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ORIGINAL ARTICLE

# Effects of Degradation on Geotechnical Properties of Municipal Solid Waste from Orchard Hills Landfill, USA

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**Abstract** In bioreactor landfills, geotechnical properties of municipal solid waste (MSW) are believed to be affected by increased moisture content and accelerated biodegradation due to leachate recirculation; however, studies to quantify the changes in the MSW properties are scarce. This study quantifies the change in geotechnical properties of field MSW as a function of level of degradation. Fresh MSW samples were collected from the working phase of Orchard Hills landfill (Davis Junction, Illinois, USA) and were subjected to leachate recirculation and enhanced anaerobic degradation in specially designed laboratory bioreactors. Samples were exhumed from the bioreactors at different stages of degradation as determined by the amount and composition of biogas generated, and subsequently tested for moisture content, organic content, unit weight, hydraulic conductivity, compressibility, and shear strength. Moisture content of MSW increased significantly, while organic content decreased with degradation. Bulk unit weight increased with degradation which led to decrease in saturated hydraulic conductivity. Primary compression ratio showed slight increasing trend with degradation, while the secondary compression ratio was not affected significantly with the degradation. The friction angle decreased from 30° to 12°, but cohesion increased from 29 to 65 kPa with degradation based on direct shear test results. The testing of saturated MSW in triaxial consolidated undrained conditions resulted in lower shear strength with no distinct correlation of friction angle and cohesion with degradation. Additional large-scale, long-duration testing is recommended using the field MSW samples with the consistent composition to establish the correlations between the engineering properties and degree of degradation. Overall this study showed that the engineering properties of field MSW are affected by degradation and these changes should be properly accounted in the analysis and design of bioreactor landfills involving leachate recirculation.

**Keywords** Bioreactor landfills · Degradation · Municipal solid waste · Hydraulic conductivity · Compressibility · Shear strength

## Introduction

Bioreactor landfills are increasingly becoming popular for disposal of municipal solid waste (MSW) due to enhanced degradation of MSW which leads to faster stabilization of landfill and lesser post-closure monitoring requirements as compared to conventional landfills. Bioreactor landfills essentially involve leachate recirculation to the MSW to increase moisture content that is optimal for enhanced biodegradation. The changing moisture and solids contents of MSW during decomposition greatly influence the physical

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stability of bioreactor landfills, and hence the viability of various bioreactor designs. Currently, there are no standard design guidelines for bioreactor landfills, and there are a number of unresolved engineering issues relating to the design and operation of safe and effective bioreactor landfills. In the past, several landfill slope failures have occurred due to improper design and management of bioreactors, leading to both environmental and public safety concerns regarding this technology.

Engineering properties of MSW change with the waste degradation and it is important to assess these changes to evaluate geotechnical stability and avoid any potential catastrophic failures. It also helps in planning the post-closure usage of the landfill. Engineering properties such as moisture content and organic content change significantly and can affect the total leachate flow collected in the leachate collection and removal system. Changes in unit weight and compressibility affect the volume of MSW in the landfill and the extent of differential settlements. Improper estimation of hydraulic conductivity can result in accumulation of leachate in waste mass resulting in excess pore pressure build-up and seepage failures. With degradation, variation in shear strength of MSW mass can result in significant impact on slope stability of the landfill. Furthermore, loss of organics in MSW, as a result of biological decomposition, can cause significant secondary MSW settlements that may range up to 25–50 % of the initial landfill height [1].

Degradation of MSW can be defined as the conversion of organic matter in MSW to biogas. This process is characterized by physical, chemical, and biological decomposition of waste mass. Breakdown of MSW mass into finer components occurs due to physical degradation and by the rinsing and flushing action of water (or leachate). Chemical decomposition occurs because of hydrolysis, precipitation, sorption and ion exchange which results in greater mobility of waste components. Presence of microbes (naturally occurring bacteria) in the organic portion of waste results in biological degradation. Under landfill conditions, as the degradation proceeds, organic fraction of waste mass is converted into nitrogen ($N_2$) and carbon dioxide ($CO_2$) initially, and methane ($CH_4$) and carbon dioxide ($CO_2$) largely in the latter stages [2]. Some of the other byproducts include decomposed solid waste, new biomass, leachate, and heat.

The degradation of MSW occurs in five phases [3]. Phase I is known as *initial adjustment or aerobic phase* because of the presence of oxygen, which is initially trapped in the voids. This phase continues for a very short period of time, and mainly nitrogen and carbon dioxide are produced during this phase. Methane production is not observed in Phase I. Phase II is known as *transition phase*, where all the oxygen is consumed by bacteria and production of carbon dioxide takes place. During phase III, acid forming bacteria converts these molecules into short chain carboxylic acids, alcohols, carbon dioxide and hydrogen. It results in lower pH. During the phases IV and V, acetogenic and methanogenic bacteria produce methane either through break down of the acids to methane and carbon dioxide or by reducing carbon dioxide with hydrogen. Concentration of methane reaches about 50–60 % in this phase and large volume of gas produced indicates high rate of methane production. However, the concentrations of $CH_4$ and $CO_2$ remain about same as in the fourth phase.

Rate of MSW degradation is affected by many factors, including MSW composition, nutrients level, presence or absence of the buffering agent, moisture content, pH, temperature and operational practices [2]. Several studies examined accelerated degradation of MSW and corresponding changes in biochemical properties due to leachate recirculation [2, 4–8]. The presence of higher moisture enhances degradation of MSW by facilitating the transport of nutrients and microbes in the landfill [3, 9–14]. Leachate recirculation is performed to increase moisture in the waste and it can be performed alone or combined with pH buffering, sludge addition, methanogenic leachate, supplemental nutrients, or temperature control.

Several studies examined the engineering properties of fresh and aged MSW [15–22]. However, only a few studies have reported the changes in properties of MSW due to degradation under leachate recirculation conditions [1, 23–27]. Recently, Reddy et al. [28] performed a comprehensive laboratory study that is aimed at studying the engineering properties of synthetic MSW at different degradation levels. The present study is focused on determining the geotechnical properties of real-field MSW during different levels of degradation due to leachate recirculation. Real field MSW samples were collected from the Orchard Hills Landfill, Davis County, IL, USA and degraded in specially designed laboratory bioreactors. The changes in moisture content, organic content, and geotechnical properties (hydraulic conductivity, compressibility, and shear strength parameters) of MSW were evaluated at different levels of degradation and the results are compared with the published studies related to field MSW.

## Materials and Methods

### Sample Collection and Initial Characterization of MSW

MSW samples were collected from the working phase of Orchard Hills Landfill (Davis Junction, Illinois, USA). The landfill commenced its operation in 1988 and expects to complete by 2018. Composition of the MSW samples was determined according to MODECOM protocol developed by French Environmental Protection Agency [29]. The detailed composition of field MSW is shown in Table 1. Non-biodegradable components comprised of 24.7 % and the remaining biodegradable components were categorized into three fractions: easily biodegradable, moderately biodegradable, and hardly biodegradable. To obtain representative composition in relatively small specimens, the samples were shredded before they were subjected to any engineering testing. Shredded MSW particles varied from 0.75 to 40 mm in size.

