



## Aging and compressibility of municipal solid wastes

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### ABSTRACT

The expansion of a municipal solid waste (MSW) landfill requires the ability to predict settlement behavior of the existing landfill. The practice of using a single compressibility value when performing a settlement analysis may lead to inaccurate predictions. This paper gives consideration to changes in the mechanical compressibility of MSW as a function of the fill age of MSW as well as the embedding depth of MSW. Borehole samples representative of various fill ages were obtained from five boreholes drilled to the bottom of the Qizhishan landfill in Suzhou, China. Thirty-one borehole samples were used to perform confined compression tests. Waste composition and volume-mass properties (i.e., unit weight, void ratio, and water content) were measured on all the samples. The test results showed that the compressible components of the MSW (i.e., organics, plastics, paper, wood and textiles) decreased with an increase in the fill age. The *in situ* void ratio of the MSW was shown to decrease with depth into the landfill. The compression index,  $C_c$ , was observed to decrease from 1.0 to 0.3 with depth into the landfill. Settlement analyses were performed on the existing landfill, demonstrating that the variation of MSW compressibility with fill age or depth should be taken into account in the settlement prediction.

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### 1. Introduction

Municipal solid waste (MSW) was simply dumped into a fill in China until the end of the 1980s when the first technical code for sanitary landfills was put into practice. In the early 1990s, the first generation of controlled landfills was designed and built in most major cities. Most of the landfills were located in valleys, and vertical engineering barriers (i.e., cut-off walls or injected grout curtains) were used to prevent leachate from contaminating the downstream ground surface and groundwater. Most of these landfills have reached their design capacity, and a solution is required for further disposal of MSW. Expansion of existing landfills appears to be the most likely solution for many cities because of the social and political problems associated with identifying new landfill sites. Consequently, landfill expansion has now become a common practice in many cities of China.

Landfill expansion may be vertical and/or lateral. One of the major technical difficulties associated with vertical expansion (e.g., piggyback type) is the design of the intermediate liner system between the existing and expanded waste bodies. The surcharge loading of the expanded landfill can result in substantial settlement of the existing landfill. Compacted clay liners and (or) geomembranes may lose their effectiveness as a hydraulic barrier when subjected to differential settlement (Edelmann et al., 1999). The leachate collection system may also lose the minimum gradient required for gravity flow, and even result in a reversal of

leachate flow. A “backfill thickness adjustment” design concept had been proposed to address the above engineering problem. The principle involves an increase in thickness of backfill at locations where settlement is anticipated to be greatest. In addition, geogrid reinforcement is to be placed under the bottom of the intermediate liner to protect against a local differential settlement. With proper design, the overlying sealing layer will not be subjected to unacceptable differential settlement during the later stages of landfill expansion. The proposed design concept requires a reasonably reliable prediction of future settlement for the existing landfill. It is well known that the prediction of landfill settlement requires understanding of both primary and secondary compression behavior of MSW. The focus of this paper is concerned with the primary compressibility of MSW and its relationship to the fill age of MSW.

Numerous theoretical models have been proposed for the prediction of landfill settlement (Sowers, 1973; Yen and Scanlon, 1975; Edil et al., 1990; Van Meerten et al., 1995; Park and Lee, 1997; Ling et al., 1998; Gabr et al., 2000; Leonard et al., 2000; Marques et al., 2003), and experimental data on the compressibility of MSW have been accumulated over the last two decades (Rao et al., 1977; Landva et al., 1984; Oweis and Khera, 1986; Bjarngard and Edgers, 1990; Wall and Zeiss, 1995; Gabr and Valero, 1995; Boutwell and Fiore, 1995; Stulgis et al., 1995; GeoSyntec, 1996; Green and Jamenjad, 1997; Oweis and Khera, 1998; Landva et al., 2000; Hossain et al., 2003; Hudson et al., 2004). However, the prediction of settlement at a specific landfill is still a challenging engineering problem due to the variety of MSW materials. The composition of MSW generally varies from country to country, region to region

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and period to period. Even within a particular landfill with similar MSW input, the composition of MSW varies with its fill age. This is primarily due to the degradation process of organic matter. MSW is also a highly structured material as a result of the method of placement and compaction. Current engineering practice associated with landfill settlement analysis usually involves the use a single value to define the compressibility of all waste sub-layers. This practice may lead to inaccurate predictions (Gabr and Valero, 1995; Wall and Zeiss, 1995). A more rational approach is to measure material parameters for each of the sub-layers in the landfill, preferably by taking undisturbed MSW samples from the landfill.

