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Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations

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This paper describes a comprehensive laboratory study performed to investigate the compressibility and shear strength properties of 1.5-year-old municipal solid waste (MSW) exhumed from a landfill cell where low amounts of leachate were recirculated. The study results are compared with results from a previous study on fresh MSW collected from the same landfill and data from previous studies with known MSW age to assess the variation in properties due to degradation. Laboratory testing was conducted on shredded landfilled and fresh MSW that consisted of similar particle-size distribution, with maximum particle size less than 40 mm and approximately 80% of the waste consisting of particles ranging from 10 to 20 mm. Standard Proctor, compressibility, direct shear, and triaxial consolidated undrained (CU) shear tests were conducted in general accordance with the American Society of Testing and Materials Standard Procedures. These tests were conducted with samples at an in-situ moisture content of 44% (dry weight basis) as well as elevated moisture contents of 60, 80 and 100% (dry weight basis). Standard Proctor compaction tests yielded a maximum dry density of 600 kg/m³ at 77% optimum moisture content for landfilled MSW compared to the 420 kg/m³ maximum dry density at 70% optimum moisture content for fresh MSW. Compression ratio values for landfilled MSW varied in a close range of 0.19–0.24 with a slight increasing trend with increase in moisture content; however, for fresh waste they were in the close range of 0.24–0.33 with no definitive correlation with moisture content. Based on direct shear tests, drained cohesion and friction angle were varied in the range of 12–64 kPa and 31–35° for landfilled MSW and 31–64 kPa and 26–30° for fresh MSW. Neither cohesion nor friction angle demonstrated any correlation with the moisture content. Based on triaxial CU tests, the average total strength parameters (TSP) were found to be 39 kPa and 12° for landfilled MSW and 32 kPa and 12° for fresh MSW, while effective strength parameters (ESP) were 34 kPa and 23° for landfilled MSW and 32 kPa and 16° for fresh MSW. This study was limited to small-scale laboratory testing using MSW samples with the specimen size relative to the maximum particle size in the range of 1.6 to 2.6; therefore, large-scale laboratory and field studies are recommended to systematically assess the influence of composition, particle size distribution and specimen size on the geotechnical properties of MSW.

Keywords: Municipal solid waste (MSW), leachate recirculation, bioreactor landfills, moisture content, biodegradation, compressibility, compaction characteristics, shear strength, friction angle, cohesion

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Introduction

Landfilling is an economical way of disposing of municipal solid waste (MSW) compared to other techniques such as incineration and composting. As stated by the United States Environmental Protection Agency, 54% of the waste generated in the United States is being disposed of in landfills (USEPA 2007). Design and implementation of new landfills or expansion of existing landfills is necessary to accommodate this ever increasing volume of MSW. Geotechnical engineering properties of MSW such as compressibility and shear strength are of prime importance in design and maintenance of these landfills (Sharma & Reddy 2004).

In recent years, there has been a paradigm shift in the philosophy and the thought process behind landfill design from the dry tomb concept towards the bioreactor approach. In the bioreactor approach, the moisture content of the MSW is increased by recirculation of leachate to enhance biodegradation of MSW. In addition to the rapid degradation, bioreactor landfills also offer a significant reduction in post-closure management (Reddy & Bogner 2003).

Bioreactor landfills have presented a number of concerns and challenges to designers as well as operators of landfills. Rapid settlement of MSW during construction and operation of a bioreactor landfill can damage the landfill infrastructure such as pipe networks. Settlement is typically estimated using compressibility characteristics that are typically assumed to be constant. However, it is not well understood how the compressibility characteristics vary with time as the biodegradation of waste continues in the landfill. Engineers are also sceptical about the stability of bioreactor landfills (Koerner & Soong 2000). Recirculation of leachate in bioreactor landfills increases moisture content and enhances the biodegradation of MSW, resulting in changes in particle size and composition of waste. Therefore, it is important to quantify the influence of such changes on shear strength properties of MSW. The time variation of compressibility and shear strength properties of MSW due to increased moisture levels and biodegradation is particularly useful to understand and assess the settlement and stability behaviour of bioreactor (or leachate recirculation) landfills. Numerous studies conducted on the geotechnical properties on MSW are reported in the literature (Landva & Clark 1990, Fassett *et al.* 1994, Gabr & Valero 1995, Kavazanjian 2001, Hossain 2002, Sharma & Reddy 2004; Dixon *et al.* 2005, Gabr *et al.* 2007); however, limited research has been conducted to investigate the effects of increased moisture content and biodegradation on the geotechnical properties of MSW.

This paper describes a comprehensive laboratory study conducted on 1.5-year-old MSW exhumed from a landfill cell subjected to low amounts of leachate recirculation to investigate compressibility and shear strength properties. The results are compared with the results from a previous study (Reddy *et al.* 2009) on fresh MSW collected from the same landfill to assess the variation in geotechnical properties due to enhanced degradation resulting from leachate recirculation. Unless stated otherwise, moisture content in this

study is defined as the dry gravimetric moisture content which is equal to the ratio of the mass of moisture to the mass of solids. All the experiments were carried out in accordance with the standard procedures established by the American Society of Testing and Materials (ASTM) for soils (ASTM 2006).