Moisture content was determined in accordance with the standard procedure ASTM D2216 with the samples dried at 60 °C. Wet gravimetric moisture content is generally used in landfill practice and it is defined as the ratio of mass of moisture to the mass of wet MSW. The organic content of the MSW was measured based on loss-on-ignition method as per ASTM D2974 (heated at 550 °C for 12 h to achieve constant mass). It represents the volatile solids present in the MSW. Particle size distribution was conducted as per ASTM D422. MSW was dried at a temperature of 60 °C and then sieved through set of sieves from sieve # 4 (4.75 mm) to sieve # 200 (0.075 mm). Fraction retained on each sieve was weighed and then percentage passing was calculated. Degree of decomposition (DOD) was calculated using the following equation [30]:

$$\mathrm{DOD} = \left(1 - \frac{X_{\mathrm{fi}}}{X_{\mathrm{fo}}}\right)\frac{1}{(1 - X_{\mathrm{fi}})} \times 100, \tag{1}$$

where $X_{\mathrm{fo}}$ is the initial organic fraction and $X_{\mathrm{fi}}$ is the organic fraction after partial decomposition. In other words, $X_{\mathrm{fo}}$ and $X_{\mathrm{fi}}$ are the initial organic content and the organic content at any degradation stage under consideration given in fractional form.

## Bioreactor Assembly and Operation

Figure 1 shows the schematic of the bioreactor assembly developed for this study and it simulated typical landfill anaerobic conditions inside the reactor. Bioreactor assembly comprised of two cells; main reactor to accommodate the field MSW and the secondary recirculation cell to accommodate the leachate used for recirculation. The reactor consisted of cylindrical cell fitted with metal plates at the top and the bottom. The tubing was made of acrylic and had a diameter of 127 mm (5″) and a length of 508 mm (20″). The metal plates made of aluminum were fixed at the top and bottom of the cylindrical cell using bolts. In the top plate, three ports were provided: one port used for leachate recirculation, second port for gas sampling and volume measurement, and through the third port, pressure gauge was placed to monitor the gas pressure build up due to anaerobic reaction in the reactor. In the

**Table 1** Composition of fresh municipal solid waste collected from Orchard Hills Landfill

| Category | Waste component | Amount present (% by total wet mass[a]) | |
|---|---|---|---|
| Easily biodegradable | Food 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 |
| | Wood | 11.7 | |
| | Nappies | 1.7 | |
| 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[b] | Fines (<20 mm) | 20.1 | 20.1 |

[a] Average in situ dry gravimetric moisture content = 44 %

[b] May include some inert fraction which is hard to visually identify and separate

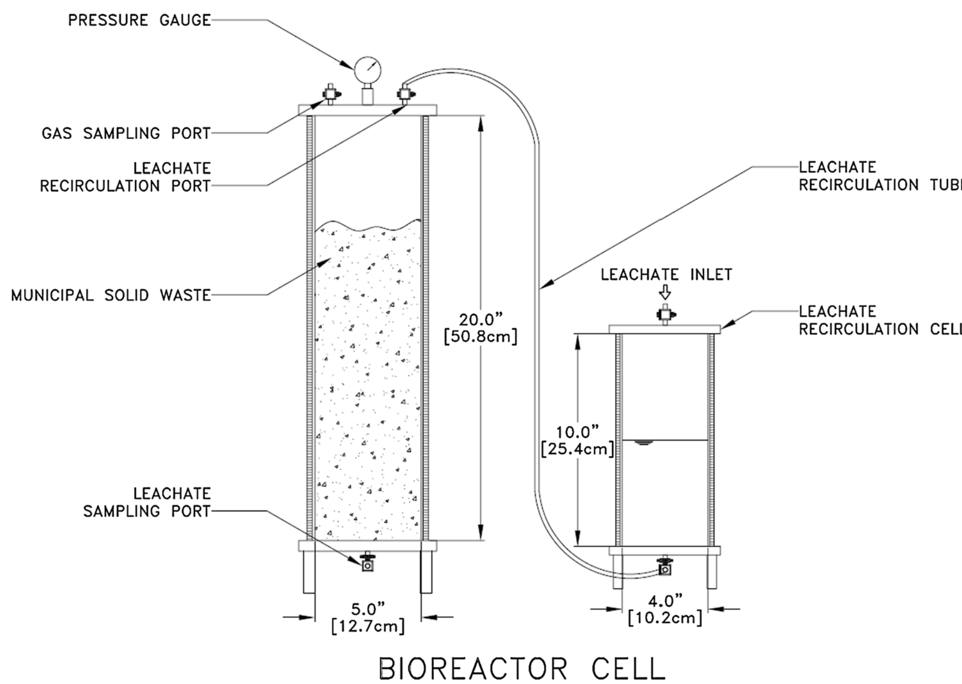



**Fig. 1** Schematic diagram of bioreactor cell setup

bottom of the main reactor, leachate collection port was provided. All connections to the reactors were properly sealed with anaerobic sealant to prevent any leak or air intrusion. The main reactor was accompanied by a recirculation cell of diameter 102 mm (4″) and a height of 254 mm (10″).

Six identical bioreactor cells were prepared to degrade the MSW to different levels of degradation and study the effect of degradation on engineering properties. Initially, two reactors were loaded with 0.5 kg shredded dry MSW and other four reactors were loaded with 0.9 kg of shredded dry MSW. Prior to the loading of MSW into the reactor, filter paper, geotextile and stainless steel wire mesh was placed to ensure proper leachate collection without clogging of the port. MSW was placed in layers and compacted using the Standard Proctor hammer. After placement of MSW, the reactor was sealed at the top. All connection ports were properly sealed using anaerobic sealant. Gas tightness of the reactors was checked through leak testing. After placing the MSW, nitrogen gas was purged into the reactor and immersed in the water bath to check for gas tightness. After the leak check, reactor was once again purged with nitrogen to displace the air if present in it; this resulted in the onset of anaerobic degradation phase. The same procedure was followed to place waste in the other five cells. After ensuring the complete anaerobic condition, all the reactors were placed in a chamber maintained at a temperature 35–38 °C which provides a favorable environment for the growth of microbes. Bioreactor cells were designated as S1–S6. Waste in cells S1–S3 were mixed with 70 % leachate and 30 % sludge on dry weight basis of MSW, whereas 50 % leachate and 50 % sludge was used for the waste in the cells S4–S6 (for faster degradation).

Bioreactor Cell S2 was dismantled without recirculation to study the effect in the initial stage. Cell S1 and S3 were operated without recirculation for the initial 88 days. Later, to enhance the degradation process, leachate recirculation was carried out in these two reactors. The other cells S4–S6 were subjected to leachate recirculation from the beginning. Leachate obtained from the reactors coupled with leachate obtained from the same Orchard Hills landfill was used for recirculation. Leachate volume of 1000 mL was recirculated thrice per week to the waste samples. Leachate pH was neutralized around 7.0 using sodium bicarbonate prior to recirculation operations.

## Degradation Monitoring

During the degradation of MSW, volume and composition of generated gas were measured. Gas volume was measured by water displacement method. To measure the gas volume, one end of the tube was connected to the gas collection port and the other end was inserted into the graduated beaker. A 4000 mL graduated beaker was submerged into the water drum, leaving no air stored within it. The graduated beaker was then inverted and roughly 150 mm of the terminal end of the reactor tubing was inserted upwards into the graduated beaker. Gas collection port of the reactor was opened slowly to allow the gas to enter into the graduated beaker. When the gas reached the

3500 mL mark on the graduated beaker, the valve was shut off. To read the amount of gas in the graduated beaker, the sealed bottom end of the graduated cylinder (which was pointed upwards) was raised above the surface of the water until the water surface in the beaker was no more than 1 cm above the water surface of the drum; the volume of gas in the graduated beaker was then read and recorded. This process was repeated until the gas flow rate diminishes to less than 5 discrete gas bubbles escaping the terminal end of the tubing in 10 s. Once gas venting was complete, the total volume of gas vented, time of venting, and date were recorded.