This paper presents a laboratory study on the mechanical compressibility of MSW within the Qizhishan landfill in Suzhou, China. This landfill is presently under design for vertical and lateral expansion. The MSW samples tested in the laboratory study were taken from five boreholes drilled to the bottom of the landfill. Thirty-one confined compression tests (i.e., oedometer tests) were carried out on the samples taken at different depths. The samples represent landfill materials corresponding to different fill ages. An attempt was made to find a relationship between the compressibility of the fill material and the fill age as well as the initial void ratio. The measured compressibility of the fill material was then used to calculate the primary settlement that would result from the surcharge loading of the expanded landfill.

## 2. Site description, borehole investigation and sampling

The Qizhishan landfill is located in a valley surrounded by hills about 13 km to the south of Suzhou, China. The landfill was put into operation in 1993. Its capacity and service life design were 4.7 million m<sup>3</sup> and 15 years, respectively. The existing landfill consists of a number of filled platforms that are set back at an embankment slope of 3H/1V. A rockfill dam retains the lowest platform as shown in Fig. 1. The bottom of the initial landfill was not lined with any form of watertight barrier. A cut-off wall, consisting of concrete diaphragm wall and injected grout curtain, was installed under the rockfill dam in an attempt to limit downstream movement of leachate. It should be noted that the design of barrier system was based on the assumption that the valley has a continuous and sufficiently thick bedrock with low permeability. However, groundwater monitoring downstream indicated that the grout curtain was not totally effective in retaining leachate. It is expected that the landfill will reach its top design level (i.e., +80 m Ordnance Datum) by the end of 2008. Vertical and lateral expansion of the existing landfill is presently under design. Fig. 1 shows how the landfill will be expanded from a level of 80 to 120 m in vertical direction, and 400 m outwards the present landfill boundary in the horizontal direction. In accordance with the new regulation, the bottom of the expanded waste body will be lined with a composite liner system, including a leachate collection layer and sealing layers. Another cement-slurry cut-off wall will be constructed

just downstream the existing cut-off wall to establish a double-barrier system.

The waste disposal practice at the Qizhishan landfill before the year of 2007 was at a low-level standard. The incoming wastes were dumped near the edge of a tipping area, and then pushed over the edge by a bulldozer where the wastes came to rest at an inclination of 3H/1V. There was no compaction by a roller. The compaction effort resulting from the bulldozer is limited because the thickness for each lift of waste mass was greater than 5 m. The simple disposal procedure tended to result in a relatively loose waste mass, especially at the shallow depths. Since 2007, the operator at the Qizhishan landfill started to improve the waste disposal practice by following the technical code for sanitary landfills updated in 2004 (CJJ117-2004). Waste compaction by a roller is carried out layer by layer and the thickness of each layer is limited to 1 m.

A borehole investigation and sampling program was carried out on the existing landfill to assist in the design of the intermediate liner system in 2006. Five boreholes (BH1–BH5) were drilled to the bottom of the existing landfill (Fig. 1). The depths of the boreholes ranged from 26 to 38 m. To avoid a collapse of the borehole wall, a system of steel casings were installed in each borehole. Each borehole consisted of three vertical sections (i.e., from top to a depth of 10 m, from 10 to 20 m and below 20 m) with different-diameter casings installed. The borehole diameters for the three sections were 130, 110 and 90 mm, respectively. MSW samples were taken using thick-walled samplers at an interval of 1 or 2 m. More than 20 samples were obtained from each of the boreholes. The diameters of the samples were about 96 mm for those taken from above a depth of 20 m and 82 mm for samples taken from below a depth of 20 m. Each sample was about 200 mm in height. Unfortunately, the samples obtained from the field investigation program are relatively small when compared to some of the large-size components of the MSW. The effect of the sample size on the test results is discussed later in this paper.

As the landfill was piled lift by lift (i.e., approximately 5 m of initial thickness for each lift), the depth of the landfill material could be correlated with the fill age. On the basis of the borehole logs and the record of the landfill operation, a correlation was made between the fill age and the depth. The range of the fill age for each sample of fill material was identified and is shown in Table 1.

