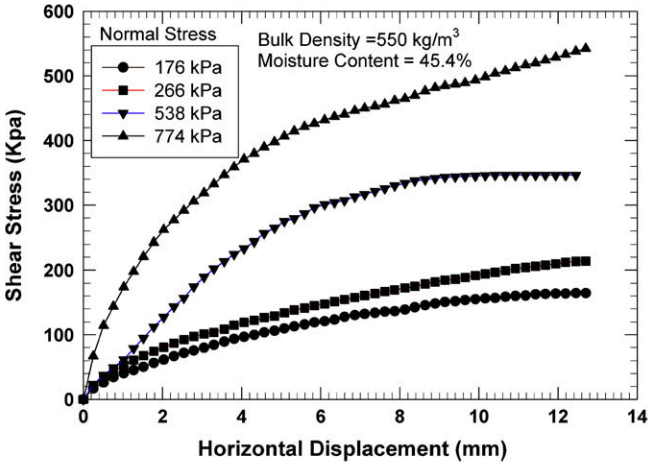

Fig. 5. Direct shear test results for shredded fresh MSW under in-situ moisture content of 44%.

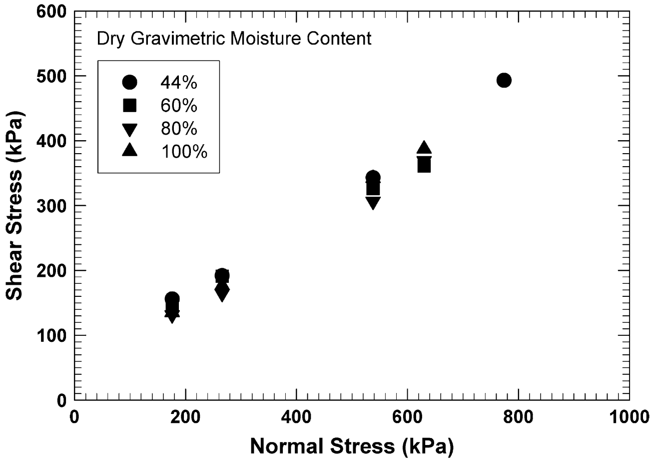

Fig. 6. Mohr-Coulomb failure criteria for fresh shredded MSW at different moisture contents.

4.5. Consolidated undrained shear strength properties

In geotechnical engineering, CU strengths are typically used for stability problems where the soils are at equilibrium after being fully consolidated and then fail with insufficient drainage occurring when additional stresses are applied quickly (Holtz and Kovacs, 1981). With the addition of more moisture, one might also expect similar situations in a bioreactor landfill. Hence CU strength results may be considered suitable to analyze stability of a bioreactor landfill.

Fig. 7 shows the triaxial CU test results for an in-situ moisture content of 44%. Similar trends were observed for the tests conducted with samples at different initial moisture contents. During the tests, the deviatoric stress increased continuously, without reaching any peak or ultimate value. The same behavior was ob-

Table 4
Drained shear strength properties of fresh MSW based on direct shear testing

Source	Cohesion (kPa)	Friction angle (degrees)	Gravimetric moisture content (%)
Current study (Fresh shredded MSW, sample diameter 63 mm, shear strength defined at 15% strain)	46	30	44
	64	26	60
	32	28	80
	31	30	100
Landva and Clark (1990) (Fresh sredded MSW from Edmonton, Canada, sample dimensions 434 mm × 287 mm)	23	24	–
Kavazanjian (1999) (Waste from OII landfill in California, USA, sample diameter 460 mm, shear strength defined at 10% strain)	43	31	–
Caicedo et al. (2002) (1 year aged unshredded MSW, sample diameter 900 mm, shear strength defined at 6.7% strain)	78	23	67