Gas composition was measured using SRI 9300B gas chromatograph (GC) equipped with a thermal conductivity detector. In GC, the column temperature was maintained at 80 °C for 5 min. Helium was used as a carrier gas. Using 1.0 mL syringe, 0.5 mL of the standard gas was injected into the TCD sample port. Nitrogen was eluted in 0.6–0.7 min, methane eluted in 0.8–1.0 min and carbon dioxide eluted in 2.7 min. Peak area was calculated after integration and then it was compared with the standard gas area, to obtain the proportion of nitrogen, carbon dioxide, and methane present in the gas sample.

The pH of leachate was measured in accordance to the procedure EPA 9040C. The pH of the sample was determined electrometrically using pH electrode. The electrode was calibrated using a series of standard solutions of known pH. Leachate generated from the reactors and leachate used for recirculating was taken in a clean beaker and electrode was inserted to measure the pH of the solution.

The total gas and methane production and concentrations of methane and carbon dioxide are summarized in Table 2. Increase in the rate of methane production was observed with leachate recirculation. The proportions of methane and carbon dioxide concentrations remained at 40 and 60 %, respectively, when the methane production rate reached maximum.

## Geotechnical Testing Procedures

Based on the volume and composition of gas generated by the reactors, the reactors were terminated to obtain waste samples that have undergone different levels of degradation. These MSW samples were characterized for moisture content, organic content, and particle size distribution and then tested for hydraulic conductivity, compressibility and shear strength. Procedures adopted for geotechnical testing are briefly outlined here and more details can be found in Reddy et al. [27, 28].

### *Hydraulic Conductivity Tests*

To measure the hydraulic conductivity of MSW, flexible-wall and rigid-wall permeability testing was performed in general accordance with ASTM standards (D2434 and D5084). Flexible-wall permeability tests were conducted at different confining pressures to study the variation of hydraulic conductivity with respect to confining pressure at different levels of degradation. MSW samples were compacted in a cylindrical mold of diameter 50 mm and height 100 mm, using a tamper. Each sample was extruded and placed in latex membrane and then it was placed in the triaxial cell. Sample was first saturated by applying an initial confining pressure of 35 kPa and then flushing deionized water under a constant hydraulic gradient. When the sample was fully saturated, hydraulic conductivity was determined by measuring the volume of outflow in a given elapsed time under the constant hydraulic gradient. Following the hydraulic conductivity measurement, the sample was consolidated under predetermined confining pressure. Three different samples were tested at confining pressures of 69, 138 and 276 kPa.

Rigid-wall constant head permeameter tests were also conducted to obtain hydraulic conductivity at zero confining pressure. Fresh MSW or degraded MSW sample was

**Table 2** MSW characterization at various stages of degradation

| Degradation stage | Cumulative gas volume (mL/g—dry) | Cumulative methane volume (mL/g—dry) | Gas composition at termination | | Moisture content (%) | | Organic content (%) | Degree of decomposition (%) |
|---|---|---|---|---|---|---|---|---|
| | | | Methane (%) | Carbon dioxide (%) | Dry weight basis | Wet weight basis | | |
| Initial (S1) | 0 | 0 | 0 | 0 | 100 | 50 | 84.1 | 0 |
| I (S2) | 4.4 | 0.0034 | 1.5 | 74.2 | 119 | 54.3 | 74.9 | 43 |
| II (S3) | 29.8 | 1.9 | 10.3 | 56.4 | 229 | 69.6 | 74.2 | 45 |
| III (S5) | 99.0 | 2.1 | 47.5 | 36.0 | 143 | 58.8 | 70.9 | 53 |
| IV (S4) | 200.0 | 86.3 | 52.1 | 40.0 | 267 | 72.8 | 69.5 | 56 |
| V (S6) | 226.1 | 105.4 | 46.6 | 41.6 | 285 | 74.0 | 58.0 | 73 |

compacted in the rigid-wall permeameters. Initial height, diameter and mass of the sample were measured. Then, testing was conducted under different constant hydraulic gradients, and the hydraulic conductivity was calculated based on the amount of outflow in known elapsed time.

*Compressibility Tests*

Confined compressibility testing was performed in an oedometer to determine compressibility characteristics of fresh and degraded MSW in general accordance with ASTM D2435. The oedometer used in this study was a floating ring type which consisted of a 63 mm diameter and 25 mm thick circular brass ring with the sample placed with one porous stone on the top and another one at the bottom of the sample. MSW sample was placed in layers into the brass ring and compacted with a tamper. Brass ring with MSW sample was placed in the loading device and then the sample was subjected to a constant vertical stress of 48 kPa. Compression of the sample was measured at different time intervals. After 24 h of elapsed time or when compression ceases, the normal stress was increased to 96 kPa and compression was measured at different time intervals. This procedure was repeated for normal stresses of 192, 383 and 766 kPa, to stimulate maximum 40 m deep landfill. Based on the total compression under each normal stress, axial strain versus normal pressure was plotted and compression ratio was calculated. Long term compressibility tests were also conducted by following the same procedure, except the loading was increased to 383 kPa and maintained constant, and the compression with elapsed time was monitored for 15 days.

*Direct Shear Tests*

Drained shear strength properties of the MSW were determined by performing direct shear testing as per ASTM D3080. For this testing, MSW samples were placed in a circular shear box with inside diameter 63 mm and thickness 34 mm in layers with each layer compacted with a tamper. Porous stones were placed on the top and the bottom of the MSW sample. A constant vertical stress was applied to the sample and then sheared at a constant strain rate of 0.035 mm/min. The horizontal deformation and shear stress were recorded periodically. The testing was continued until the horizontal displacement reached 15 % of the sample diameter (none of the samples exhibited peak shear response). Different samples were prepared and tested under different normal stress conditions. The horizontal displacement versus shear stress was plotted for each normal stress. Based on these results, the shear stress corresponding to horizontal deformation of 15 % sample diameter was plotted against normal stress. Using the Mohr–Coulomb failure envelope, shear strength parameters (cohesion and friction angle) were determined.

*Triaxial Consolidated Undrained Shear Tests*

Consolidated undrained triaxial testing was conducted in accordance with ASTM D4767. MSW sample was placed in a cylindrical mold in layers. Each layer was compacted using a tamper. Sample was extruded from the mold and transferred to a latex membrane. Sample was then placed in the triaxial chamber. Three identical samples were prepared by following the same procedure. All samples were initially subjected to confining pressure of 35 kPa and saturated under back pressure. The samples were then consolidated under different effective confining pressures of 69, 138, or 276 kPa, and the total volume change was measured based on the amount of outflow for over 24 h. MSW samples were finally subjected to shear under undrained condition. Pore-water pressure was measured during shearing. Shearing was done at a constant strain rate of 2.1 mm/min, to ensure approximate equalization of pore pressures throughout the specimen. Samples were sheared to the maximum axial strain in excess of 30 % as there was no peak shear response observed. Based on the results, the axial strain versus deviator stress and pore water pressure was plotted. The maximum and minimum total and effective principal stresses at failure were calculated, and the Mohr–Coulomb failure envelope was drawn to determine the total and effective shear strength parameters at axial strain level of 15 %.