Sample collection and characterization

MSW samples were collected from the Orchard Hills landfill (Davis Junction, Illinois, USA) owned and operated by Veolia Environmental Services. Landfilling started in the year 1988 and is expected to be completed by 2018. Leachate recirculation was accomplished by spraying the working face during filling operations and thereafter using a network of multi-level horizontal leachate recirculation lines (LRLs) installed within the waste. The LRLs consisted of perforated HDPE pipes 15-cm in diameter in gravel-filled trenches spaced at 15–20 m between centres. Leachate was recirculated intermittently depending on the availability of leachate at the site.

Landfilled MSW samples were collected from borehole #16 at a depth of 20 m. The borehole was drilled using a bucket auger that was 0.9 m in diameter and 1.5 m long. Samples collected from borehole #16 were approximately 1.5 years old. Two LRLs were located at a close proximity to the sampling location at borehole #16: LRL29 located 7.5 m south of borehole #16 at a depth of 12 m and LRL26 located 12 m north of GEW16 at a depth of 22 m. Approximately 530 and 620 m³ of leachate was recirculated at LRL26 and LRL29, respectively, for approximately 1 year. Consequently, the samples collected at borehole #16 represent MSW at 1.5 years of age that has been subjected to low amounts of leachate recirculation.

Composition of the MSW samples was determined according to MODECOM protocol developed by the French Environmental Protection Agency (as referenced in Grellier *et al.* 2007). The detailed composition of waste is shown in Table 1 and compared with the composition of fresh waste at the same landfill. Samples from the working face are assumed to represent the fresh waste disposed at the location of borehole #16. As summarized in Table 1, MSW from borehole #16 and fresh waste consisted of approximately 29% nonbiodegradable (inert) components. The initial 7% easily biodegradable fraction has been reduced to 1% in the landfilled waste. Assuming the samples recovered from borehole #16 had an initial biodegradable fraction equivalent to that of fresh waste, a reduction of approximately 6.5% can be attributed to the enhanced degradation by leachate recirculation.

Based on testing of four large samples (greater than 5 kg each), in-situ moisture content of both fresh and landfilled waste was found to have approximately the same value of 44% (dry weight basis). During the moisture content determinations, the temperature was maintained at 60 °C to avoid combustion of volatile organic components. The effect of

Table 1: Composition of fresh and landfilled MSW at Orchard Hills landfill.

Category	Waste type	Fresh waste composition (% by wet mass [*])		Landfilled waste composition (% by wet mass [*])	
Easily biodegradable	Cooking waste	6.6	6.9	0.5	0.5
	Garden waste	0.3		0.0	
Medium biodegradable	Paper	8.2	24.6	6.6	23.8
	Cardboard	13.3		16.1	
	Food carton	0.0		0.0	
	Sanitary waste	3.1		1.1	
Hardly biodegradable	Textiles	5.8	19.2	4.8	13.4
	Nappies	1.7		0.1	
	Wood	11.7		8.5	
Inert waste	Metal	4.4	29.2	4.1	28.5
	Plastic bottles	5.7		5.7	
	Other plastics	5.3		9.7	
	Special waste	0.0		0.0	
	Medical waste	0.1		0.0	
	Other waste	3.5		3.6	
	Inert waste	5.8		5.0	
	Glass	4.4		0.4	
Residual fines ^{**}	Fines (< 20 mm)	20.1	20.1	33.8	33.8

* Both fresh and landfilled waste had approximately the same initial moisture content of 44%.

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

temperature was investigated initially by heating the samples at 40, 60 and 105 °C for different elapsed time periods for a maximum duration of 72 h. Based on this testing, it was found that heating the samples at 60 °C for 24 h resulted in approximately the same value as heating the sample at 105 °C for 24 h. The similar moisture content of fresh and landfilled waste indicates that the leachate recirculation operations did not increase the moisture content of the waste and it may be mainly attributed to the low amounts of leachate that were injected.

The four dry samples were then heated in large porcelain dishes to 440 °C in a muffle furnace to determine the organic content of both fresh and landfilled MSW in accordance with ASTM D2974. The influence of the furnace temperature and duration of heating was investigated by heating the samples at 440 and 550 °C for different elapsed time periods for a maximum duration of 24 h. The variation between the organic content values at the two temperatures was quasi constant after approximately 4 h, with the maximum difference ranging between 6 and 10%. The organic content based on testing at 440 °C for 24 h was found to be $76.2 \pm 6.0\%$ for fresh waste and $63.1 \pm 9.1\%$ for landfilled waste. This demonstrates that a reduction of over 10% in organic content has occurred due to degradation within 1.5 years. The specific gravity of solids determined in respect to ASTM D854 showed specific gravity of 0.85 ± 0.13 for fresh MSW and 0.97 ± 0.06 for landfilled MSW. The specific gravity is inversely proportional to the organic content; therefore, increase in specific gravity indicates reduction in organic content in the landfilled MSW.