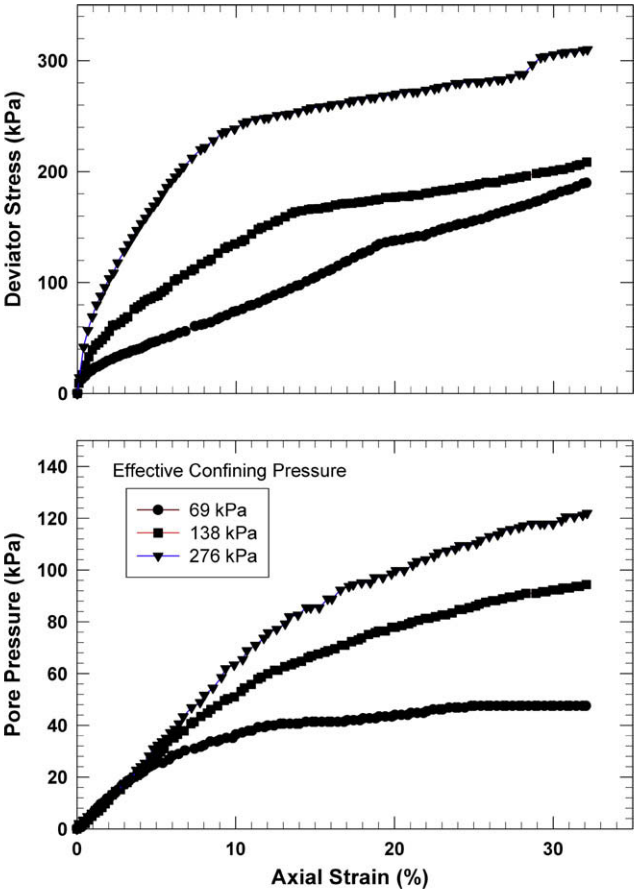

Fig. 7. Triaxial consolidated undrained test results for shredded fresh MSW.

served in all the samples tested. To be in agreement with the procedure followed in the direct shear testing, shear strength parameters were defined at 15% strain. Table 5 summarizes the total and effective shear strength properties obtained from the CU tests. The average total strength parameters (c and φ) were found to be 32 kPa and 12°, while effective stress parameters (c' and φ') were found to be 38 kPa and 16°. The effective consolidated undrained angle of friction (14°) reported by Caicedo et al. (2002) for relatively fresh MSW from Dona Juana landfill is in agreement with the results from the current research (see Table 4). The effective consolidated undrained cohesion (45 kPa) reported by Caicedo et al. (2002) is slightly higher than what was found for fresh MSW from Orchard Hills Landfill. As explained before, this discrepancy may be attributed to the presence of a higher percentage of organic matter in the MSW from Don Juana Landfill. The results from CU tests are also included in Fig. 8 to compare with the results from the direct shear tests. In general, the angle of friction results by CU tests on fresh MSW are approximately 50% of what was produced by the direct shear tests. Cohesion values yielded by the CU tests remain within the same range as produced by the direct shear tests. However they are approximately 50% of the maximum cohesion reported for the fresh MSW, particularly finer components such as food MSW.

Many researchers have observed strain hardening behavior in MSW irrespective of the age of MSW or the testing technique (Jessberger and Kockel, 1993; Gabr and Valero, 1995; Grisolia et al., 1995; Kavazanjian, 2001; Caicedo et al., 2002; Vilar and Carvalho, 2004). Therefore, it is generally believed that the shear strength properties of MSW are strain-dependent. In geotechnical testing of clay, it is common to assume the stress at 15% or 20% strain if the sample begins to bulge without failing. However strength testing on MSW has not evolved to a standardized criteria and a wide range of strains 5–30% has been adopted as the failure strain (Grisolia et al., 1995; Vilar and Carvalho, 2004). Currently, there is no standard strain to define the strength of MSW. High strains and hardening behavior at strains greater than 30% demonstrate the ability of MSW to undergo high plastic deformation prior to failure. However, from a geotechnical stability viewpoint, it may not be desirable to define strength at such a high strain.

In this study, the CU testing was continued beyond 20% strain. Consolidated undrained shear strength was determined at 5%, 10%, 15%, and 20% strains. The average values obtained are plotted in Fig. 9. The φ decreased, while c increased with increase in strain. The c' increased with increased strains, while φ' decreases first and

Table 5
Consolidated undrained (CU) shear strength properties of fresh MSW based on triaxial CU testing

Source	Cohesion (kPa)	Friction angle (degrees)	Stress calculation method
Current research (Fresh shredded MSW, sample diameter 70 mm, shear strength defined at 15% strain)	32	12	TSP
	38	16	ESP
Caicedo et al. (2002) (1 year aged unshredded MSW, sample dimensions: diameter 300 mm, height 600 mm, shear strength defined at 15% strain)	45	14	ESP