## Results and Discussion

### Moisture Content

Moisture contents of MSW samples exhumed from the cells at different levels of degradation are shown in Table 2. The initial field moisture content of fresh MSW was 44 % based on dry weight basis. However, in this study, the baseline initial testing was conducted at moisture content of 100 % (on dry basis) to represent elevated moisture content immediately upon leachate recirculation. Moisture content of the exhumed samples from the reactors varied from 119 to 285 % (based on dry weight). Results show a general trend of increasing moisture content with increase in degradation and all samples appear to reach field capacity. Increase in moisture content may also be contributed to increase in field capacity of MSW due to disintegration of particles.

Gomes et al. [31] found the moisture content of recent wastes (fresh) near the surface to be 61 % and for a 3-year-old waste at a depth of 11 m to be 117 %. The moisture content of waste increased with depth because of degradation. Similar trends were reported in other studies [16, 17]. Little information is available in literature about the changes in moisture content due to degradation. Penmethsa [32] reported the moisture content values of MSW at various phases of degradation from bioreactor cells subjected to leachate recirculation. Results show that moisture content increased from 149.1 to 198.4 % (dry weight basis) with degradation, and this increase in moisture content was attributed to the particle disintegration resulting in decrease of pore spaces and increase in MSW moisture holding capacity. In general, it can be noted that the moisture content increases with waste degradation.

### Organic Content

The organic content of fresh MSW was 84.1 % and it gradually decreased to 58.0 % in the highly degraded sample (Table 2). Based on the organic content (volatile solids), percent reduction in organic content was 11, 12, 16, 17 and 31 % for degradation stages I, II, II, IV and V, respectively, while the corresponding DOD for each stage calculated using Eq. 1 found to vary from 43 to 73 % (Table 2).

Previous published studies show that organic content of MSW typically ranges from 5 to 75 % for most of the landfills in the United States [3, 16]. Generally, organic content is higher at the surface of landfill and it decreases with depth. This was evident from the study conducted by Gomes et al. [31] on a Portugal landfill (Santo tirso landfill). They found the organic content of fresh wastes near the surface to be 43–63 % and for 3 year old waste at a depth of 11 m to be 56 %. Based on laboratory studies, Hossain [25] also reported that the organic content decreases with increase in degree of degradation.

### Particle Size Distribution

Figure 2 shows the particle size distribution of the MSW at its various levels of degradation. Initially, MSW contained approximately 20 % particles finer than 10 mm and due to degradation it increased to approximately 38 % in the highly degraded sample (S6). Results show a general trend of decrease in particle sizes in low degradation sample (S2) to high degradation sample (S6). Degradation causes particles to disintegrated causing reduction in size of the particles.

Gabr and Valero [16] also made similar observations with decreased particle sizes in MSW samples at deeper depth due to degradation. The larger particles of the MSW break up their structure due to the biochemical reaction. Similar results were also presented by Penmethsa [32] with increase in fine contents from 14 to 40 % with degradation.

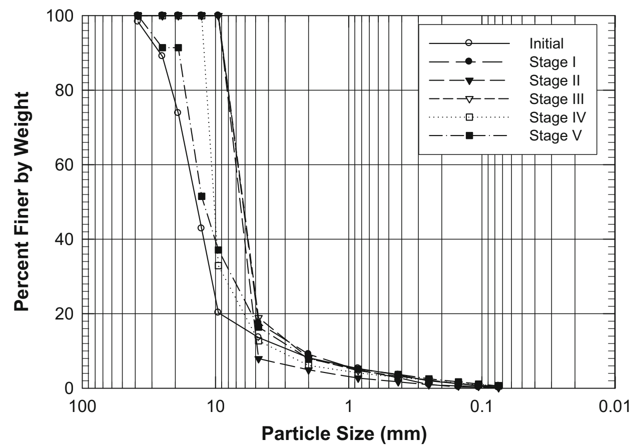



**Fig. 2** Particle size distribution of MSW at different stages of degradation

### Hydraulic Conductivity

Hydraulic conductivity of MSW is shown to be significantly affected by degradation due to changes in particle size distribution and unit weight [28]. Hydraulic conductivity values of fresh and degraded MSW samples measured based on rigid-wall and flexible wall permeameter tests are shown in Fig. 3. Results indicate that hydraulic conductivity decreased with degradation from $10^{-4}$ to $10^{-6}$ cm/s at lower confining pressure of 35 kPa and from $10^{-6}$ to $10^{-8}$ cm/s at higher confining pressure 276 kPa. This decrease in hydraulic conductivity can be attributed to the increase in density at higher confining pressure. At any given state of degradation, this trend of decrease in hydraulic conductivity with increase in density (or confining pressure) was found valid. This behavior was also observed with the synthetic MSW when the same tests were conducted using similar laboratory conditions [28]. Furthermore, unit weight of MSW was found to increase with degradation. This can be related to the reduction in particle size with phases of degradation, the increased percentage of fines, and therefore, resulting higher unit weight (density).

The rigid-wall hydraulic conductivity values of MSW at different stages of biodegradation were plotted against the levels of degradation (Fig. 4). Based on the results, it is found that the saturated hydraulic conductivity of MSW decreases with DOD. The decrease in hydraulic conductivity with increase in degradation is consistent with the published studies. Gabr and Valero [16] determined the hydraulic conductivity of waste collected from Pioneer Crossing Landfill, PA, which was about 15–30 years old. Constant and falling head hydraulic conductivity tests revealed permeability to vary from $10^{-5}$ to $10^{-3}$ cm/s. Landva and Clark [15] conducted constant head hydraulic

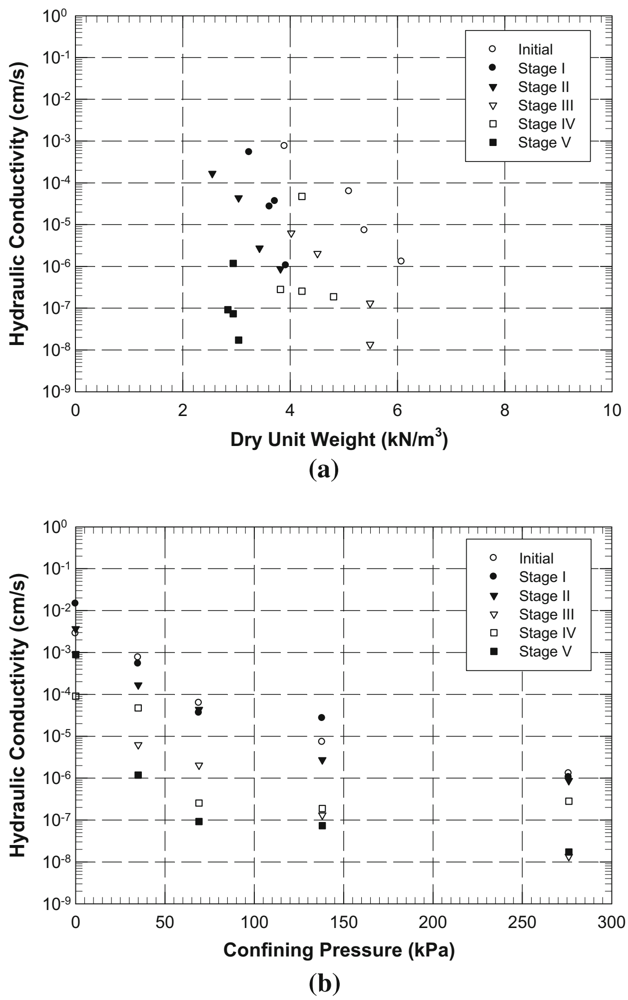



**Fig. 3** Variation of hydraulic conductivity of MSW with dry unit weight and confining pressure at different stages of degradation