A set of three large sieves with opening diameters of 100, 50 and 20 mm were used to determine the gradation of the landfilled and fresh waste samples collected from the landfill. The fresh MSW samples had approximately 53, 16 and 11% (by wet weight basis) of the MSW retained on 100, 50 and 20 mm sieves and 20% (by wet weight) finer than 20 mm. The landfilled MSW had approximately 40, 12 and 13% retained on 100, 50 and 20 mm sieves, respectively, and the percentage passing the 20 mm sieve was 35%. These results show that greater amounts of finer materials were present in the landfilled waste, which may be due to degradation of waste as well as the presence of daily cover soil.

Since large-scale laboratory testing was not available for this study, the MSW samples were shredded using a slow-speed, high torque shredder (Shred Pax Corp., AZ-7H, Wood Dale, IL). The shredding resulted in approximately the same size distribution for both landfilled and fresh MSW as shown in Figure 1. The maximum particle size was less than 40 mm, with about 20% of the MSW having particles smaller than 10 mm. Standard Proctor compaction tests conducted using a 102 mm interior diameter mould on the landfilled MSW yielded a maximum dry density of 600 kg m^{-3} at 77% optimum moisture content (see Figure 2) in comparison with 420 kg m^{-3} maximum dry density at 70% optimum moisture content in the fresh MSW obtained from the same landfill (Figure 2). The increase in the maximum dry density is believed to be due to the presence of finer particles resulting from degradation in landfilled MSW.

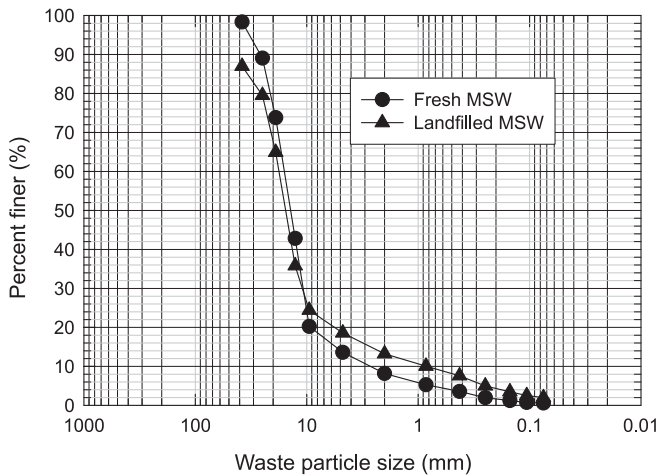


Fig. 1: Size distribution of shredded landfilled and fresh MSW.

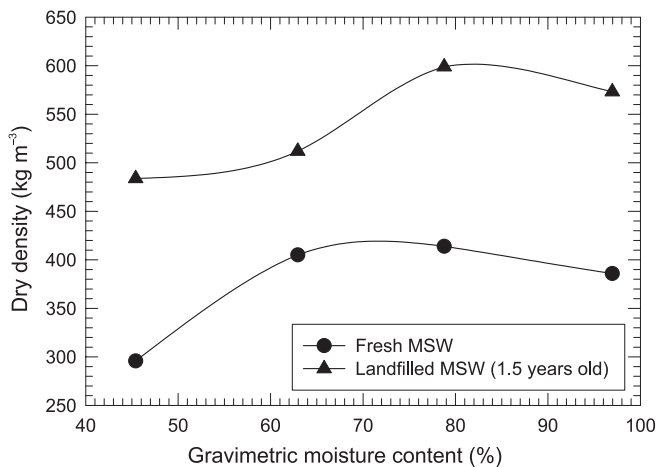


Fig. 2: Dry density-moisture content relationship for shredded MSW.

Testing methods

The majority of the previous studies have focused on testing either individual waste components or reconstituted waste samples with predefined proportions (Landva & Clark 1990, Grisolia *et al.* 1991, Gabr & Valero 1995, Wall & Zeiss 1995). In this study, the waste samples collected from the field were shredded without any pre-sorting. Compressibility and shear strength tests were conducted. These test results reflect the properties of the 1.5 years old MSW subjected to low amounts of leachate recirculation.

Compressibility tests

Confined compressibility testing was carried out in a floating ring oedometer to determine the compressibility characteristics of landfilled MSW with varying moisture content. In this investigation, the MSW sample was placed in an oedometer with one porous stone on the top and another beneath the MSW sample. Landfilled MSW was compacted into 63 mm inside diameter and 27 mm thick circular oedometer rings with a tamper. Leachate was added to MSW to prepare samples at in-situ moisture content of 44% and elevated moisture contents of 60, 80, and 100%. The average initial dry

density of the samples was 530 kg m^{-3} . An instantaneous compression, followed by gradual time-differed compression, characterizing a process of mechanical compression, was observed during loading. For each load increment, strain vs. time readings were recorded until the primary compression process was complete.

Direct shear tests

Direct shear tests were conducted to determine the drained shear strength parameters (cohesion and the angle of internal friction) of landfilled MSW at different moisture contents. Tests were performed in accordance with ASTM D3080 in a circular shear box with 63 mm inside diameter and 49 mm height. Leachate was added to MSW to prepare samples at four different moisture contents of 44, 60, 80 and 100%. The average initial dry density of the samples was 450 kg m^{-3} . The samples were sheared at a constant strain rate under four different normal stress conditions: 176, 266, 538 and 774 kPa.