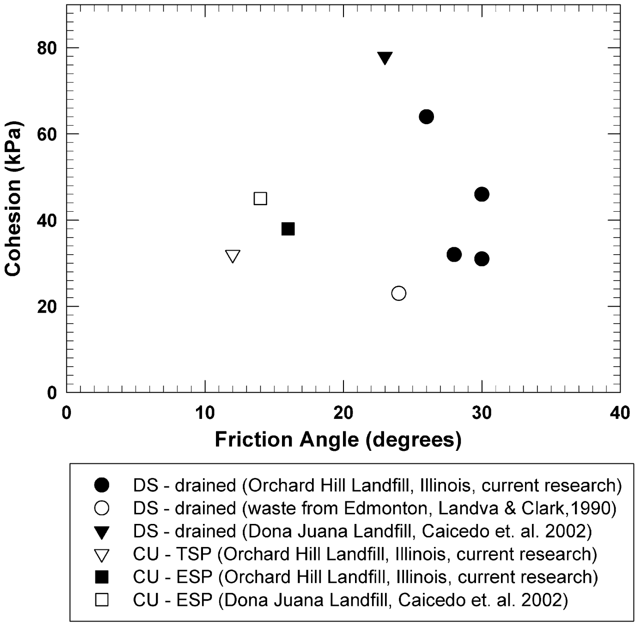

Fig. 8. Distribution of shear strength parameters for fresh shredded MSW (DS- direct shear test, CU- consolidated undrained triaxial test, TSP- total stress parameters, and ESP- effective stress parameters).

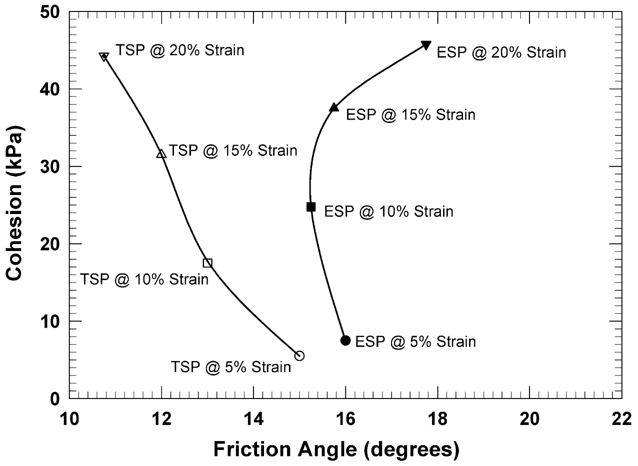

Fig. 9. Strain dependency of shear strength parameters for fresh shredded MSW (TSP- total stress parameters, and ESP- effective stress parameters).

then increases with the increase in strain. The minimum φ' was observed approximately at 10% strain. Therefore, the strain to define shear strength based on consolidated undrained shear test results should be critically examined.

Small-scale laboratory testing performed in this research provided a general understanding of the geotechnical properties of shredded fresh MSW. Generally, the specimen size was approximately 1.6–2.6 times the maximum size of the particle in the shredded MSW samples used for testing; therefore, a systematic evaluation of the gradation of MSW as well as the specimen size in relation to the maximum particle size in the MSW on geotechnical properties of MSW, based on large-scale testing using representative field MSW samples, should be performed. The validity of laboratory test results should be examined based on in-situ test results and back-analysis of field performance data. The effects of degradation on geotechnical properties of MSW should also be investigated.

5. Summary and conclusions

Fresh MSW collected from the working phase of Orchard Hills Landfill in Illinois (USA) was tested for compaction characteristics, hydraulic conductivity, compressibility, and shear strength properties. The following conclusions can be drawn from the results of this study:

A maximum dry density of 420 kg/m^3 was observed at 70% optimum moisture content; however, a maximum dry density of 620 kg/m^3 was measured under higher confined stress conditions. The composition of MSW should be taken into account when the compaction characteristics are interpreted.

The hydraulic conductivity of fresh MSW varied in a wide range of 10^{-8}– 10^{-4} m/s and decreased with increase in dry density. Assuming confinement as a measure of overburden stress, it may be concluded that the fresh MSW near the surface had 10^{-5}–10^{-4} m/s and at deep depths it may be as low as 10^{-8}–10^{-7} m/s.

Compression ratio values varied in a close range of 0.24–0.33 (with 0.27 average and 0.04 standard deviation). The results did not indicate any specific increase or decrease in compressibility with the increase in moisture content.

Drained cohesion of fresh MSW varied from 31–64 kPa and the drained friction angle ranged from 26–30°. Neither cohesion nor friction angle demonstrated any correlation with the moisture content. It was also concluded that cohesive behavior of MSW may be due to the presence of biodegradable organic matter such as food.

The average total strength parameters (c and φ) were found to be 32 kPa and 12° while effective stress parameters (c' and φ') were 38 kPa and 16°. The φ was lower and c was higher with the increase in strain. The effective cohesion parameter, c', increased with increased strains; but the effective friction parameter, φ', decreased first and then increased with the increase in strain. The minimum φ' was observed approximately at 10% strain and therefore attention should be paid on the selected strain to define shear strength properties of fresh MSW.

Acknowledgements

The authors are thankful to Veolia Environmental Services, particularly Chris Peters, for supporting field activities, including MSW sampling. The assistance of Solenne Grellier in MSW sampling and characterization is appreciated. Funding for this research is received from the National Science Foundation (Grant#0600441) and is gratefully acknowledged.

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