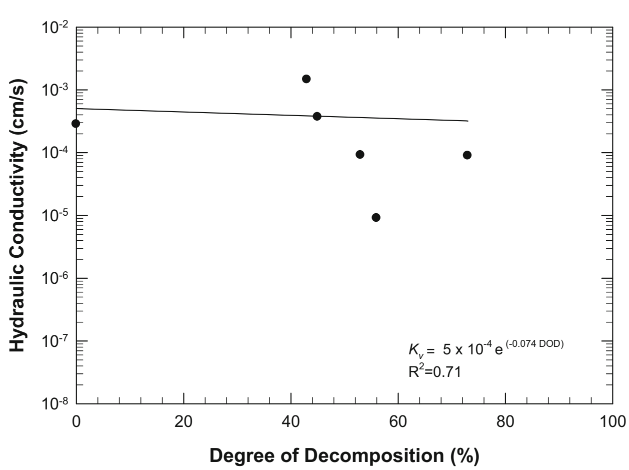



**Fig. 4** Correlation of hydraulic conductivity with degradation

conductivity tests on the field waste samples collected from various landfills in Canada and reported the permeability as $2 \times 10^{-3}$ to $2 \times 10^{-6}$ and $1 \times 10^{-3}$ to $4 \times 10^{-5}$ cm/s for vertical and horizontal placement of permeameter setup, respectively. Durmusoglu et al. [33] also conducted permeability tests for MSW obtained from Rock Prairie Road Landfill, Texas, which was approximately 10 years old and found the hydraulic conductivity of order $10^{-4}$ to $10^{-2}$ cm/s. They concluded that there was no scale effect for the permeability tests. Reddy et al. [28] also found similar results for synthetic MSW under different levels of degradation. It was found that hydraulic conductivity decreased ($10^{-2}$ to $10^{-4}$ cm/s) from fresh MSW to the highly degraded condition. In addition, at higher levels of degradation, hydraulic conductivity was found to be lower, but less dependent on the density, which was also evident from the results of this study (Fig. 3).

## Compressibility Characteristics

All compression tests demonstrated an instantaneous compression, followed by gradual time dependent compression. The maximum axial strain under 766 kPa was 54, 52, 62, 53, 48 and 53 % for fresh waste and subsequent degradation levels I, II, III, IV and V, respectively. The amount of compression immediately upon the first load application varied, but the subsequent compression with time was similar for all of the tests. The compressibility is expressed in terms of primary compression ratio (modified compression index) and secondary compression ratio (modified secondary compression index). The compression ratio or modified compression index ($C_{c\varepsilon}$) is defined as:

$$C_{c\varepsilon} = \frac{-\Delta\varepsilon}{\Delta \log \sigma}, \tag{2}$$

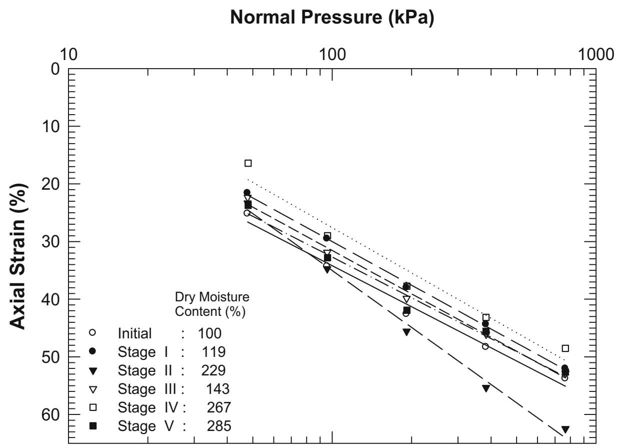
where $\Delta\varepsilon$ is the change in linear strain defined as the ratio of change in height ($\Delta H$) to the original height ($H_0$) and $\Delta\log\sigma$ is the change in vertical effective stress. The secondary compression ratio or modified secondary compression index ($C_{\alpha\varepsilon}$) is defined as:

$$C_{\alpha\varepsilon} = \frac{-\Delta\varepsilon}{\Delta \log t} \tag{3}$$

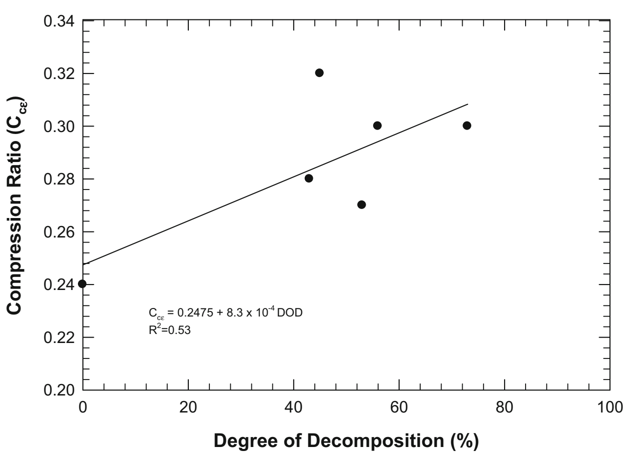
Figure 5 shows the compression behavior of MSW tested at different stages of decomposition. The slope of the best-fit line provides the primary compression ratio and these values are also summarized on this figure. It should be noted that compression ratio ($C_{c\varepsilon}$) is related to compression index ($C_c$) by:

$$C_{c\varepsilon} = C_c/(1 + e_0),$$

where $e_0$ is the initial void ratio. For a normal pressure of 48 kPa, the axial strain was found be higher for the fresh and Stage 1 (S1) MSW as compared to the other degraded samples; primarily their initial lower density and large particle size [28]. Similar trend can be seen for any given




**(a)**




**(b)**

**Fig. 5** Compressibility test results: **a** normal pressure versus axial strain at different stages of decomposition and **b** correlation of primary compression ratio with degradation

normal pressure, as the MSW sample degrades the axial strain is lowered. The compression ratio values ranged from 0.24 to 0.32 with different levels of degradation (Fig. 5b). The values of compression ratio obtained in this study are within the range reported in previously published studies. An increasing trend can be seen for the compression ratio ($C_{c\varepsilon}$) with degradation. This contradicts the correlation found for synthetic MSW which showed decreasing compression ratio with increase in degradation [28]. Some other reported studies reported no definitive correlation between the compression ratio and degradation [29, 33]. Further research is needed to determine the reasons for the lack of conclusive relationship between compression ratio and degree of degradation. Some factors that could affect the compression ratio values include compositional differences in the field samples used in different bioreactors and also small-scale testing performed in this study.

Long-term compressibility behavior (under the constant vertical pressure of 383 kPa) was tested on MSW that is undergone different levels of degradation. The slope of axial strain versus log time plot is defined as secondary compression ratio ($C_{\alpha\varepsilon}$). Figure 6 shows the correlation between secondary compression ratio and degree of degradation. The secondary compression ratio for all of the waste samples was very close, ranging from 0.012 to 0.015, demonstrating no significant effect of degradation on secondary compression over the period of testing considered. Tests for much longer time may be needed to assess the contribution of biodegradation-induced compression.