Consolidated undrained triaxial tests

In order to perform consolidated undrained (CU) triaxial testing, the landfilled MSW was compacted in a cell. The tests were conducted on samples with four different initial moisture contents of 44, 60, 80 and 100%. Tests were performed according to the ASTM D4767 with cylindrical samples with an average diameter of 70 mm and height of 140 mm. Three samples were prepared with the same moisture content, extruded and then inserted into latex membranes. All samples were initially subjected to a confining pressure of 35 kPa and 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. Pore water pressures were measured during shearing. To ensure uniform pore pressures throughout the specimen, samples were sheared at a constant strain rate (approximately 1% per minute). The initial average dry density of all samples was 440 kg m^{-3} and it increased by an average 27% under a low confining pressure of 69 kPa and an average 55% under high confining pressure of 276 kPa.

Results and discussion

Compressibility

Compression test results of the landfilled waste are shown in Figure 3 and the compression ratios obtained for each moisture content test are presented in Table 2. The compression ratio of the landfilled MSW showed a slight increasing trend with increase in moisture content, even though no definitive correlation was observed within the range of moisture contents considered in this study. All four compression ratio values fell into a close range of 0.19–0.24 (with an average of 0.21 and 0.02 standard deviation). Fresh MSW collected from the working face of the same landfill had compression ratio values in the close range of 0.24–0.33 (with an average

Table 2: Variation of compressibility with the MSW age.

Source	Age of MSW (years)	Test type	Compression ratio
Reddy <i>et al.</i> (2009)	Fresh	Laboratory	0.28 (44%)*
			0.25 (60%)
			0.33 (80%)
			0.24 (100%)
Hettiarachchi (2005)	Fresh	Laboratory	0.18–0.21
Hossain <i>et al.</i> (2002)	Fresh	Laboratory	0.16–0.25
Landva & Clark (1990)	Fresh	Laboratory	0.35
Hunte <i>et al.</i> (2007)	0.5	Field	0.21
Current research	1.5	Laboratory	0.19 (44%)
			0.20 (60%)
			0.20 (80%)
			0.24 (100%)
Dermusoglu <i>et al.</i> (2006)	10	Laboratory	0.13–0.26
Sheurs & Khera (1980)	5–15	Field	0.18
Burlingame (1985)	5–15	Field	0.15
Vilar & Carvalho (2004)	15	Laboratory	0.21
Oweis & Khera (1990)	15–20	Field	0.06–0.26

*Numbers in parenthesis are the moisture contents at which the compression tests were conducted.

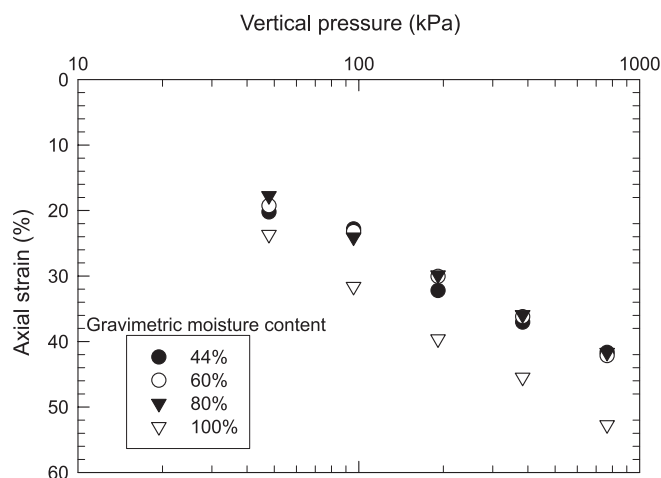


Fig. 3: Variation of compressibility of shredded MSW with moisture content.

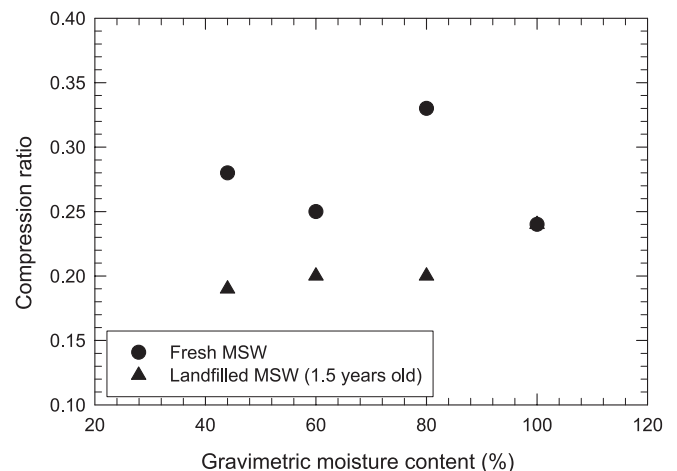


Fig. 4: Compression ratio vs. moisture content for shredded MSW.

of 0.27 and standard deviation 0.04). These results did not exhibit any specific increasing or decreasing trend in compressibility for the same range of moisture content (Reddy *et al.* 2009). This variation in compressibility of fresh and 1.5-year-old landfilled MSW is compared in Figure 4. Durmusoglu *et al.* (2006) observed a decrease in compression ratio value with increasing moisture content from small-scale consolidometer tests, but an increase in compression ratio with increasing moisture content when a large-scale consolidometer was used. Despite the differences in the type of consolidometer and the moisture content, the compression ratio values varied in a relatively narrow range of 0.13 to 0.26. Vilar & Carvalho (2004) studied the compressibility of 15-years-aged MSW recovered from Bandeirantes sanitary landfill in Brazil. The compressibility of this aged waste was found to be 0.21, but it was not influenced by saturation.

