RESEARCH PAPER

Experimental and statistical evaluation of compressibility of fresh and landfilled municipal solid waste under elevated moisture contents

B. M. Basha*[1], N. Parakalla[2] and K. R. Reddy[2]

An investigation of the variability associated with primary and secondary compression indices of municipal solid waste (MSW) is conducted in the present study. A controlled laboratory experimental program was conducted to quantify the compressibility of fresh MSW and landfilled MSW (subjected to leachate recirculation for a year in the field) under different elevated moisture content conditions. Several series of one-dimensional compressibility experiments were conducted on fresh and landfilled waste samples under the field moisture content of 44% (by dry weight) and three elevated moisture contents of 60, 80 and 100% (by dry weight). The compression of waste samples was measured at different elapsed time periods under incremental normal stresses of 48, 96, 192, 383, and 766 kPa. The modified compression indices (or compression ratios) were calculated based on the measured compression versus stress data. Long term secondary compression behavior was determined by performing long term compression tests on fresh and landfilled waste samples under normal stress of 383 kPa. The steep slope is not evident on the vertical stress – strain plot for the 44% moisture content sample, potentially owing to breakdown of micro-fabric and mini-fabric of fresh waste and rearrangement of the particles. It is observed from the present study that the magnitudes of modified primary compression index (C'_c) for fresh MSW exhibited no specific correlation with an increase in moisture content from 44 to 100% owing to variations in the initial composition of fresh MSW, small scale laboratory testing, and rate of biodegradation of MSW. For a constant vertical stress, the landfilled waste compressed less than the fresh waste at initial and elevated sample moisture contents owing to reduction of organic content in the degraded waste. Based on the compilation of compression indices from several published studies, the average values of mean, standard deviation and coefficient of variation for modified primary compression and secondary compression indices are computed. Overall, this study demonstrated that the long term compression characteristics can highly vary depending on the waste composition, moisture content, and biodegradation. From the statistical analysis, it is determined that the variability associated with secondary compression index (C'_α) is significantly higher than the primary compression index (C'_c), which may be attributed to significant differences in the biodegradable content of waste and associated extent and rate of biodegradation of waste.

Keywords: Municipal solid waste, Landfill, Compression, Fresh waste, Landfilled waste, Compression indices, Moisture content, Variability

Introduction

There is a significant increase in the number of landfills that are being operated with leachate recirculation, often known as bioreactor landfills or leachate recirculation landfills. The advantages of bioreactor landfills to accelerate biodegradation of municipal solid waste (MSW) are

[1]Department of Civil Engineering, Indian Institute of Technology Hyderabad, Yeddumailaram 502205, India
[2]University of Illinois at Chicago, Department of Civil and Materials Engineering, 842 West Taylor Street, Chicago, IL 60607, USA, Email: geoenlab@gmail.com

*Corresponding author, email basha@iith.ac.in

Received 27 June 2015; accepted 19 July 2015
DOI 10.1179/1939787915Y.0000000018

generally well documented. However, the design and operation of landfills as bioreactors raise some concerns, including compressibility of MSW. It is known that the dry unit weight, water content and biodegradable organic content are the most significant factors that affect the compressibility of MSW, which is often represented by the compression ratio. In addition, as observed from the recent studies conducted by Vilar and Carvalho (2004) and Reddy *et al.* (2009a), the compressibility of MSW is expected to change with increasing moisture content. These changes must be considered during the design phase to ensure slope and cover stability. The enhanced rate of waste decomposition can result in an enhanced rate of waste settlement as organic fraction of MSW is converted to landfill gas. While there are significant economic advantages to the operation of landfills as bioreactors, our understanding of the mechanics governing accelerated waste degradation with an increase in its moisture content and its impact on waste compression is limited. As such, there is a need to explain and quantify such impact on compressibility parameters. Unfortunately, there are difficulties in performing these tests on MSW materials owing to the heterogeneity and wide range of particle sizes. Addition of liquid wastes and recirculation of leachate may have a significant influence on both the magnitude and distribution of moisture contents, and hence on the magnitude of compressibility of the waste.

Background

Compression indices of MSW

The compression ratio of MSW is an essential parameter for evaluation of waste settlement and landfill design. It represents the slope of the curve of the strain versus the logarithm of effective pressure. Properties necessary for settlement analysis include the compression index (C_c) or the modified compression index (C'_c) to estimate primary settlement, with the secondary compression index (C_α) or the modified secondary compression index (C'_α) used to estimate the settlement that occurs while the waste is subjected to a constant load (Holtz and Kovacs, 1981). They are commonly determined through one-dimensional compression tests and defined as follows:

The compression index (C_c) is given by

$$C_c = \frac{-\Delta e}{\Delta \log P} = \frac{-\Delta e}{\log (P_0/P_1)} \tag{1}$$

where, Δe is the change in void ratio and $\Delta \log P$ is the change in vertical effective stress from $\log P_0$ to $\log P_1$. The modified compression index (C'_c), which can also be called as the compression ratio, is written as

$$C'_c = \frac{-\Delta \varepsilon}{\Delta \log P} = \frac{-\Delta H/H_0}{\log (P_0/P_1)} = \frac{-\Delta e/(1+e_0)}{\log (P_0/P_1)} = \frac{C_c}{1+e_0} \tag{2}$$

where, $\Delta \varepsilon$ is the change in linear strain defined as the ratio of change in height (ΔH) to the original height (H_0) and e_0 is the initial void ratio.

The secondary compression index (C_α) is given by

$$C_\alpha = \frac{-\Delta e}{\Delta \log t} = \frac{-\Delta e}{\log (t_2/t_1)} \tag{3}$$

where, $\Delta \log t$ is the change in time from $\log t_2$ to $\log t_1$. Further, the modified secondary compression index or secondary compression ratio (C'_α) is written as

$$C'_\alpha = \frac{-\Delta \varepsilon}{\Delta \log t} = \frac{-\Delta H/H_0}{\log (t_2/t_1)} = \frac{-\Delta e/(1+e_0)}{\log (t_2/t_1)} \tag{4}$$

Previous studies on compressibility of MSW

Numerous researchers have investigated the influence of various parameters on waste compressibility and compression ratio. Research on compressibility of MSW was first initiated by Sowers (1973) who related the compression index (C_c) to the initial void ratio (e_o) and found it to range from $0.15e_o$ to $0.55e_o$. Sowers (1973) also reported that the value of the secondary compression index (C_α) to vary from $0.03e_o$ to $0.09e_o$. Landva and Clark (1990) performed consolidation tests on coarse waste materials and reported that the modified compression index (C'_c) ranges from 0.2 to 0.5. Gabr and Valero (1995) conducted compressibility tests on 63-mm diameter samples compacted at natural moisture content and reported that C_c ranges from 0.4 to 0.9, and C_α ranges from 0.03 to 0.009.

Wall and Zeiss (1995) performed six tests in 0.57-m diameter and 1.7-m height cells using MSW to investigate both settlement and decomposition over testing duration of 225 days. They reported that there was no significant increase in the settlement rate owing to biodegradation in short term. Manassero, Van Impe and Bouazza (1996) demonstrated that the MSW settlement behavior is similar to that of peaty soils, which involves immediate settlement followed by large additional settlements with low or no dissipation of pore pressures. Espinance *et al.* (1999) studied the compressibility behavior of landfills by using two 0.80-m diameter lysimeters for evaluating the MSW settlements. Kavazanjian, Matasovic and Bachus (1999) presented the results of 24 large diameter (454 mm) one-dimensional compression tests on MSW obtained from OII landfill in California, USA, with varying degrees of degradation and found values of C_c between 0.12 and 0.25 (on a volumetric strain basis) and the values of the recompression index (C_R) varied from 0.003 to 0.017.

Hossain (2002) studied the change in refuse compressibility owing to decomposition of waste in landfills. Vilar and Carvalho (2004) studied the compressibility of MSW recovered from the Bandeirantes sanitary landfill, Sao Paulo, Brazil. The study reported that C_α values ranged from 0.021 to 0.044 with an average value of 0.032. Durmusoglu, Sanchez and Corapcioglu (2006) tested the waste materials with a natural moisture content and field capacity moisture. Their results indicate that wastes with field capacity moisture have a higher C'_c than those with natural moisture content. Experimental works by Sowers (1973), Swati and Joseph (2008) and Chen, Zhan, Wei and Ke (2009) on waste settlement showed that increasing

organic components and compressible materials increase the value of C'_c Karimpour-Fard and Machado (2012) and Chen *et al.* (2009) examined compressibility of the waste samples with different ages. The results of their study explained that increasing the age, and thus further waste decomposition will decrease the waste compressibility and compression ratio. However, Hossain, Gabr and Barlaz (2003) reported an opposite relationship.