Lack of conclusive relationship between the compression ratio and degradation as well as nearly constant secondary compression ratio under short-term biodegradation conditions as observed in this study are also consistent with several published studies. Landva and Clark [15] performed consolidation tests on old waste materials and reported that the range of compression ratio ($C_c$) was 0.2–0.5. Kavazanjian [19] presented the results of 24 one-dimensional compression tests on MSW obtained from OII landfill with varying degrees of degradation and found values of compression ratios between 0.12 and 0.25 (on a volumetric strain basis). Vilar and Carvalho [21] studied the compressibility behavior of MSW recovered from the Bandeirantes sanitary landfill, Sao Paulo, Brazil. In their study, the MSW compression ratio ($C_{c\varepsilon}$) was observed to be about 0.21 based on the initial void ratio, whereas, the secondary compression ratio ($C_{\alpha\varepsilon}$), characterizing the creep behavior of the MSW, ranged from 0.021 to 0.044 with an average value of 0.032. Similar results for 15–30 years old MSW were reported by Gabr and Valero [16] with $C_c$ values ranging from 0.4 to 0.8, while secondary compression ($C_\alpha$) values ranged from 0.03 to 0.09 for the initial void ratio range of approximately 1.0–3.0. Wall and Zeiss [1] constructed six landfill test cells to simulate conventional and bioreactor landfills and found that there was no significant correlation between the settlement rate due to biodegradation in short term. Espinance et al. [34]

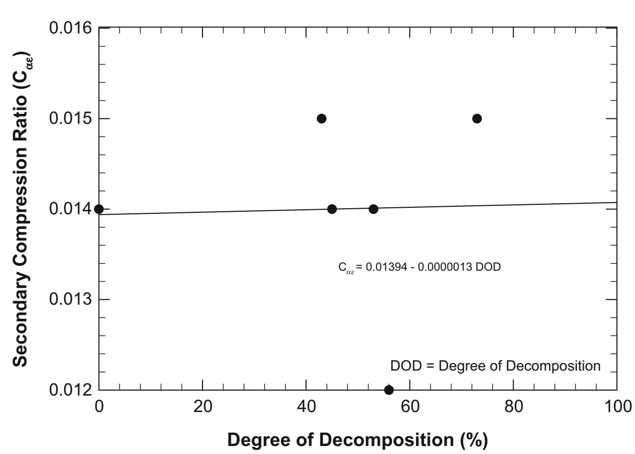



**Fig. 6** Correlation of secondary compression ratio with degradation

conducted two lysimeter tests and found that the settlement in the re-circulating lysimeter was almost two and half times greater than that of the conventional lysimeter after approximately 100 days from the beginning of operation. Since the samples simulating bioreactor landfill degraded faster when compared to the samples simulating conventional landfill, all results indicate that degraded MSW compressed more than fresh MSW.

### Drained Shear Strength

Figure 7a, b shows the typical horizontal displacement versus shear stress results from direct shear tests on fresh and the highly degraded (S6) MSW samples, respectively. A similar behavior was exhibited by other degraded samples as well. All specimens exhibited continuous gain in strength with increase in horizontal deformation. Shear strength parameters were determined at a horizontal deformation of 15 % of sample diameter. Figure 8 compares the failure envelopes obtained for MSW from all

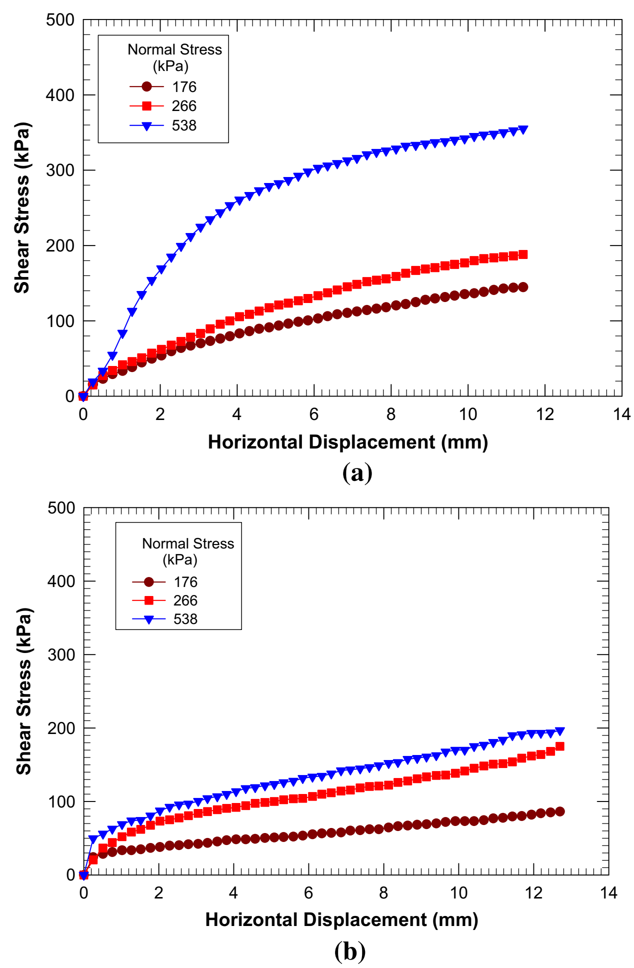



**Fig. 7** Typical direct shear test results for **a** fresh MSW and **b** most degraded MSW from Stage V

levels of degradation and a summary of shear strength parameters is also presented in this figure. As shown in Fig. 9, there is no distinct correlation of shear strength parameters with the degree of degradation; which could be contributed to the differences in the composition of the initial MSW samples used in bioreactors and/or those used for testing. However, the general trend observed is that the angle of friction decreased with degradation (from 30° to 12°), whereas the cohesion did not exhibit any consistent trend but varied from 29 to 65 kPa.

Caicedo et al. [35] used large-scale samples to conduct direct shear tests on relatively new (1 year aged) non-shredded MSW from Don Juana landfill in Bogota, Colombia and found the shear strength properties to be 78 kPa and 23°. The effects of degradation on shear strength parameters were determined by Hossain [25] based on direct shear tests on laboratory degraded MSW samples. The extent of degradation was documented by gas production rates as well as cellulose (C), hemicellulose (H), lignin (L), and (C + H)/L ratios. Angle of friction for bioreactor samples decreased from 32° to 24° as (C + H)/L ratio decreased from 1.29 (fresh waste) to 0.25 (phase IV/degraded waste). No cohesion was reported. These experimental results showed that as the degradation of organic material occurs, the percentage of non-degradable plastic increases to contribute to the decrease in friction angle. The friction angle followed similar trend, and cohesion existed and it increased with degradation.

### Consolidated Undrained Shear Strength

Figures 10 and 11 show the axial strain versus deviator stress and pore water pressure based on triaxial CU tests conducted on fresh and the highly degraded (S6) MSW samples, respectively. During the testing, deviator stress