In order to determine if there is any correlation between compression ratio of MSW and its age, the findings from the current study were compared with the compression ratios reported in the literature for MSW of known age (Table 2). Values reported for fresh MSW were comparable and varied in a wide range from 0.16 to 0.35 (Landva & Clark 1990, Hossain 2002, Hettiarachchi 2005, Reddy *et al.* 2009). The compression ratios for MSW older than 10 years also varied in a wide range from 0.06 to 0.26 (Sheurs and Khera 1980; Burlingame, 1985, Oweis and Khera, 1990; Vilar and Carvalho 2004; Durmusoglu *et al.* 2006). However, the mean value of the range for old MSW (≈ 0.16) is much less compared to the mean value of the range for fresh MSW (≈ 0.26). In contrast, results from Hunte *et al.* (2007) and from the current study (0.5 and 1.5-year-old MSW, respectively) varied in a very narrow range from 0.19 to 0.24 falling between the mean values

for old and fresh MSW. Although it is difficult to statistically support a firm conclusion, this simple comparison shows a decreasing trend in compression ratios with increasing age.

Variation in the testing procedures is one reason why it was not possible to conduct a quantitative analysis with the data presented in Table 2. These variations did not provide a fair basis to make any definitive conclusions because the equipment and/or method utilized in those studies differed. Sample diameters varied from 63.5 mm (traditional oedometer cell) to 470 mm (large consolidometer). Not all of the tests were laboratory studies. Values reported by Oweis & Khera (1990), Sheurs & Khera (1980), and Burlingame (1985) were based on field studies. Hunte *et al.* (2007) back-calculated compression ratio using stress–strain data collected during the filling phase of the Calgary Biocell Landfill in Canada.

A fair comparison was also prevented by the variation in gradation and composition of waste samples. Gradation data was only available for a few studies. Field results were based on real scale MSW, but most tests were conducted using shredded MSW or reconstituted MSW to accommodate the specimens in oedometers. Of all these disparities, the difference in composition of MSW is perhaps the most influential factor on compressibility. Composition changes with time as a result of biodegradation. Different types of waste (such as food waste, plastics, and metal) exhibit different levels of compressibility. The composition of MSW varies not only from place to place but also over time. There can be seasonal variations in the composition of the MSW received by the same landfill. Due to increased recycling activities, the average annual composition of MSW received at a particular landfill 10 years ago may be different from what it receives now. Biodegradation occurs rapidly in bioreactor landfills; therefore, the composition of MSW that was subjected to leachate recirculation during a certain period of time will not be similar to the composition of MSW that was not subjected to leachate recirculation even if the original compositions were comparable. Such differences in initial composition and rate of biodegradation make compressibility data from different studies difficult to compare irrespective of the similarity in age of the samples.

Drained shear strength

Drained shear strength parameters for the landfilled MSW were determined at different moisture contents by direct shear tests. Figure 5 shows the direct test results for landfill waste at an in-situ moisture content of 44%. Similar trends were observed for specimens tested at increased moisture contents (60, 80, and 100%). MSW is known for not exhibiting a peak shear stress during shearing. Many researchers have observed hardening behaviour of MSW irrespective of the age of MSW or the testing technique (Jessenberger & Kockel, 1993, Gabr & Valero 1995, Grisolia *et al.* 1995, Kavazanjian 2001, Caicedo *et al.* 2002, Vilar & Carvalho 2002). Therefore it is generally believed that the shear strength

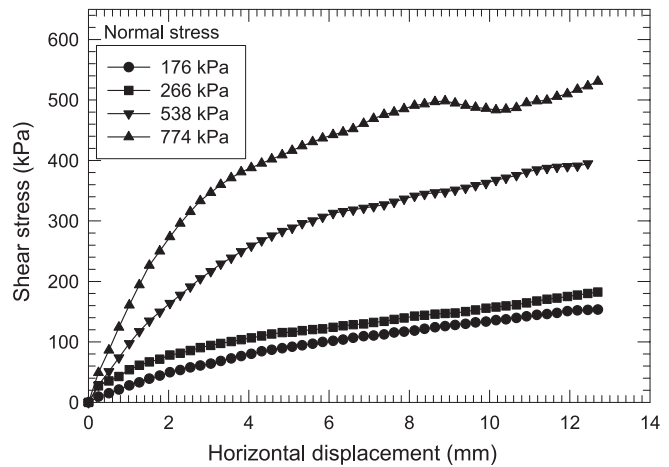


Fig. 5: Direct shear test results under in-situ moisture content (44%) for shredded landfilled MSW.