Previous studies on compressibility of MSW at increased densities and degradation

Chen, Chen and Liu (2010) tested waste samples with different initial densities. The study demonstrated that an increase in the waste density reduces the value of C'_c. Similar results were also reported by Landva, Valsangkar and Pelkey (2000). Reddy *et al.* (2009c), Reddy, Hettiarachchi, Gangathulasi and Bogner (2011) conducted laboratory investigation to determine the variation of geotechnical properties of synthetic MSW at different phases of degradation and reported the hydraulic conductivity, compressibility and shear strength of initial and degraded synthetic MSW determined at constant initial moisture content of 50% on wet weight basis. In addition, Yu-xin *et al.* (2013) reported that an increase in dry density will lead to a decrease in waste compressibility, while the stiffness modulus increases. Recently, Castelli and Maugeri (2014) conducted geotechnical investigation on MSW materials retrieved from the 'Cozzo Vuturo' landfill in the Enna area (Sicily, Italy). They reported that the maximum sample compression reached more than 50% of the original sample height for the degraded waste and 80% for the fresh waste.

Previous studies on compressibility of MSW at elevated moisture contents

The increased or elevated moisture contents will have commensurate effects on the compressibility of waste. It can be noted from the review of literature that most of the studies were focused on compressibility behavior of MSW at field moisture content and a few studies have been reported in the literature that is exclusively conducted on compressibility behavior of MSW at elevated moisture contents. Wong (2009) reported that the magnitude of apparent compression ratio decreases significantly from 0.46 to 0.12 when the moisture content increased from 30 to 110%. Reddy *et al.* (2009a) reported compressibility properties of landfilled MSW samples, 1.5 years old, exposed to low amounts of leachate recirculation with different moisture contents. They reported that the compression ratio of the landfilled MSW showed a slightly increasing trend with increasing moisture content, and the fresh waste showed no specific correlation within a range of 44 and 100% moisture content. Reddy *et al.* (2009b) conducted laboratory tests on fresh MSW collected from the working phase of Orchard Hills Landfills in Illinois, USA and reported compaction characteristics, hydraulic conductivity, compressibility and shear strength properties. They reported that the compression ratio values varied in a close range of 0.24–0.33 with no specific trend with the increase in moisture content.

Published range of compression indices

The ranges of values for C'_c and C'_α for MSW have been reported by various researchers. Landva *et al.* (2000) compiled a table presenting the range of values of compression indices reported in literature. Table 1 provides an updated compilation of C'_c and C'_α values from Landva *et al.* (2000), Hossain *et al.* (2003), Marques, Filz and Vilar (2003), Park, Lee and Do (2002), Anderson, Balanko, Lem and Davis (2004), Durmusoglu *et al.* (2006), and Sharma and De (2007).

Variability associated with compression indices

The compressibility properties of waste are of special importance when designing the interim and final closure covers for solid waste landfills. Geoenvironmental engineers are well aware of the existence of many sources of uncertainties associated compressibility parameters owing to changes in the waste properties with time and stress level, methods for evaluation of the magnitude and rate of settlement as a function of moisture content and the impact of leachate recirculation on waste strength and above-grade slope stability. Review of the literature clearly indicates that there is a dearth of variability data on the compressibility properties of MSW. As can be seen from the Table 1, there is a high degree of variability associated with compression indices. In order to quantify the waste settlement, the Reliability Based Design (RBD) framework can be constructed that is formulated based on probability theory. It requires the mean and standard deviation associated with compression indices.

Objectives of the present study

The data pertaining to the effect of elevated moisture contents on compressibility behavior are scarce. Moreover, the past research did not systematically characterize the change in waste compressibility as a function of degradation and moisture content. The review of the literature clearly indicates that only few studies are available to understand the compressibility behavior of MSW under elevated moisture contents and hence its effect on degradation and final settlement. Therefore, efforts have been made in the present study to critically examine the existing results with new data on the effect of elevated moisture contents and degradation on compressibility behavior. Several series of one-dimensional compressibility experiments were conducted on fresh waste and landfilled waste (subjected to leachate recirculation for a year) under field moisture content of 44% (by dry wt.) and three elevated moisture contents of 60, 80 and 100% (by dry wt.). The statistical analysis was also conducted based on extensive review of the literature on compression indices including the indices obtained in the present study. The mean, standard deviation and coefficient of variation (COV) associated with the modified primary and secondary compression indices are proposed.

Research methodology

This study was conducted using MSW samples collected from Orchard Hills Landfill, located in Davis Junction, IL,

Table 1 Summary of modified primary and secondary compression indices (C'_c and C'_α) of MSW from previous studies

Reference	C'_c	C'_α	Comments
Sowers (1973)	0.10–0.41	0.02–0.07	–
Rao, Moulton and Seals (1977)	0.16–0.235	0.012–0.046	–
Landva *et al.* (1984)	0.2–0.5	0.0005–0.029	–
Burlingame (1985)	0.35	0.055	Monitored for 1.8 years
Oweis and Khera (1986)	0.08–0.217	–	
Oweis and Khera (1986)	0.15–0.33	0.013–0.03	–
Oweis and Khera (1986)	0.25–0.30	0.07	–
Sargunan, Mallikarjun and Ranapratap (1986)	–	0.0038–0.0050	10- to 50-year-old waste in Madras, India
Bjarngard and Edgers (1990)	–	0.003–0.01	–
Zaminskie, Kabir and Haddad (1994)	0.01–0.04	0.001–0.006	–
Boutwell and Fiore (1995)	0.09–0.19	0.006–0.012	–
Gabr and Valero (1995)	0.20–0.23	0.015–0.023	–
Stulgis, Soydemir and Telgener (1995)	0.16	0.02	–
Wall and Zeiss (1995)	0.21–0.25	0.033–0.056	–
Green and Jamenjad (1997)	–	0.01–0.08	–
El-Fadel and Al-Rashed (1998)	–	0.1–0.32	1576 days old waste
Coumoulous and Koryalos (1999)	–	0.02–0.07	–
Earth Tech Consultants (2001), Atlantic Landfill	–	0.02–0.088	–
Earth Tech Consultants (2001), Central Landfill	–	0.006–0.035	–
Earth Tech Consultants (2001), CrowwingLandfill	–	0.18–0.26	–
Sharma, Fowler and Cochrane (1999)	–	0.02–0.07	10- to 15-year-old waste
Sharma (2000)	–	0.02	–
Landva *et al.* (2000)	0.17–0.24	0.01–0.016	–
Yolo County, Planning and Public Works Department (2000)	–	0.04	Fresh waste
Yolo County, Planning and Public Works Department (2000)	–	0.16	Waste in bioreactor
Machado, Carvalho and Vilar (2002)	0.21	0.012–0.016	Waste in bioreactor
Park *et al.* (2002)	–	0.014–0.063	Fresh waste
Park *et al.* (2002)	–	0.087–0.34	Waste undergoing AD*
Marques *et al.* (2003)	0.073–0.132	–	FM*
Hossain *et al.* (2003)	0.16–0.37	0.015–0.03	Laboratory testing
Anderson *et al.* (2004)	0.17–0.23	0.024–0.030	FM*
Lewis, Mansfield, Ashraf and Zicko (2004)	–	0.014	FM* and for waste treated with DDC*
Lewis *et al.* (2004)	–	0.045	FM* and for waste treated with surcharge
Vilar and Carvalho (2004)	0.21	0.012–0.016	15-years-old waste,
Durmusoglu *et al.* (2006)	0.128–0.260	0.043–0.083	
Sharma and De (2007)	–	0.01–0.07	Under external load
Sharma and De (2007)	–	0.014	Under external load with pretreatment using DDC*
Sharma and De (2007)	–	0.03	Under external load with pretreatment using RC*
Sharma and De (2007)	–	0.045	Under external load pretreatment using SL*
Sharma and De (2007)	–	0.014–0.06	Fresh waste under self-weight
Sharma and De (2007)	–	0.1–0.34	Under self-weight and waste undergoing AD*
Sharma and De (2007)	–	0.1–0.34	For bioreactor landfills under self-weight

DDC: deep dynamic compaction; RC: roller compaction; AD: active decomposition; SL: surcharge loading; FM: field monitoring.