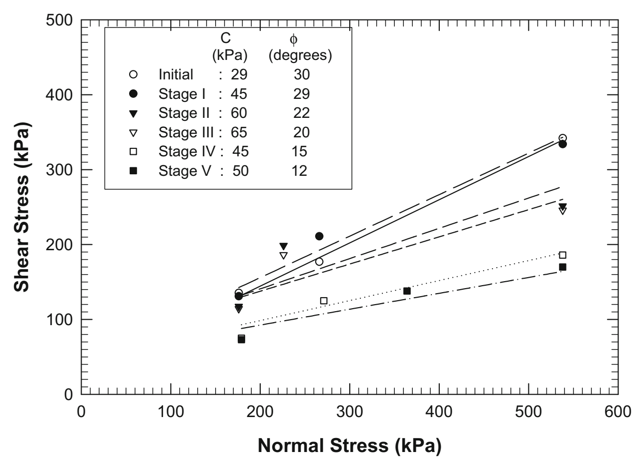



**Fig. 8** Failure envelope of different stages of degraded MSW based on direct shear test results

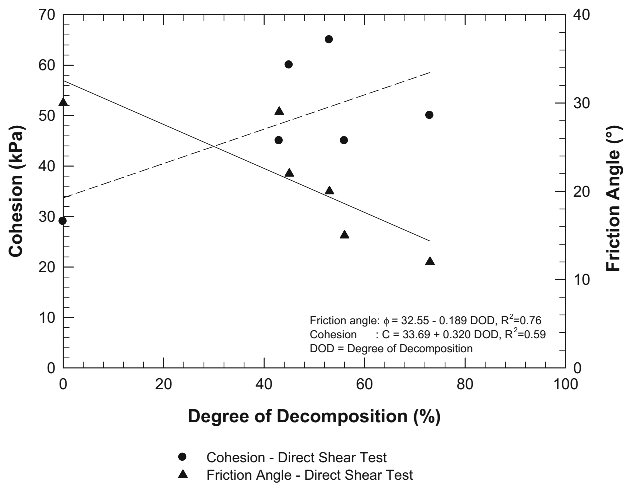



**Fig. 9** Variation of MSW shear strength parameters with decomposition based on direct shear test results

increased continuously with increase in axial strain, without exhibiting any peak or ultimate response. Other samples at different levels of degradation (S2–S5) showed similar trends. Many researchers have observed similar strain hardening behavior in the triaxial tests conducted using field MSW [17, 20, 22, 34, 35]. Therefore, the shear strength properties of MSW are strain dependent. In geotechnical testing, it is common to assume 15–20 % strain level as a failure condition and corresponding stresses were used to calculate shear strength parameters in this study. To compare the results with the direct shear test results, shear strength parameters were defined at 15 % strain in this study. Figure 12 shows calculated total and effective shear strength parameters. With regards to the total stress parameters, cohesion ranged from 14 to 51 kPa and angle of friction ranged from 7 to 14°; while the effective stress parameters, cohesion ranged from 14 to 48 kPa and angle of friction ranged from 6 to 13°. Figure 13 shows the plot between cohesion and angle of

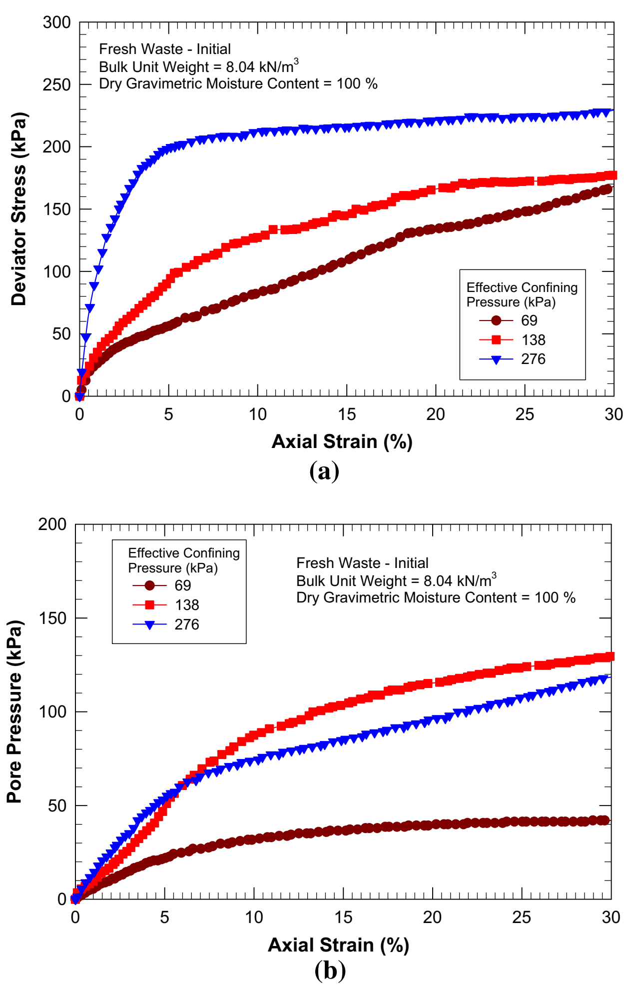



**Fig. 10** Typical triaxial consolidated undrained (CU) test results for fresh MSW: **a** stress–strain and **b** pore water pressure

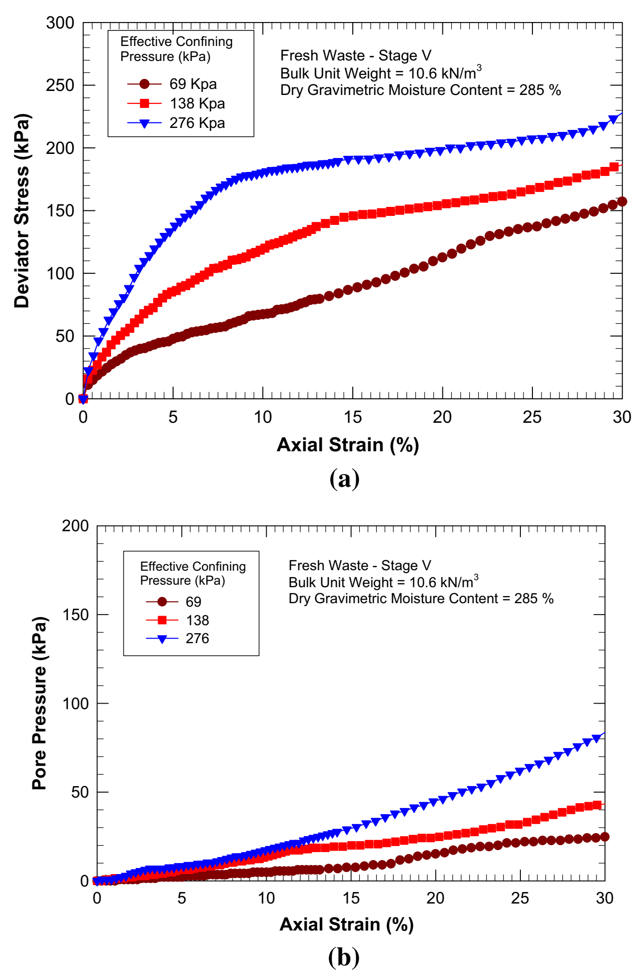



**Fig. 11** Typical triaxial consolidated undrained (CU) test results for the most degraded sample in Stage V: **a** stress–strain and **b** pore water pressure

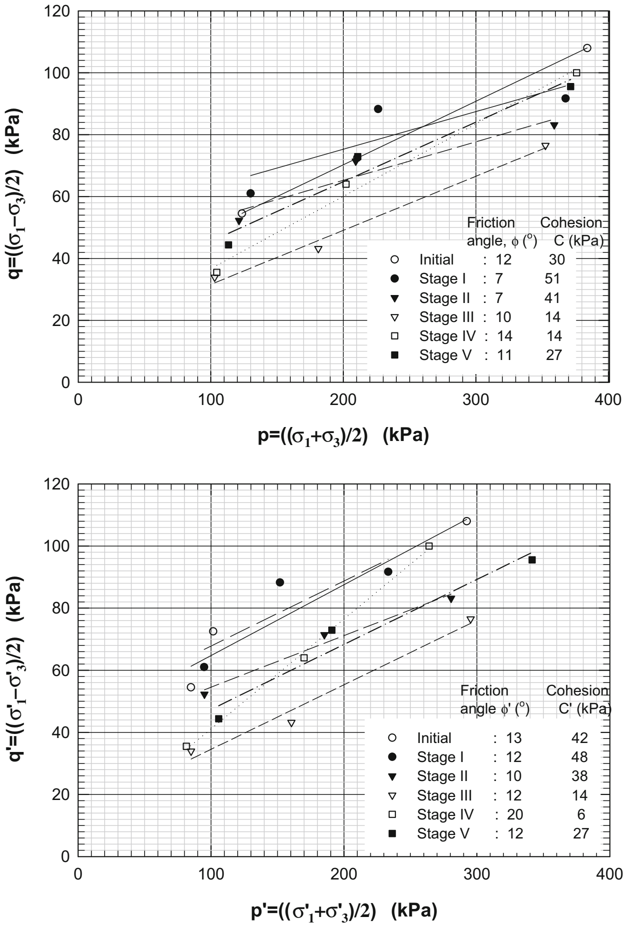



**Fig. 12** Shear strength of MSW at different stages of decomposition based on triaxial CU tests: **a** total shear strength parameters and **b** effective shear strength parameters