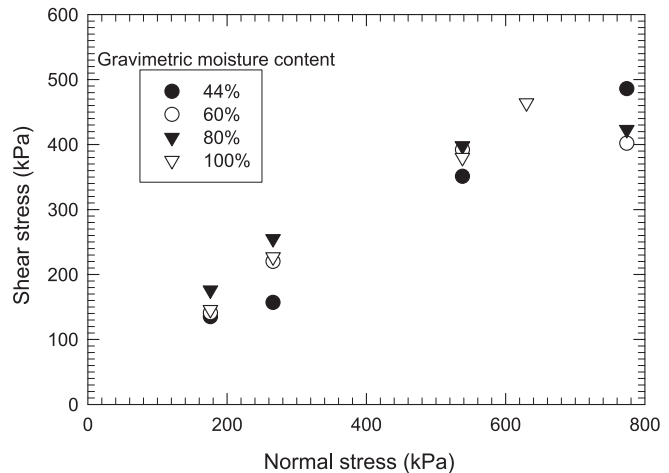


Fig. 6: Mohr–Coulomb failure envelope for shredded MSW at different moisture contents established by direct shear tests.

properties of MSW are displacement dependent. During this study, the landfilled MSW showed continuous strength gain at horizontal deformation well in excess of 15% of the specimen diameter. It is customary in geotechnical engineering to define strength at 15 to 20% strain in the event of a continuous strength gain. Currently, no standard cut-off displacement value is used to define MSW shear strength. Data found in literature often uses 10–20% deformations to define MSW shear strength (Gabr & Valero, 1995, Kavazanjian *et al.* 1999, Caicedo *et al.* 2002). During this research the strength was defined at 15% horizontal deformation so that the results can be compared to the values reported in the published literature.

Mohr–Coulomb shear strength envelopes for tests at 44, 60, 80 and 100% moisture contents are given in Figure 6 and the shear strength parameters calculated from Figure 6 are summarized in Table 3. It is observed that the cohesion of landfilled MSW varied from 12–63 kPa and the drained friction angle ranged from 31–35°. As shown in Figure 7, both cohesion and friction angle of 1.5-year-old landfilled MSW

Table 3: Drained shear strength properties of MSW based on direct shear testing.

Source	Age (years)	Strain at strength (%)	Cohesion (kPa)	Friction angle (°)
Reddy <i>et al.</i> (2009)	Fresh	15	46 (44%)*	30 (44%)*
			64 (60%)	26 (60%)
			32 (80%)	28 (80%)
			31 (100%)	30 (100%)
Landva & Clark (1990)	Fresh	–	23	24
Caicedo <i>et al.</i> (2002)	1	15	78	23
Current research	1.5	15	12 (44%)	32 (44%)
			63 (60%)	31 (60%)
			34 (80%)	35 (80%)
			56 (100%)	32 (100%)
Howland & Landva (1992)	10–15	–	17	33
Gabr & Valero (1995)	15–30	5–10	0–28	20–39

*Numbers in parenthesis are the moisture contents at which the direct shear tests were conducted

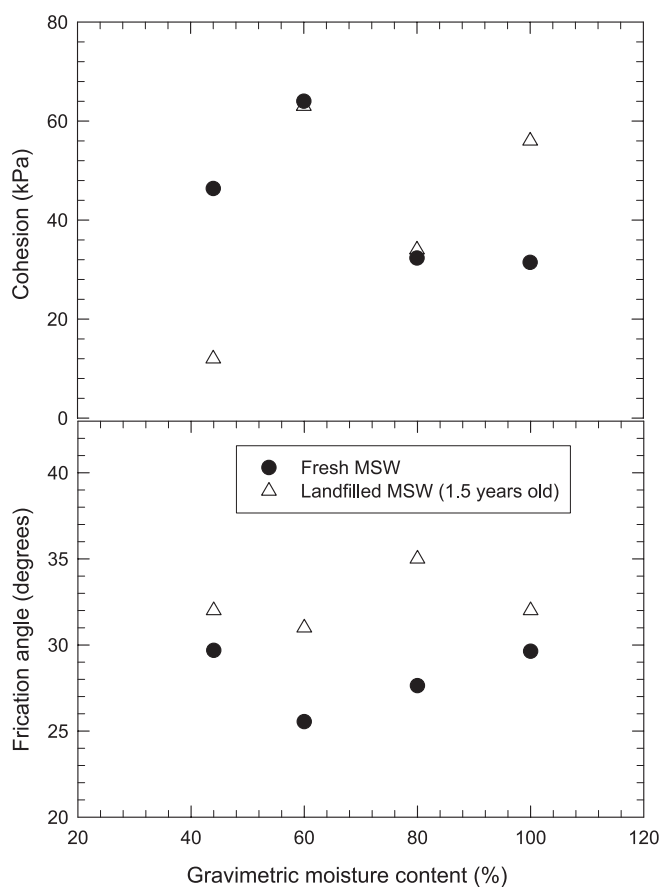


Fig. 7: Drained shear strength parameters for shredded MSW at different moisture contents based on direct shear tests.

did not show any specific increase or decrease for the range of moisture content tested in this study. This is in agreement with the shear strength behaviour of fresh MSW from the same landfill at the same moisture levels (Table 3 and Figure 7). No specific correlation between shear strength and moisture content was also observed for fresh MSW (Reddy *et al.* 2009).