USA. The landfill was opened in 1988 and is expected to be closed by 2018. The total landfill area is approximately 135 ha with 71 ha currently permitted for waste disposal (Reddy *et al.*, 2009b). Landfilled waste was collected by drilling a borehole (#16M2) through the landfill and collecting the MSW samples within the depth zone of 0–20 m below the landfill surface. Fresh MSW samples were also collected at the working (disposal) area of the landfill as the waste is being unloaded. MSW samples were collected in large plastic bags. The waste samples were characterized for composition and size distribution in the field. Then, the samples were transported to the laboratory for determination of moisture content and organic content of samples. Leachate was also collected from the landfill and transported to the laboratory.

Both the fresh waste and the landfilled waste were analyzed for composition using the method known as MODECOM^{TM} developed by the French Environmental Protection Agency (Reddy *et al.*, 2009a). This method essentially involves sieving about 500 kg of fresh wet waste (or 100 kg of landfilled waste) through a set of three large sieves with opening diameters of 100, 50 and 20 mm. The waste retained on each sieve was sorted into 16 components as summarized in Table 2(a) (wood, cardboard, textile, sanitary textile, disposable napkins, metal, plastic bottles, other plastics, glass, paper, cooking waste, garden

Table 2(a) Fresh and landfilled MSW composition

Waste component	Fresh waste composition (per cent by wet mass)	Landfilled waste composition (per cent by wet mass)
Soil-like material (less than 20 mm in size)	20.1	33.8
Cardboard	13.3	16.1
Wood	11.7	8.5
Paper waste	8.2	6.6
Cooking waste	6.6	0.5
Textiles	5.8	4.8
Inert waste	5.8	5.0
Plastic bottles	5.7	5.7
Other plastics	5.3	9.7
Metal	4.4	4.1
Glass	4.4	0.4
Sanitary waste	3.1	1.1
Nappies	1.7	0.1
Garden waste	0.3	0
Medical waste	0.1	0
Other waste	3.5	3.6

waste, medical waste, inerts, other waste, and residual fines). It can be noted from Table 2(a) that both the fresh and landfilled waste samples consisted of fines (soil-like material consisting of both organic and inorganic constituents) which are <20 mm in size.

The fresh and landfilled MSW samples were shredded and then air-dried. The waste samples were then mixed with different amounts of leachate (obtained from the same landfill) to prepare the samples of different elevated moisture content. The selected moisture contents were 44% (represents *in situ* condition) and 60, 80 and 100% (represent potential elevated conditions in typical bioreactor landfills).

Confined compressibility testing was carried out in an oedometer to determine compressibility characteristics of all prepared fresh and landfilled waste samples. The compressibility test unit consisted of an oedometer and a loading device. In preparation for compressibility tests, the selected waste sample with known moisture content was compacted into 63-mm diameter and 25-mm thick circular oedometer ring with a tamper. The oedometer used in this study was a floating ring oedometer. The floating ring oedometer consisted of a brass ring, in which the sample was placed. In this testing, the waste sample was placed in the oedometer ring with one porous stone on the top and another one at the bottom of the waste sample.

Following the specimen preparation, the initial height and volume of the sample were recorded. Oedometer was placed in the loading device, and the sample was subjected to increments of constant vertical stresses of 48, 96, 192, 383 and 766 kPa through a pressure chamber, which applies compressed air. In a floating ring oedometer, compression of the specimen occurs from the top and bottom toward the center. Compressibility test results are dependent upon the duration of each load increment. After the application of load, there was an almost instantaneous compression, followed by gradual time dependent compression, characterizing a process of MSW secondary compression (owing to creep, biodegradation, or both). The constant vertical stress was applied and allowed to stand until there was no change in dial gage readings. Then the procedure was repeated for successive load increments. At each loading, the vertical compression of the sample at different time intervals was recorded. For each normal pressure, per cent strain versus the elapsed time is plotted.

Long term secondary compression behavior was determined by performing compression tests on the waste samples under normal stress of 383 kPa for 14 days. A normal stress of 383 kPa approximately represents the overburden pressure of 50 m high landfill with an average unit weight of 8 kN m^{-3}. Load was incrementally increased to 48, 96, 192 and 383 kPa. Load was increased after primary compression ceased or the rate of compression was very low. Finally, the constant load of 383 kPa was continued till 14 days to provide adequate data to assess secondary compression behavior. From these results, the modified compression index (C'_c), and modified secondary compression index (C'_α) were calculated.

Results and discussion

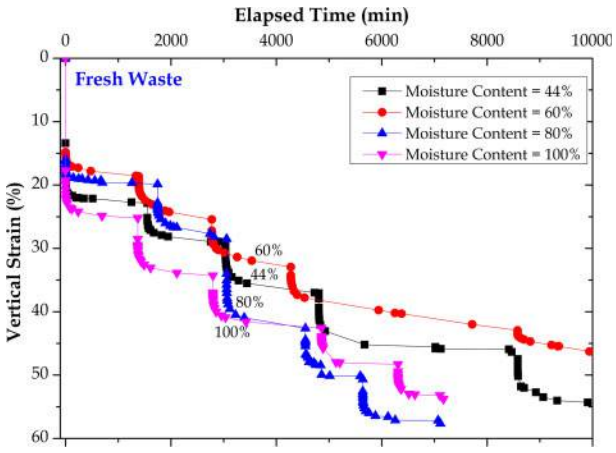
Table 2(b) shows the initial characterization of fresh and landfilled wastes. The organic content as determined based on loss-on-ignition (LOI) is found to be around 78 and 63% for fresh and landfilled wastes, respectively. Table 2(b) also shows the density of each waste sample as compacted in the oedometer at the beginning of testing. The test results allowed investigation of influence of elevated moisture contents on compression behavior of fresh waste and landfilled waste. The uncertainty associated with the compression behavior is further quantified using the results of this study as well as those reported in several published studies.

Effect of elevated moisture contents of fresh and landfilled MSW on vertical strain

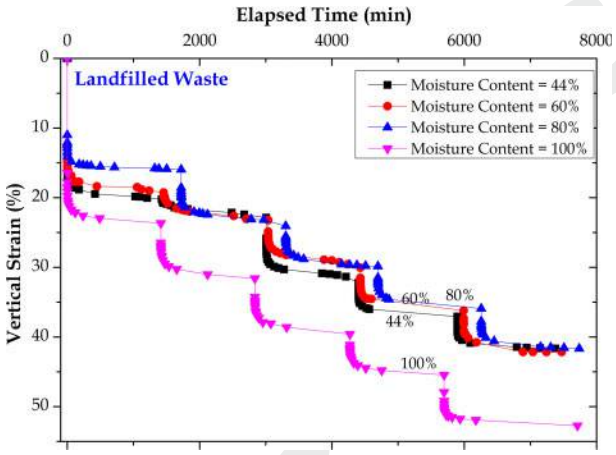
The incremental loading relationships of vertical strain versus time for fresh waste are presented in Fig. 1 for elevated moisture contents of 44, 60, 80 and 100%. Similarly, the variation of vertical strain with time for landfilled waste is presented in Fig. 2 for the moisture content

Table (2b) Characteristics of fresh and landfilled MSW

MSW sample	Target moisture content (%)	Dry gravimetric moisture content (%)	Wet gravimetric moisture content (%)	Loss on Ignition (LOI) (%)	Compacted bulk density (g cm^{-3})
Fresh waste	44	45.4	31.2	78.3	0.74
	60	62.9	38.6	78.4	0.61
	80	78.8	44.0	77.1	0.75
	100	96.9	49.1	75.8	0.76
Landfilled waste	44	44.7	30.9	63.9	0.77
	60	56.3	36.0	62.1	0.80
	80	77.0	43.5	53.8	1.06
	100	95.4	48.8	63.4	1.12



1 Incremental loading relationships of vertical strain versus elapsed time for fresh municipal solid waste (MSW) at initial and elevated moisture contents of 44, 60, 80 and 100%