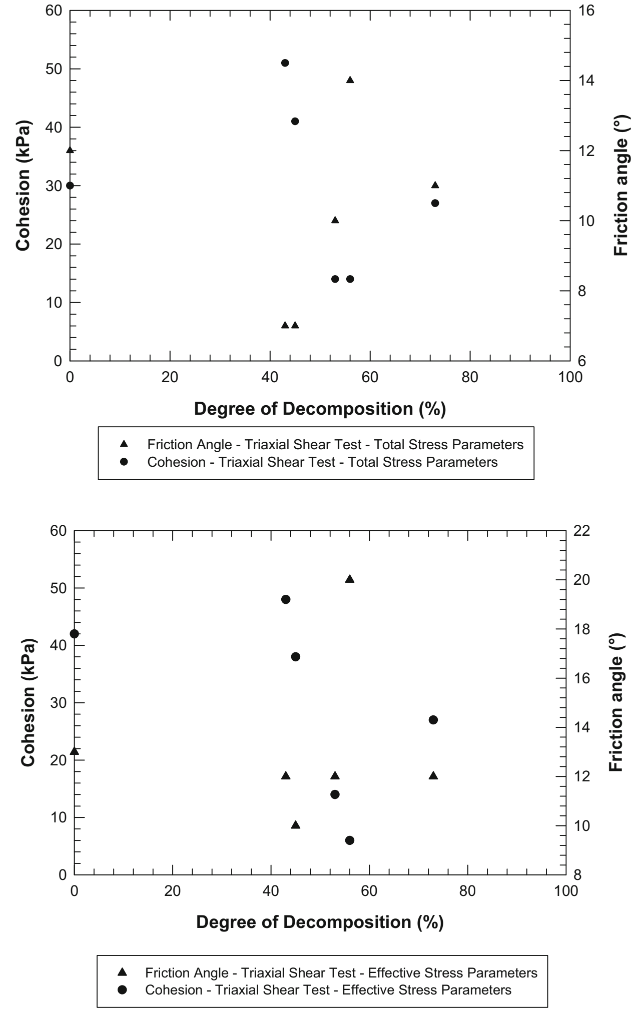



**Fig. 13** Correlation of shear strength parameters with degradation based on triaxial CU tests: **a** total shear strength parameters and **b** effective shear strength parameters

friction based on degree of degradation for all MSW samples tested using CU triaxial tests. In this study, no particular correlation was observed for shear strength parameters with respect to degradation, possibly due to heterogeneous nature of initial fresh MSW samples used in bioreactors. With the field MSW samples, it is difficult to achieve the same composition in the prepared samples.

Very limited triaxial testing on MSW has been reported in the literature. A small-scale consolidated undrained triaxial tests without pore pressure measurement, with 15–30 year-old waste resulted in cohesion and friction angle of 17 kPa and 34°, respectively [16]. Another CU triaxial test with pore water measurement on 1-year old MSW from the Dona Juana landfill did not reach peak strength for deformations up to 15 %, and resulted in an effective cohesion intercept of 45 kPa and a friction angle of 14° [35]. Zekkos [20] performed a comprehensive laboratory triaxial testing program on waste samples collected from the Tri-Cities landfill located in Fremont, California (without full saturation and without the pore water pressure measurement) and found a friction angle of 42°. Overall, the shear strength parameters of saturated waste samples in this study showed similarity to those reported elsewhere [35]; however, much lower friction angles were found for the degraded samples.

## Conclusions

Fresh MSW obtained from Orchard Hills landfill (Davis Junction, Illinois, USA) was degraded anaerobically in specially designed bioreactor cells with leachate recirculation and was tested at different levels of degradation to evaluate the geotechnical engineering properties of MSW (moisture content, organic content, unit weight, saturated hydraulic conductivity, compressibility, and shear strength properties). The following conclusions can be drawn from the results of this study:

- Leachate recirculation resulted in increase in the gas production and acceleration of biodegradation of MSW. Anaerobic degradation of MSW was evident from the measured concentrations of methane and carbon dioxide. Moisture content of MSW increased significantly (100–285 % on dry weight basis or 50–74 % on wet weight basis). Organic content of MSW decreased from initial (fresh) 84–58 % for the highly degraded stage (S6) considered in this study. Bulk unit weight of MSW increased from 7.12 to 10.79 kN/m$^3$ for highly degraded stage (S6) due to degradation. A linear trend of increase in unit weight was observed with cumulative gas production, since loss of organic matter resulted in increase in gas production, resulting in reduction in organic content, particle sizes and void ratio.
- Rigid-wall permeability tests on degraded MSW samples revealed that the hydraulic conductivity reduced from $10^{-2}$ cm/s for fresh waste to $10^{-4}$ cm/s for highly degraded sample (S6). Flexible-wall permeability tests showed that hydraulic conductivity decreases significantly with increase in confining pressure which causes density of the sample to increase. For initial and low levels of degradation, hydraulic conductivity decreased with increase in dry unit weight of the MSW; however, such reduction was not clearly evident for the most degraded MSW (S6) in this study.
- Primary compression ratio values varied from 0.24 to 0.32 and found to be within the range of previous published studies. The primary compression ratio shows a slightly increasing trend with degree of degradation, which needs further investigation by testing the samples with the same composition in a large-scale setup. The secondary compression ratio under short-term biodegradation conditions ranged narrowly from 0.012 to 0.015. Long-term biodegradation effects on secondary compression ratio should be further investigated.
- Direct shear tests showed angle of friction to decrease from 30° to 12° for initial stage to the most degraded stage (S6). However, cohesion values did not show any particular trend with degradation but showed generally decreasing trend from 29 to 65 kPa.
- In case of triaxial testing with pore pressure measurement, the total strength parameters, cohesion and friction angle ranged from 14–51 kPa and 7–14°, respectively. While the effective strength parameters, cohesion ranged from 14 to 48 kPa and angle of friction ranged from 6 to 13°. No particular correlation was observed for any of these shear strength parameters with respect to degradation parameters.

The lack of correlation between the geotechnical properties and the degree of degradation is attributed the heterogeneous nature of MSW collected from a landfill site. The composition and particle size distribution of the initial MSW samples used in each bioreactor may differ, making it difficult to ascertain the correlation between the geotechnical property and degree of degradation. In addition, large-scale testing should be undertaken to address the scale effects. Overall this study showed that engineering properties of field MSW are significantly affected by levels of degradation and these changes should be properly accounted in analysis and design of bioreactor landfills incorporating leachate operations.

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