Landva & Clark (1990) conducted direct shear tests on large specimens of shredded fresh MSW from Edmonton,

Canada and reported 23 kPa and 24° as shear strength properties. Caicedo *et al.* (2002) also used large specimens to conduct direct shear tests on relatively new (1-year-old) unshredded MSW from Don Juana landfill in Bogota, Colombia. The shear strength properties were found to be 78 kPa and 23°. Howland & Landva (1992) reported 16 kPa and 33° as the shear strength properties for 10–15-year-old MSW. Gabr and Valero (1995) conducted direct shear tests on 15–30-year-old MSW and the resulting shear strength properties ranged from 0–28 kPa and 20–39°. To investigate the possible variation in shear strength as it correlates to the age of MSW, results from the current study were compared with data from the studies conducted on MSW with known ages as explained above. This comparison is also presented in Table 3. It is evident from Table 3 that the cohesion as well as drained angle of friction varies over a wide range. Even though it is difficult to prove statistically, a slight increase in angle of friction can be observed with increasing age.

The information presented in Table 3 is not sufficient to identify any correlation between cohesion and the age of MSW. The wide variation in cohesion may be attributed to the differences in the initial composition of MSW and level of biodegradation. According to Caicedo *et al.* (2002), the MSW samples from Dona Juana landfill had a much higher percentage of biodegradable material (47.8% by weight) in comparison with the landfills in Japan and United States and the corresponding cohesion (78 kPa) was also high. Gabr & Valero (1995) reported 0–27 kPa for 15–30-year-old landfilled MSW. A low percentage of organic matter is expected in MSW after such a long period of time in a landfill; therefore, it is possible that degradable organic matter such as food waste could be responsible for the cohesive properties of MSW. It is difficult to identify a correlation between the shear strength properties and biodegradation because MSW from different locations have different initial compositions and they may have been subjected to different rates of biodegradation. Ideally, to identify such a correlation, tests should be conducted on samples with the same initial composition but at different levels of biodegradation.

Table 4: Shear strength properties of MSW based on triaxial consolidated undrained (CU) testing.

Source	Age (years)	Cohesion (kPa)	Friction angle (degrees)	Stress calculation method
Reddy <i>et al.</i> (2009)	Fresh	32	12	TSP
		38	16	ESP
Caicedo <i>et al.</i> (2002)	1	45	14	ESP
Current research	1.5	38	12	TSP
		34	23	ESP
Gabr & Valero (1995)	15 – 30	17	34	TSP

Note: Gabr & Valero (1995) defined shear strength at 20% strain. All other studies in the table considered 15% strain.

Consolidated undrained shear strength

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 no drainage occurring when additional stresses are applied quickly (Holtz & 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 more suitable to analyze stability of a bioreactor landfill. Based on the measured pore water pressures, effective stresses and effective shear strength parameters can also be calculated.

Figure 8 shows the triaxial CU test results of landfilled waste at an in-situ moisture content of 44%. Similar trends were observed for the tests conducted with samples at higher

initial moisture contents of 60, 80 and 100%. Deviator stress increased continuously, without reaching any peak or ultimate value. This behaviour was observed 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 4 summarizes the total and effective shear strength properties obtained from CU tests. The average total strength parameters (c and ϕ) were found to be 38 kPa and 12°, while the effective strength parameters (c' and ϕ') were 34 kPa and 23°. In the case of fresh MSW, the average total strength parameters (c and ϕ) were found to be 32 kPa and 12°, while effective strength parameters (c' and ϕ') were found to be 38 kPa and 16° (Reddy *et al.* 2009). Gabr and Valero (1995) reported average effective strength parameters of cohesion of 17 kPa and friction angle of 23° for 15-year-old landfilled MSW. 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 that found for fresh MSW from the Orchard Hills landfill (Reddy *et al.* 2009). As explained before, such differences are assumed to be due to the presence of higher percent of organic matter in the MSW from Don Juana landfill. All CU test results from the Orchard Hills Landfill are compared in Figure 9 with the results reported by Caicedo *et al.* (2002) and Gabr & Valero (1995). ESP showed a general trend of decreasing cohesion and increasing angle of friction with the age of MSW. Overall, the shear strength of MSW under CU conditions is low, leading to serious slope stability concerns. However, it should be recognized that CU conditions represent the worst-case condition where drainage is not permitted and the potential for existence of such conditions in real-world landfill conditions, particularly continued leachate recirculation in moderately or highly degraded waste, should be critically evaluated.

The large size and heterogeneous nature of MSW makes performance of any in-situ or laboratory testing difficult and interpretation of the test results challenging. In particular, the gradation and composition of the MSW may not be replicated exactly in laboratory testing. Although large-scale laboratory testing is preferred over small-scale testing in order to more closely simulate the conditions of the field MSW, the