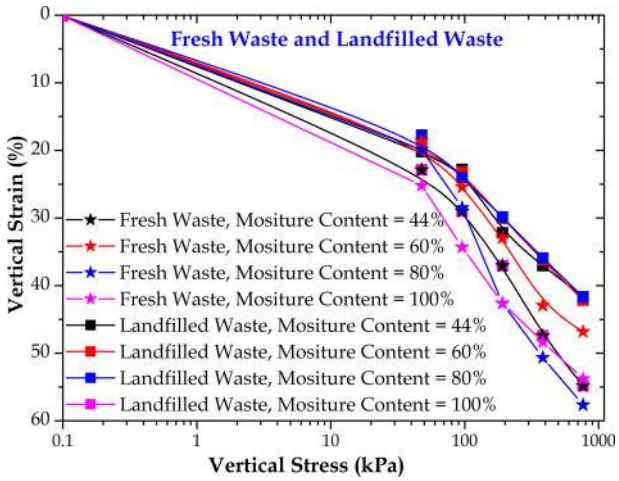


2 Incremental loading relationships of vertical strain versus elapsed time for landfilled municipal solid waste (MSW) at initial and elevated moisture contents of 44%, 60, 80 and 100%

increases from 44 to 100%. It can be noted from Figs. 1 and 2 that a rapid accumulation of strain occurs immediately after each load application (immediate compression), which is followed by a decreased compression with time. The immediate and time-dependent compression of waste is attributed to various mechanisms: (1) physical and mechanical processes that include the reorientation of particles, movement of the fine materials into larger voids, and collapse of void spaces; (2) chemical processes that include corrosion, combustion and oxidation; (3) dissolution process that consists of dissolving soluble substances by percolating liquids and then forming leachate; and (4) biological decomposition of organics with time depending on the humidity and amount of organics present in the waste (Sharma and Reddy, 2004). Similar compressibility behavior occurred in all tests conducted in this study and has also been reported by others (Rao *et al.*, 1977; Jessberger and Kockel, 1995; Kavazanjian *et al.*, 1999; Landva *et al.*, 2000; Vilar and Carvalho, 2004; Durmusoglu *et al.*, 2006; Chen *et al.*, 2010). It may be observed from Figs. 1 and 2 that, at the field moisture content of 44%, the maximum vertical strain owing to primary compression is 54% for fresh waste and 42% for landfilled waste. Figures 1 and 2 also show the primary compression of fresh waste and landfilled waste at increased moisture contents. It is noted from these results that the maximum primary compression values are 47, 57 and 53% for fresh waste and 42, 42 and 52% for landfilled waste, respectively, for corresponding moisture contents of 60, 80 and 100%. It may be concluded that the increase in moisture content from 60 to 80% does not seem to have any effect on the compression of landfilled waste. An important observation that can also be made from Figs. 1 and 2 is that the maximum vertical strain owing to primary compression for fresh waste is reduced by 47–42%, 57–42% and 53–52% under elevated moisture contents of 60, 80 and 100%, respectively. However, 15% reduction in the maximum vertical strain owing to primary compression can be noted under high moisture content of 80% for landfilled waste.

Vertical stress versus vertical strain for fresh MSW at elevated moisture contents

The modified primary compression index (C'_c), also known as compression ratio, is used to estimate the primary settlement of MSW resulting from an increase in vertical stress. Figure 3 shows the variation of vertical strain with the vertical stress for fresh and landfilled wastes at initial and elevated moisture contents of 44, 60, 80 and 100%. All samples with the exception of the 44% moisture content sample show a generally similar behavior upto 43% strain. The initial raveling of the waste compression



3 Vertical strain versus vertical stress for Fresh and landfilled MSW at initial and elevated moisture contents of 44, 60, 80 and 100% (semi logarithmic plot)

for the 44% moisture content is clearly evident in Fig. 3. The fresh MSW stress–strain curves for the three samples at 60, 80 and 100% presented in Fig. 3 had an initially steeper slope. The steeper slope is not evident on the stress-strain plot for the 44% moisture content sample, potentially owing to the breakdown of micro-fabric and mini-fabric of fresh waste and rearrangement of particles. Durmusoglu *et al.* (2006) reported the scale effects on the compression behavior of MSW and concluded that the small scale laboratory testing may significantly affect the compression behavior as observed in the present study.

The vertical strain of the fresh MSW increased with increasing moisture content of 60 and 80%. It can be noted from Fig. 3 that the fresh MSW samples at 60, 80 and 100% moisture contents showed noticeably more gradual yielding up to a vertical strain of 43%. Once the vertical strains in Fig. 3 exceeded 43%, the stress–strain curve for the sample at 100% moisture content began to show locking as the components of fresh MSW rearranged. It may be attributed to the waste structure had already softened and broken down during placement owing to the additional water. Increasing the moisture content for fresh MSW beyond 80% resulted in less compression.

Based on the approximately linear portion of each strain versus log stress plot as shown in Fig. 3, the magnitudes of modified primary compression index (C'_c) are calculated using equation (2). The values of compression indices are summarized in Table 3. It may be noted from Table 3 that the magnitude of C'_c is 0.039 for fresh waste at field moisture content of 44%. Table 3 also shows the magnitude of C'_c for fresh waste at increased moisture contents. The magnitudes of C'_c are 0.033, 0.042 and 0.027, respectively, under elevated moisture contents of 60, 80 and 100%. Although the values calculated are believed to represent compression characteristics of the fresh MSW, the development of excess pore pressures were not measured during the experiments. If excess pore pressure did develop, the stress–strain curve would become shallower and the compressions indices will decrease. It can be noted from Table 3 that the magnitude of C'_c decreased

Table 3 The modified compression index (C'_c) for fresh and landfilled MSW

Moisture content (%)	Fresh waste	Landfilled waste
44	0.039	0.027
60	0.033	0.028
80	0.042	0.028
100	0.027	0.038

from 0.033 to 0.027 for the sample with moisture contents of 60 and 100%, respectively. Several similarities between the MSW stress–strain plots of this study and the trends reported by Wong (2009) for MSW were observed. Wong (2009) reported that the magnitude of apparent compression ratio decreased significantly from 0.46 to 0.12 when the moisture content increased from 30 to 110%. In the present study, the values of C'_c increased from 0.033 to 0.042 as the moisture content increases from 60 to 80%. An inverse relationship between moisture content and C'_c is observed sometimes for fresh MSW; however, the magnitudes of modified primary compression index (C'_c) for fresh MSW in this study showed no direct correlation with increase in sample moisture content. This may be owing to variation in composition of fresh MSW samples used for testing and small scale laboratory testing.

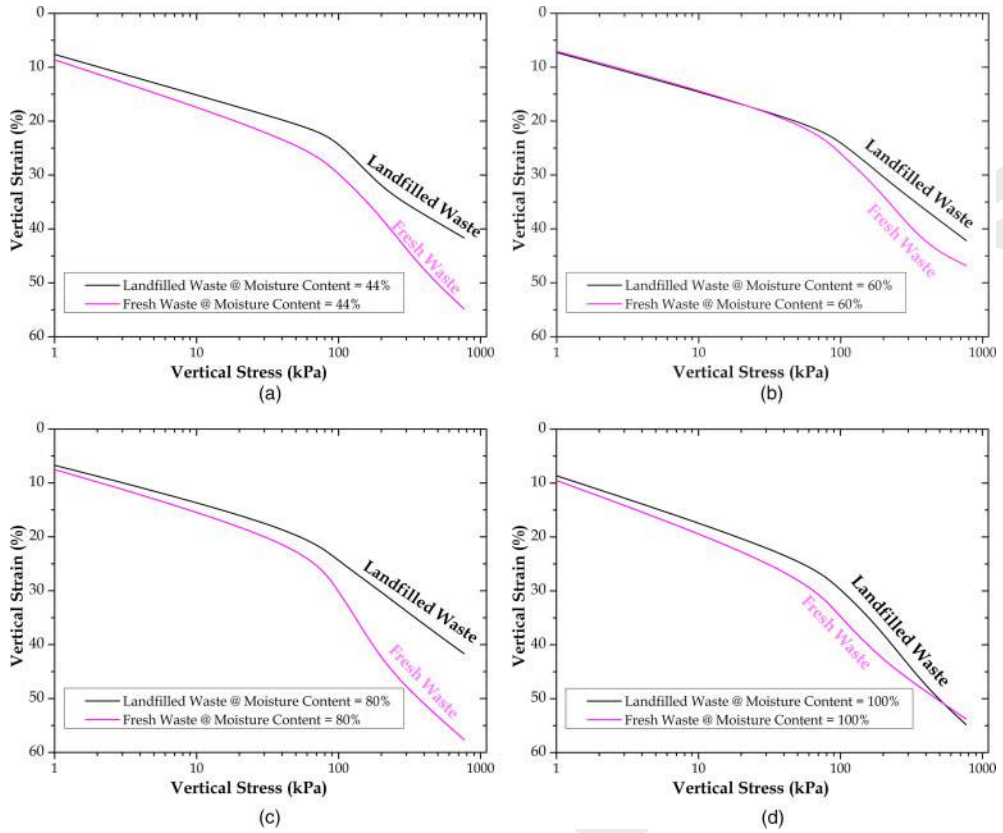
Vertical stress versus vertical strain for landfilled MSW at elevated moisture contents

Figure 3 also shows the variation of vertical strain with the vertical stress for landfilled MSW at initial and elevated moisture contents of 44, 60, 80 and 100%. It may be observed from Fig. 3 that the landfilled MSW at 44, 60 and 80% moisture contents showed insignificant difference in the magnitude of vertical strain as vertical stress increases. It may be owing to the fact that the applied moisture contents except 100% may be less than the field capacity, which is the maximum amount of moisture that can be retained by waste subjected to drainage by gravity. The stress–strain curve for the landfilled MSW at 100% moisture content showed significant increase in the vertical strain as the vertical stress increases. This is owing to the fact that the landfilled MSW is partially degraded and softened.