## 3. Laboratory testing method

### 3.1. Experimental design

The following procedures were adopted in handling each of the borehole samples used for compression testing. Firstly, the weight and dimensions (i.e., diameter and height) of the sample were measured for the determination of the bulk density. Secondly, the sample was placed in a specially designed 1-D compression

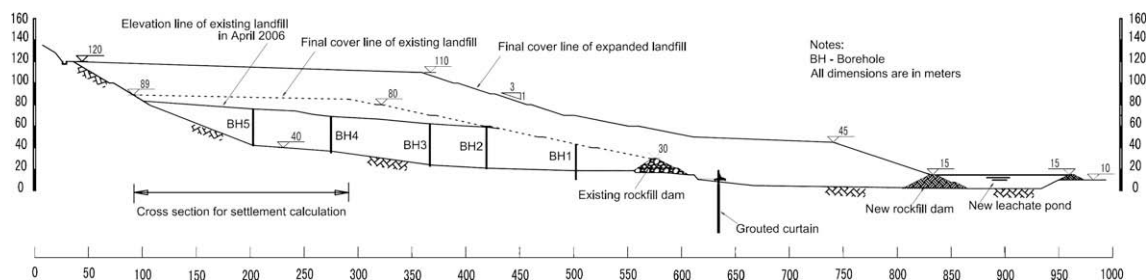


Fig. 1. Cross-section of the existing and expanded landfills in Suzhou, China.

**Table 1**  
Sample information

Borehole No.	Specimen ID	Depth (m)	Fill age (year)	Diameter (mm)	$e_0$	$C_e$	$C_c$
BH1	1-1	2.5	6.5	95	2.35	0.193	0.647
	1-2	7.6	7.8	90	2.12	0.199	0.623
	1-3	12.4	8.8	93	2.80	0.194	0.738
	1-4	18.4	10.2	81	2.06	0.195	0.598
	1-5	21.4	10.8	82	2.03	0.177	0.538
BH2	2-1	3.7	2.7	94	1.90	0.218	0.633
	2-2	9.4	4.4	95	1.75	0.185	0.509
	2-3	13.4	6.1	95	1.21	0.140	0.309
	2-4	22.4	8.4	93	1.11	0.154	0.327
	2-5	24.4	8.9	93	1.42	0.131	0.317
	2-6	26.4	9.3	80	1.69	0.143	0.384
	2-7	32.4	10.6	79.5	0.72	0.134	0.231
BH3	3-1	5.4	3.0	94	4.20	0.216	1.122
	3-2	7.4	3.5	95	2.07	0.190	0.584
	3-3	12.4	5.6	95	1.70	0.170	0.459
	3-4	19.0	7.7	80	1.86	0.152	0.435
	3-5	22.0	8.3	80	2.86	0.252	0.972
	3-6	26.0	9.2	81	1.58	0.135	0.349
	3-7	30.0	10.0	81	2.66	0.181	0.662
BH4	4-1	2.7	0.8	95	3.54	0.313	1.421
	4-2	8.7	2.1	94	1.45	0.209	0.511
	4-3	12.7	2.9	94	2.31	0.267	0.883
	4-4	16.7	4.0	82	1.28	0.159	0.362
	4-5	22.7	6.6	82	1.10	0.169	0.354
	4-6	26.7	7.6	82	1.72	0.084	0.229
BH5	5-1	3.9	0.1	94	3.81	0.256	1.232
	5-2	7.9	0.9	80	3.40	0.183	0.806
	5-3	11.9	1.7	75	1.20	0.113	0.249
	5-4	17.9	3.0	82	1.64	0.174	0.460
	5-5	21.9	4.1	81.5	1.15	0.181	0.391
	5-6	25.9	5.9	82	1.54	0.119	0.302