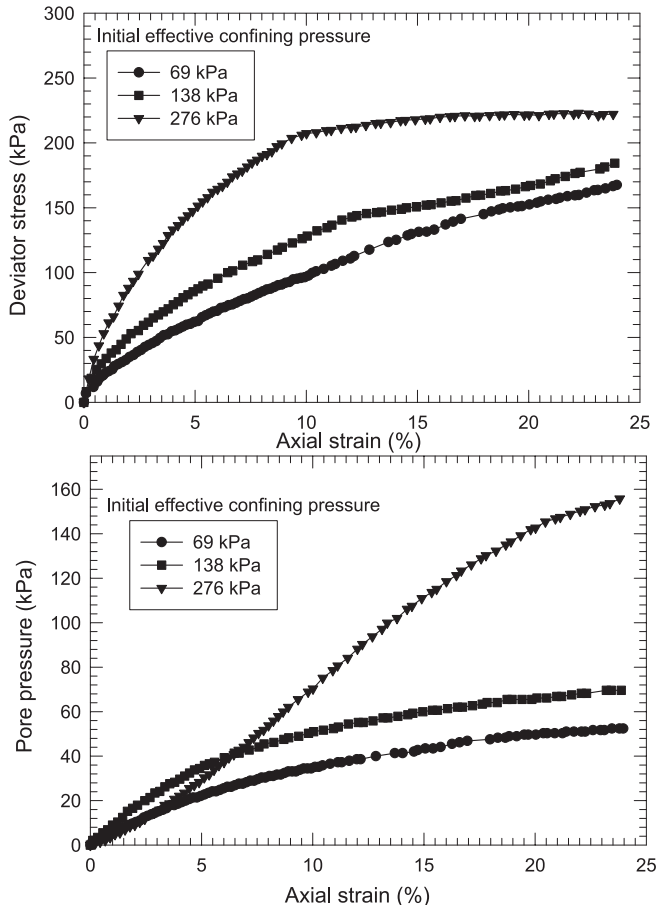


Fig. 8: Triaxial consolidated undrained test results for shredded landfilled MSW under in-situ moisture content of 44%.

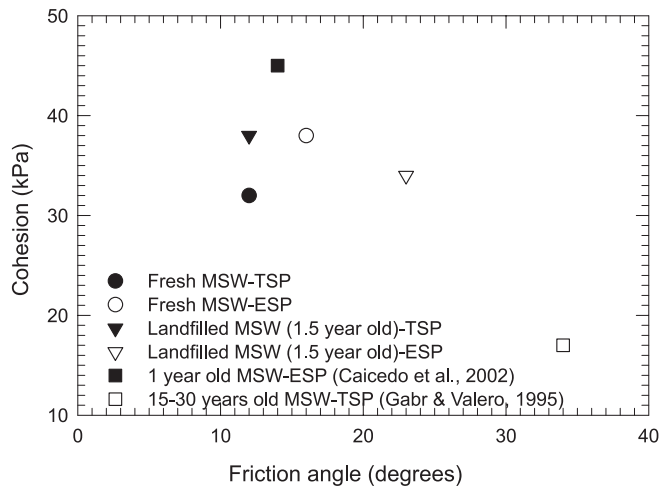


Fig. 9. Distribution of shear strength parameters for shredded MSW: TSP, total stress parameters; ESP, effective stress parameters.

development of such large-scale equipment is expensive and any such testing is time-consuming. Therefore, systematic evaluation of gradation and composition of MSW and the influence of specimen size relative to the maximum particle size of the MSW on geotechnical properties is needed to develop standard testing methods. Nevertheless, small-scale laboratory experiments are useful in understanding the general behaviour of MSW which can aid in designing and operating landfills in a safe manner.

Summary and conclusions

Landfilled MSW samples, 1.5 years old, exposed to low amounts of leachate recirculation were tested under in-situ moisture content (44%) and elevated moisture contents (60, 80 and 100%) for compressibility and shear strength properties. The results were compared with compressibility and shear strength of fresh MSW collected at the same landfill and data from previous studies with known MSW age. The following conclusions can be drawn from the results of this study.

- Compression ratio values varied in a close range of 0.19–0.24 (with average 0.21 and standard deviation, 0.02) for landfilled MSW and in the close range of 0.24–0.33 (with average 0.27 and standard deviation, 0.04) for fresh MSW.

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The compression ratio of the landfilled MSW showed a slightly increased trend with increasing moisture content, but no specific correlation was found for fresh waste within a range of 44 and 100% moisture content. Differences in testing techniques and initial composition and rate of biodegradation of MSW make compressibility data from published studies difficult to compare irrespective of the similarity in the age.

- Based on direct shear tests, drained cohesion of landfilled MSW varied from 12–64 kPa and the drained friction angle ranged from 31–35°. It was observed that the cohesion of fresh MSW varied 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 in the range of 44–100% for both landfilled and fresh MSW. Although it is difficult to prove statistically, a slight increase in angle of friction can be observed with increasing age. MSW from different locations have different initial compositions and they may have been subjected to different rates of biodegradation. Therefore it is not possible to identify a correlation between the shear strength properties and biodegradation if the results are not from tests conducted on samples from a single origin at different levels of biodegradation.
- Based on triaxial CU tests on landfilled MSW, the average total strength parameters (TSP) were found to be 39 kPa and 12°, while effective stress parameters (ESP) were 34 kPa and 23°. For fresh MSW, the average total strength parameters were 32 kPa and 12°, and effective strength parameters were 38 kPa and 16°. TSP produced low angle of friction and high cohesion with the increase in strain. ESP produced increased cohesion and friction with increased strains. ESP also showed a trend of decreasing cohesion and increasing angle of friction with the age of MSW.

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