Using the approximately linear portion of each strain versus log stress plot as shown in Fig. 3, the magnitudes of modified primary compression index (C'_c) are calculated and provided in Table 3. It may be noted from Table 3 that the magnitude of C'_c is 0.027 for landfilled waste at field moisture content of 44%. The magnitudes of C'_c are 0.028, 0.028 and 0.038 respectively, under elevated moisture contents of 60, 80 and 100%. It may be observed from Table 3 that the magnitude of C'_c increased from 0.027 to 0.038 as the moisture content increases from 60 to 100%.

Comparison of vertical strain versus vertical stress for fresh waste and landfilled waste at elevated moisture contents

A comparison of compressibility behavior of fresh waste and landfilled waste at initial and elevated moisture contents is made (Fig. 4). Figure 4*a–d* show the comparison of vertical strain versus vertical stress for fresh waste and landfilled

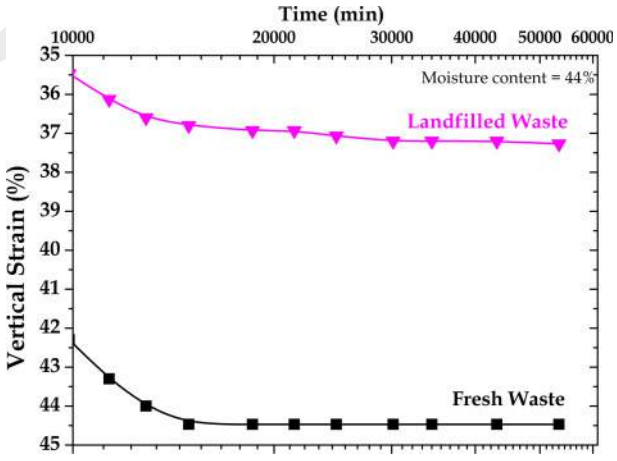


4 Comparison of vertical strain versus vertical stress for fresh waste and landfilled waste at initial and elevated moisture contents: *a* 44% *b* 60% *c* 80% and *d* 100%

waste at elevated moisture contents of 44, 60, 80 and 100%, respectively. It can be noted from Fig. 4 that for a constant vertical stress, the magnitude of vertical strain is more for the fresh waste than the landfilled waste at initial and elevated sample moisture contents. It may be owing to the reduction of organic content in the degraded waste. The results presented in Fig. 4 clearly indicate that fresh waste compressed more than the landfilled waste. Similar behavior was reported by Chen *et al.* (2009) who concluded that increase in waste decomposition will decrease the waste compressibility and compression ratio. Further, Castelli and Maugeri (2014) reported similar vertical compression behavior that the degraded waste compression reached about 50%, while the fresh waste compression was about 80%.

Secondary compression behavior of fresh waste and landfilled waste

The modified secondary compression index (C'_α) is used to estimate the settlement that occurs after completion of the primary settlement. It usually occurs while the waste is subjected to a constant load. It is calculated using equation (4). Figure 5 shows the secondary creep for fresh waste and landfilled waste. It can be noted from Fig. 5 that for a constant value of vertical stress of 383 kPa, landfilled waste is subjected to a maximum vertical strain of 36%. Further, it may be observed that the magnitude of vertical strain increases to 45% for the fresh waste. It may be found from Fig. 5 that the modified secondary compression index (C'_α)



5 Secondary compression behavior of fresh waste and landfilled waste at field moisture content of 44%

value is 0.09 for both fresh and landfilled wastes as the curves showing the strain variation with time for the fresh and landfilled waste are parallel to each other.

Mean, standard deviation and probability density functions associated with C'_c and C'_α

Range of modified primary and secondary compression indices (C'_c and C'_α) of MSW at initial and elevated

moisture contents as obtained in the present study are presented in Table 4. As seen in Table 1, there is a wide range in the published values of these parameters. This wide range is owing to the large variations in compositions of wastes involved, the various ages of the landfills, and the stresses to which wastes have been subjected. In general, the results of this study are comparable with other published values. The major sources of uncertainties in the estimation of modified primary and secondary compression indices of MSW can be attributed to the following: (1) the heterogeneity owing to wide-ranging constituents; (2) tests conducted at different scales, mostly small scale in laboratory settings; (3) methods used to calculate the compression indices; (4) the degree of biodegradation of waste, i.e. collection of fresh waste and landfilled waste; and (5) increased moisture contents owing to precipitation, biodegradation and leachate recirculation (in case of bioreactor landfills).

A quantitative assessment of the uncertainty in compressibility indices is conducted. It requires use of statistics as well as reliability modeling, which relies on sets of measured data. The data provided in Tables 1 and 4 have been used to calculate the range of statistical parameters, i.e., mean (μ), standard deviation (σ) and coefficient of variation (COV) associated with the modified primary compression index (C'_c) and modified secondary compression index (C'_α). The uncertainty in the measured data associated with C'_c and C'_α (say n number of measured data sets) is expressed in terms of sample means ($\mu_{C'_c}, \mu_{C'_\alpha}$), standard deviations ($\sigma_{C'_c}, \sigma_{C'_\alpha}$) and coefficients of variation (COV), which are evaluated using the following normal and Weibull probability density functions

$$f(C'_c) = \frac{1}{\sigma_{C'_c}\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left(C'_c \frac{C'_c - \mu_{C'_c}}{\sigma_{C'_c}}\right)^2\right\} \quad (5)$$

$$f(C'_\alpha) = \begin{cases} \frac{m}{v^m}(C'_\alpha)^{m-1} e^{-(C'_\alpha/v)^m} & C'_\alpha \geq 0 \\ 0 & C'_\alpha < 0 \end{cases} \quad (6)$$

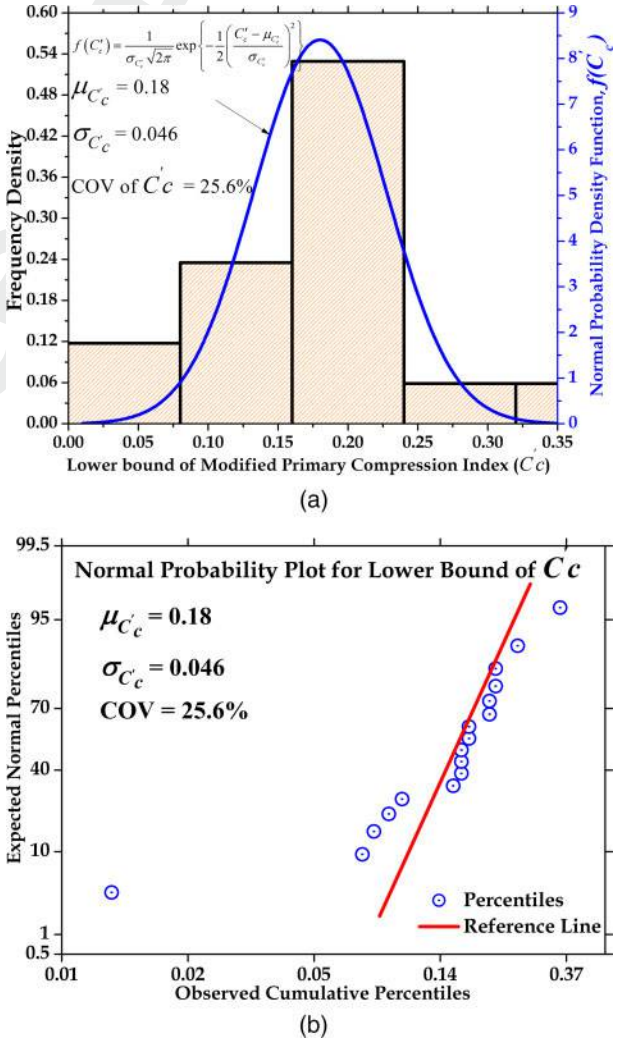
where m and v are the shape and scale parameters