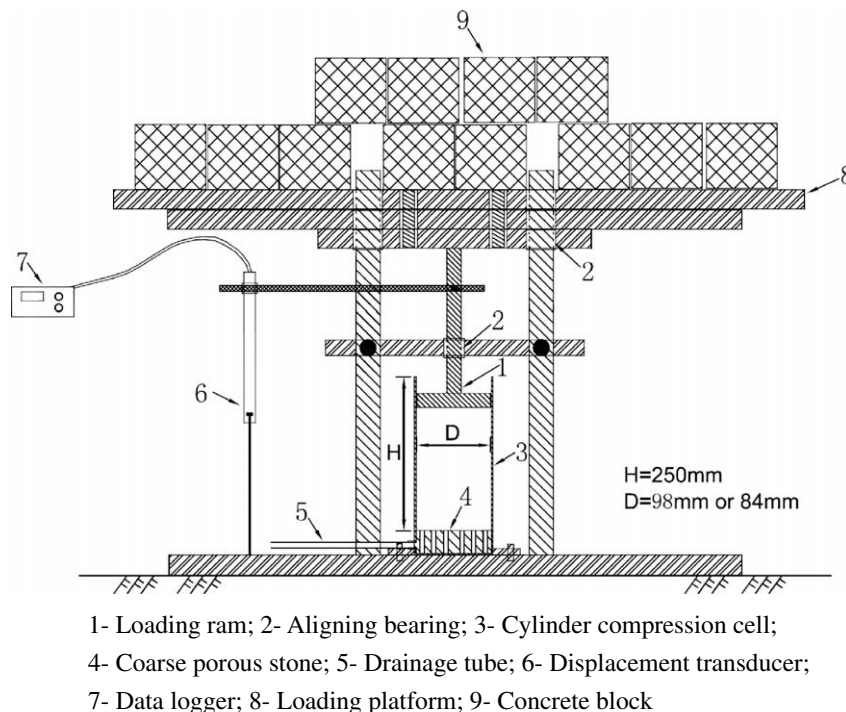
Notes:  $C_e$  – slope of compression curve between 0 and 25 kPa.

$C_c$  – slope of compression curve between 50 and 1000 kPa.

cell. Thirdly, after the completion of the compression test, all the material was retrieved from the cell, and then dried at an oven temperature of 60 °C. The water content of the sample can be calculated from the measurements of initial wet weight and dry weight of each sample. Fourthly, the major components of the sample (i.e., plastic, paste, textiles, wood, metal, glass, ceramic, etc.) were identified using visual observation and individually weighed. Finally, all materials were divided into two parts, each having a similar weight and composition. For the first portion, all materials except the plastic matter were incinerated for 2 h in an oven at a temperature of 300 °C. This allowed the organic content to be determined by weighing the amount of incineration loss. For the second portion, all materials were placed in a cylindrical container with a siphonal tube. The overall specific gravity of each sample was measured using the water replacement method. The void ratio of each sample was calculated from the measurements of overall specific gravity and dry density.

### 3.2. Mechanical compression test

Compression tests were conducted on 31 samples taken from five boreholes (i.e., BH1–BH5). Descriptions and data on each of the samples are shown in Table 1. There appears to be no standardized equipment or test procedures for conducting compression tests on MSW samples. In this study, two compression apparatuses were specially designed for performing compression tests on the borehole samples (Fig. 2). The two compression apparatuses are similar apart from the diameter of compression cells. The inner diameters were 84 mm and 98 mm for accommodating the borehole samples with diameters of approximately 82 mm and 96 mm, respectively. Both apparatuses accommodated specimens that were 250 mm in height. During testing, the inner wall of each cell was lined with a smooth plastic sheet of specified thickness. The thickness of the plastic sheet was selected to minimize the



**Fig. 2.** Specially designed oedometer for compression tests on borehole samples.

potential clearance between the sample and the inner wall of the cell. In this way, one-dimensional deformation could be simulated. Another purpose of the lined plastic sheet was to reduce friction between the sample and the cell wall. In this way the entire bore-hole sample could be installed in the compression cell without the necessity of trimming the specimen. The simulation of the surcharge loading on the samples was accomplished using a dead loading frame, which consists of a loading platform aligned by four vertical steel bars. The dead load was made up of a designated number of concrete blocks each with a weight of 5 kg. The loading frame was designed to apply a maximum vertical pressure of 1000 kPa. Liner voltage displacement transformers (LVDTs) were used to monitor vertical displacement during testing. In addition, a drainage hole was produced near the bottom of each compression cell to allow for the dissipation of pore pressures in the specimen.