$$\text{COV} = \left(\frac{\sigma}{\mu}\right) \times 100 \quad (7)$$

Given a set of independent observations of C'_c and C'_α as presented in Tables 1 and 4, a first step is to organize and present them properly so that they can be easily interpreted and evaluated. When there are a large number of observed data, a histogram is an excellent graphical representation of the data. It can be noted from the Tables 1 and 4 that the lower bound values of C'_c vary from 0.01 to 0.35. Dividing this range into 'n' equal intervals and plotting the total number of observed C'_c values in each interval as the height of a rectangle over the interval, results in the histogram as shown in Fig. 6*a*. A frequency diagram is obtained if the ordinate of the histogram is divided by the total number of C'_c observations, 21 in this case, and by the interval width. It can be noted that the histogram or the frequency diagram gives an immediate impression of the range, relative frequency, and scatter associated with the observed data. From the modeling point of view, it is reasonable to select a normal distribution as the probabilistic model for lower bound values of C'_c by observing that its random variations are the resultant of major sources of uncertainties as discussed earlier. The normal probability density function with mean, $\mu_{C'_c} = 0.18$, standard deviation, $\sigma_{C'_c} = 0.046$ and COV of $C'_c = 25.6\%$ is superimposed on the frequency diagram in Fig. 6*a*, which shows a reasonable match.

Table 4 Range of modified primary and secondary compression indices (C'_c and C'_α) of MSW at initial and elevated moisture contents from the present study

Waste Type	C'_c	C'_α
Fresh waste	0.027–0.042	0.9
Landfilled waste	0.027–0.038	0.09

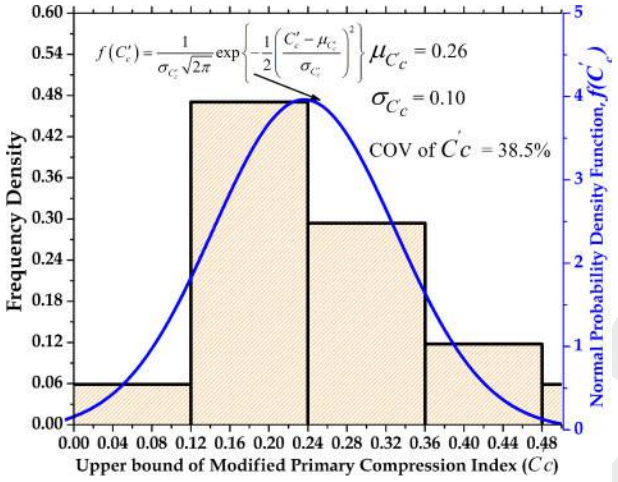


6 *a* Histogram and frequency diagrams for lower bound of modified primary compression index (C'_c) *b* Normal probability plot for lower bound of modified primary compression index (C'_c)

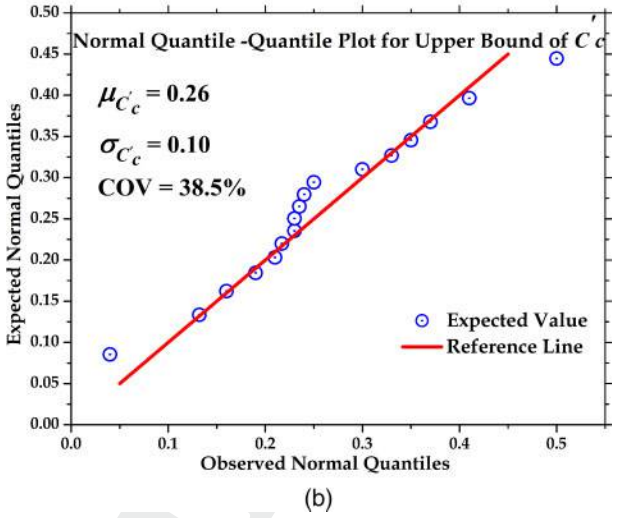
Moreover, the normal probability plot as shown in Fig. 6*b* is drawn to investigate whether the lower bound data of modified primary compression index (C'_c) exhibit the standardized normal distribution. It can be noted from Fig. 6*b* that the normal probability plot shows a strong linear pattern. There are only minor deviations from the reference line to the points on the probability plot. Therefore, it can be concluded that the normal distribution appears to be a good model for lower bound of (C'_c).

Similarly, the histogram and frequency diagrams for upper bound of C'_c are obtained and presented in Fig. 7*a*. It may be observed from normal quantile–quantile plot presented in Fig. 7*b* that the normal distribution appears to be a good model for upper bound of C'_c.

Further, the histograms and frequency diagrams for the lower and upper bounds of the modified secondary compression index (C'_α) are plotted and presented respectively in Figs. 8*a* and 9*a*. It can be noted from the frequency

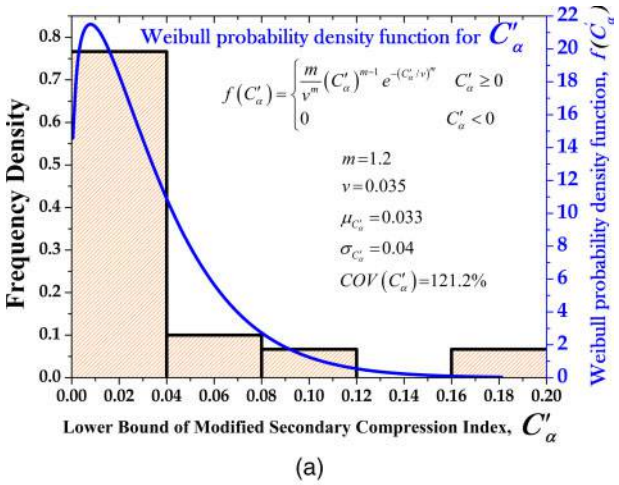


(a)

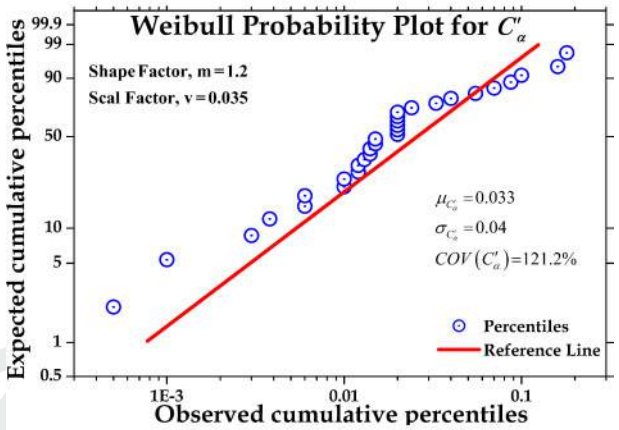


(b)

7 ***a*** **Histogram and frequency diagrams for upper bound of modified primary compression index (C'_c)** ***b*** **Normal quantile-quantile plot for upper bound of modified primary compression index (C'_c)**



(a)

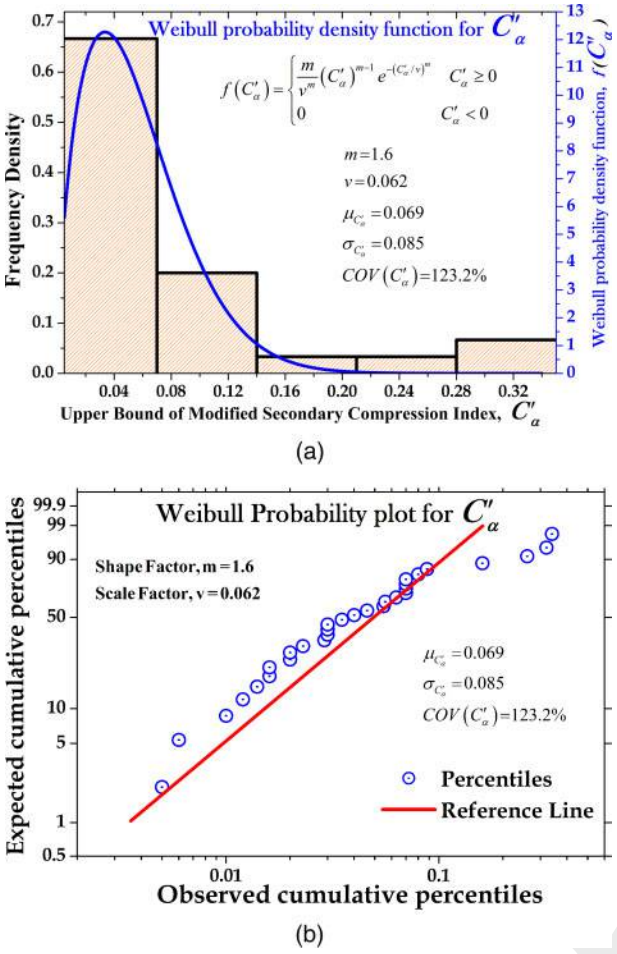


(b)

8 ***a*** **Histogram and frequency diagrams for lower bound of modified secondary compression index (C'_α)** ***b*** **Weibull probability plot for lower bound of modified secondary compression index (C'_α)**

diagrams of C'_α as shown in Figs. 8*a* and 9*a* that the normal distribution may not be a good fit and hence, Weibull probability distribution is superimposed on the frequency diagram. It is noted from Fig. 8*b* and 9*b* that the Weibull probability plot shows a strong linear pattern and the departure from reference line is minimal. Therefore, the Weibull distribution appears to be a reasonably good model for the lower and upper bounds of C'_α.

The values of these statistical parameters are summarized in Table 5 considering the statistics of lower and upper bounds of compression indices. It can be noted from Table 5 that the values of mean (μ), standard deviation (σ) and COV associated with modified primary compression index (C'_c) are 0.22 ± 0.04, 0.073 ± 0.027 and 32.05 ± 6.45%, respectively. It may also be noted from Table 5 that the values of μ, σ and COV associated with modified secondary compression index (C'_α) are 0.051 ± 0.018, 0.063 ± 0.023 and 122.2 ± 1%, respectively. An important observation that can be made from this assessment is that the COV of secondary compression index (C'_α) is significantly higher than the COV of primary compression index (C'_c) which may be attributed to significant differences in the biodegradable content of



9 *a* Histogram and frequency diagrams for upper bound of modified secondary compression index (C'_α) *b* Weibull probability plot for upper bound of modified secondary compression index (C'_α)

waste and associated extent and rate of biodegradation of waste.

The ratio of compression indices (C'_α/C'_c) for MSW is calculated and presented in Table 6. An observation that can made from Table 6 that the ratio of (C'_α/C'_c) for

Table 5 Range of statistical parameters associated with the modified primary compression index (C'_c) and modified secondary compression index (C'_α) obtained from previous studies and the present study

Statistical parameters	Lower and upper bounds of Modified primary compression index C'_c	Lower and upper bounds of Modified secondary compression index C'_α
Mean (μ)	0.22 ± 0.04	0.051 ± 0.018
Standard deviation (σ)	0.073 ± 0.027	0.063 ± 0.023
Coefficient of variation (COV)	32.05 ± 6.45%	122.2 ± 1%

Table 6 Comparison of ratio of compression indices for MSW and inorganic clays

C'_α/C'_c for MSW	C_α/C_c for inorganic clays as reported by Mesri and Castro (1987)
0.224 ± 0.041	0.04 ± 0.01

MSW is significantly higher than the ratio of C_α/C_c for inorganic clays (Mesri and Castro, 1987). This may be attributed to the biodegradable content of waste.

Conclusions

Fresh and landfilled MSW samples collected from Orchard Hills Landfill (Davis Junction, IL, USA) were tested under *in situ* moisture content (44%) and elevated moisture contents (60, 80 and 100%) for compressibility properties. The results were compared to determine compressibility of fresh MSW versus landfilled MSW and data from previous studies reported in the literature. A statistical evaluation of compressibility parameters was also performed. Based on this study, the following conclusions can be drawn:

1. The fresh waste and landfilled waste samples with the exception of the 44% sample moisture content show a generally similar behavior up to 43% strain. The steeper slope is not evident in the vertical stress – vertical strain plot for the 44% moisture content sample, potentially owing to breakdown of micro-fabric and mini-fabric of fresh waste and rearrangement particles.
2. The magnitudes of modified primary compression index (C'_c) for fresh MSW exhibited no specific correlation with increase in moisture content. It may be owing to variation in initial composition of fresh MSW, small scale laboratory testing, and rate of biodegradation of MSW.
3. For the landfilled MSW, the increase in moisture content from 44 to 80% does not appear to have significant effect on the compression behavior. It may be owing to the fact that the applied moisture content may be less than the field capacity, which is the maximum amount of moisture that can be retained by waste subjected to drainage by gravity. However, the vertical stress-strain curve at 100% moisture content exhibits significant increase in the vertical strain as the vertical stress increases as the landfilled MSW is partially degraded and softened.
4. For a constant vertical stress, the fresh waste compressed more than the landfilled waste at initial and elevated sample moisture contents owing to presence of more organic content in the fresh waste.
5. The modified secondary compression index (C'_α) value is constant for both fresh and landfilled wastes as the curves showing the strain variation with time are parallel to each other.
6. From the statistical analysis, it is observed that the normal probability density function shows a reasonable match for the experimental values of modified primary and secondary compression indices.

7. The mean, standard deviation and COV are 0.2 ± 0.04, 0.073 ± 0.027 and $32.05 \pm 6.45\%$, respectively, for modified primary compression index and 0.051 ± 0.018, 0.063 ± 0.023 and $122.2 \pm 1\%$, respectively, for modified secondary compression index. These results show that the *COV* of secondary compression index is significantly higher than the *COV* of primary compression index, which can be attributed to differences in biodegradation. Such potential large variation in the compressibility properties should be accounted in the reliability-based analysis and design of landfills.
8. The statistical analysis of data indicates that the normal and Weibull distributions appear to be a reasonably good model for primary and secondary compression indices, respectively.

Overall, this study sheds light on compressibility characteristics of typical fresh and landfilled MSW. However, this study is limited to small scale testing on shredded MSW samples for a shorter total testing duration. In order to accurately assess the compressibility of MSW, large-scale laboratory or field testing is recommended on actual field MSW without shredding for a long duration to capture compression owing to both mechanical creep and biodegradation. Moreover, relationships between the compressibility properties and the composition and extent of degradation of MSW should also be explored. Compressibility properties should also be validated based on monitoring of settlement at actual MSW landfills.

Acknowledgements

The authors thank the former graduate student, J. Gangathulasi, for his assistance in conducting laboratory experiments. The first author acknowledges the financial support received from the Indian Institute of Technology Hyderabad, which made it possible to perform this study at the University of Illinois, USA.

References

Anderson, E. O., Balanko, L. A., Lem, J. M. and Davis, D. H. 2004. Field monitoring of the compressibility of municipal solid waste and soft alluvium, in 5th International Conference on Case Histories in Geotechnical Engineering, Paper No. 8.08, New York, NY, April 13-17.

Boutwell, G. P. and Fiore, N. A. 1995. Settlement of clay cover on saturated garbage, in Geoenvironment 2000, (eds. Y. B. Acar and D. Daniels), 964–979, New York, American Society of Civil Engineers.

Burlingame, M. J. 1985. Construction of a highway on a sanitary landfill and its long-term performance, *Transportation Research Record*, **1031**, 34–40.

Castelli, F. and Maugeri, M. 2014. Mechanical properties of municipal solid waste by SDMT, *Waste Management*, **34**, 256–265.

Chen, R. H., Chen, K. S. and Liu, C. N. 2010. Study of the mechanical compression behavior of municipal solid waste by temperature-controlled compression tests, *Environmental Earth Science*, **61**, 1677–1690.

Chen, Y. M., Zhan, T. L. T., Wei, H. Y. and Ke, H. 2009. Aging and compressibility of municipal solid wastes, *Waste Management*, **29**, 86–95.

Coumoulous, D. G. and Koryalos, T. P. 1999. Prediction of long-term settlement behavior of landfill covers after closure, in Proceeding of the 7th International Waste Manage and Landfill Symposium, Sardinia, Italy.

Dixon, N. and Jones, D. R. V. 2005. Engineering properties of municipal solid waste, *Geotextiles and Geomembranes*, **23**, 205–233.

Durmusoglu, E., Sanchez, I. and Corapcioglu, M. 2006. Permeability and compression characteristics of municipal solid waste samples, *Environmental Geology*, **50**, 773–786.

Earth Tech Consultants. 2001. Settlement and density enhancement for leachate recirculation landfills, in Proceeding of the Waste Tech, San Diego.

El-Fadel, M. and Al-Rashed, H. 1998. Settlement in municipal solid waste landfills I field scale experiments, *Journal of Solid Waste Technology Management*, **25**, (2), 89–98.

Fassett, J. B., Leonards, G. A. and Repetto, P. C. 1994. Geotechnical properties of municipal solid wastes and their use in landfill design, in Proceeding of the Waste Tech 94, 1–31, Silver Springs, MD, USA, Solid Waste Association of North America.

Gabr, M. A. and Valero, S. N. 1995. Geotechnical properties of municipal solid waste, *Geotechnical Testing Journal*, **18**, 241–251.

Green, D. and Jamenjad, G. 1997. Settlement characteristics of domestic waste, in Contaminated Ground, 319–324, Cardiff, Wales, British Geotech Society.

Holtz, R. D. and Kovacs, W. D. 1981. An introduction to geotechnical engineering, Englewood Cliffs, NJ, Prentice-Hall.

Hossain, M. S. 2002. Mechanics of compressibility and strength of solid waste in bioreactor landfills. PhD Dissertation, Raleigh, NC, Department of Civil Engineering, North Carolina State University at Raleigh.

Hossain, M. S., Gabr, M. A. and Barlaz, M. A. 2003. Relationship of compressibility parameters to municipal solid waste decomposition, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **129**, 1151–1158.

Jessberger, H. L. and Kockel, R. 1995. Determination and assessment of the mechanical properties of waste materials, in Geotechnics Related to the Environment, (ed. R. W. Sarsby), 313–322, Rotterdam, Netherlands, Balkema.

Karimpour-Fard, M. and Machado, S. L. 2012. Deformation characteristics of MSW materials, *Electronic Journal of Geotechnical Engineering*, **17**, (A), 2009–2024.

Kavazanjian, E., Matasovic, N. and Bachus, R. C. 1999. Large-diameter static and cyclic laboratory testing of municipal solid waste, in 7th International Waste Manage and Landfill Symposium. Cagliari, Italy, 437–444.

Landva, A. O. and Clark, J. I. 1990. Geotechnics of waste fill, in Geotechnics of Waste Fills. ASTM STP 1070, (eds. A. O. Landva and G. D. Knowles), Philadelphia, PA, American Society for Testing and Materials, 86–103.

Landva, A. O., Valsangkar, A. J. and Pelkey, S. G. 2000. Lateral earth pressure at rest and compressibility of municipal solid waste, *Canadian Geotechnical Journal*, **37**, 1157–1165.

Lewis, P. J., Mansfield, J., Ashraf, S. and Zicko, K. 2004. Performance of highway embankment constructed over landfill material, in 5th International Conference on Case Histories in Geotechnical Engineering, New York.

Machado, S. L., Carvalho, M. F. and Vilar, O. M. 2002. Constitutive model for municipal solid waste, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **128**, 940–951.

Manassero, M., Van Impe, W. F. and Bouazza, A. 1996. Waste disposal and containment, in Proceedings of the 2nd International Congress on Environ Geotech. Osaka 3, 193–242.

Marques, A. C. M., Filz, G. M. and Vilar, O. M. 2003. Composite compressibility model for municipal solid waste, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **129**, 372–378.

Mesri, G. and Castro, A. 1987. $C\alpha/Cc$ concept and K_0 during secondary compression, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **113**, (3), 230–247.

Oweis, I. S. and Khera, R. 1986. Criteria for geotechnical construction on sanitary landfills, in Symposium on Environmental Geotechnical Engineering. Allentown, PA, 215–222.

Park, H., Lee, S. R. and Do, N. Y. 2002. Evaluation of decomposition effect on long-term settlement prediction for fresh municipal solid waste landfills, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **128**, (2), 107–118.

Rao, S. K., Moulton, L. K. and Seals, R. K. 1977. Settlement of refuse landfills, in Geotechnical Practice for Disposal of Solid Waste Materials, 574–599, Ann Arbor, MI.

Reddy, K. R., Gangathulasi, J., Parakalla, N. S., Hettiarachchi, H., Bogner, J. E. and Lagier, T. 2009a. Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations, *Waste Management and Research*, **27**, 578–587.

Reddy, K. R., Hettiarachchi, H., Gangathulasi, J. and Bogner, J. E. 2011. Geotechnical properties of municipal solid waste at different phases of biodegradation, *Waste Management*, **31**, 2275–2286.

Reddy, K. R., Hettiarachchi, H., Gangathulasi, J., Bogner, J. and Lagier, T. 2009c. Geotechnical properties of synthetic municipal solid waste, *International Journal of Geotechnical Engineering*, **3**, 429–438.

Reddy, K. R., Hettiarachchi, H., Parakalla, N. S., Gangathulasi, J. and Bogner, J. E. 2009b. Geotechnical properties of fresh municipal solid waste at Orchard Hills Landfill, USA, *Waste Management*, **29**, 952–959.

Sargunan, A., Mallikarjun, N. and Ranapratap, K. 1986. Geotechnical properties of refuse fills of Madras, India, in International Symposium on Environmental Geotechnology, (ed. H. Y. H. Y. Fang).

Sharma, H. D. and De, A. 2007. Municipal solid waste landfill settlement: post closure perspectives, *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, **133**, (6), 619–629.

Sharma, H. D. and Reddy, K. R. 2004. Geoenvironmental engineering: site remediation, waste containment, and emerging waste management technologies, Hoboken, NJ, Wiley.

Sharma, H. D., Fowler, W. L. and Cochrane, D. A. 1999. Evaluation and remediation of ground cracking associated with refuse settlements, in 7th International Waste Management and Landfill Symposium. Cagliari, Italy.

Sharma, H. D. 2000. Solid waste landfills: Settlements and post closure perspectives, in Proceeding of the ASCE National Conf on Environmental and Pipeline Engineering, (ed. R. Y. Surampalli), Reston, VA, ASCE, 447–455.

Sowers, G. F. 1973. Settlement of waste disposal fills, in 8th International Conference on Soil Mechanics and Foundation Engineering. Moscow, 207–210.

Stulgis, R. P., Soydemir, C. and Telgener, R. J. 1995. Predicting landfill settlement, in Geoenvironment 2000, (eds. Y. B. Acar and D. Daniels), 980–994, New York, American Society of Civil Engineers.

Swati, M. and Joseph, K. 2008. Settlement analysis of fresh and partially stabilized municipal solid waste in simulated controlled dumps and bioreactor landfills, *Waste Management*, **28**, 1355–1363.

USEPA. 2007. Municipal solid waste in the United States: 2005 facts and figures. Available from: <http://www.epa.gov/> [Accessed 11 May 2015].

Van Impe, W. F. 1998. Environmental geotechnics, in 11th Danube-European Conf on Soil Mechanics and Geotechnical Engineering, Rotterdam, Balkema, 127–156.

Vilar, O. M. and Carvalho, M. F. 2004. Mechanical properties of municipal solid waste, *Journal Testing and Evaluation*, **32**, (6), 438–449.

Wall, D. K. and Zeiss, C. 1995. Municipal landfill biodegradation and settlement, *Journal of Environmental Engineering*, **121**, (3), 214–224.

Wong, W. W. Y. 2009. Investigation of the geotechnical properties of municipal solid waste as a function of placement conditions. MS thesis, San Luis Obispo, CA, USA, Faculty of California Polytechnic State University.

Yolo County, Planning and Public Works Department. 2000. A beneficial investment in trash controlled landfill bioreactor project. Urban Consortium Energy Task.

Yu-Xin, J., Wen-Jie, X., Danzeng, D., Yi-Feng, W., Tao, P. and Zai-Yang, Z. 2013. Laboratory testing of a densified municipal solid waste in Beijing, *Journal of Central South University of Technology*, **20**, 1953–1963.

Zaminskie, E. M., Kabir, M. G. and Haddad, A. 1994. Settlement evaluation for cap closure performance, in Vertical and horizontal deformations of foundations and embankments, Settlement 94, (eds. A. T. Yeung and G. Y. Felio), ASCE, Vol. **1**, 462–475.