A step-loading method was adopted to measure primary compression of the landfill samples. After each specimen was installed in the compression cell, dead loads equivalent to vertical pressures of 25, 50, 100, 200, 500 and 1000 kPa were applied in succession. The duration for each step of loading was set as 8 h. The duration was determined on the basis of five trial compression tests that lasted 24 h. The trial compression test results demonstrated that over 95% of the compression occurred within 8 h. The test duration adopted here is consistent with that used by Hossain et al. (2003). Grisolia and Napoleoni (1996) suggested that the primary compression, consisting of an instant reduction in the macro-porosity caused by the re-arrangement of deformable elements and a subsequent compression of individual deformable elements, lasts about 200 to 300 min.

## 4. Experimental results

### 4.1. Composition of MSW

MSW typically consists of food and garden wastes, paper products, plastics, rubber, textiles, wood, ashes, and soils. These components are different in size, shape, compressibility, tensile strength and degradability. MSWs with different compositions will exhibit different mechanical properties (e.g., compressibility and shear strength). Knowledge of waste composition can assist in the evaluation of the compressibility of MSW.

Fig. 3 shows the changes in the composition of the MSW collected in Suzhou, China between 1990 and 2006. The content of each component was measured and calculated on a wet weight basis. Fig. 3 shows that there is a significant decrease in the cinder content between 1990 and 2000. The change was the result of an

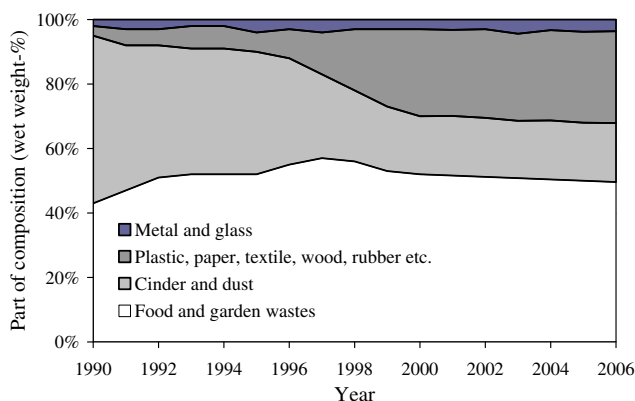


Fig. 3. Change in composition of MSW as collected in Suzhou, China over the last decade.

increasing use of natural gas for cooking. At the same time, there was an increase in the recyclable content, food and garden wastes with time, particularly between 1996 and 2000. After 2000, the change in the composition of MSW was relatively small. The MSW in China contains more food and garden wastes (e.g., between 50% and 60%) than is found in western countries. This is attributable to differences in cooking styles. In addition, the recyclable content of MSW in China is less than in western countries, particularly with regard to paper waste. It should be noted that the Qizhishan landfill started to receive wastes in 1993.

Fig. 4 shows the changes in the MSW composition with the fill age of MSW. The data were obtained from the composition analysis conducted on the borehole samples. The content of each component was measured and calculated using a dry weight basis, rather than the wet-basis for Fig. 3. As a result, the organic content of the MSW in Fig. 4 appeared to be significantly less than that shown in Fig. 3. The initial data point (i.e., at zero yr) is determined from the composition of the fresh MSW collected in 2006. After the MSW was placed into the landfill, its organic content decreased significantly with time during the first 2 years. Then the organic content remained at a value of approximately 18%. The decrease in organic content is related to the fast degradation of the putrescent organic (e.g., food and garden wastes). At the same time there was a significant increase in the cinder content with the fill age. The increase in the cinder content is mainly the result of the decrease in the organic wastes. Daily placement of cover soils used during the landfill operation also contributed to an increase in cinder content. The decrease in fiber content with fill age as well as the plastic content, is partly due to the change in the composition of the fresh MSW collected over the last decade (see Fig. 3).

Unlike a mineral porous media, MSW contains a substantial amount of compressible materials including organics, plastics, paper, wood and textiles. The content of the compressible components has a significant effect on the compressibility of the MSW (Dixon and Langer, 2006). Fig. 5a and b shows the variations in the compressible and incompressible contents with the fill age of MSW, respectively. The compressible components consist of organics, paper, plastic, textile, and wood, and the incompressible components including soils, ceramics, glass, and metal (Dixon and Langer, 2006). It should be clarified that the terms “compressible” and “incompressible” here refer to the compressibility of the individual solid phase in the MSWs rather than that of a porous medium. Although the experimental data show considerable scatter, there is a general trend that can be identified in Fig. 5a and b. The figures show that the compressible components are decreasing with the fill age and the incompressible components are increasing with the fill age.

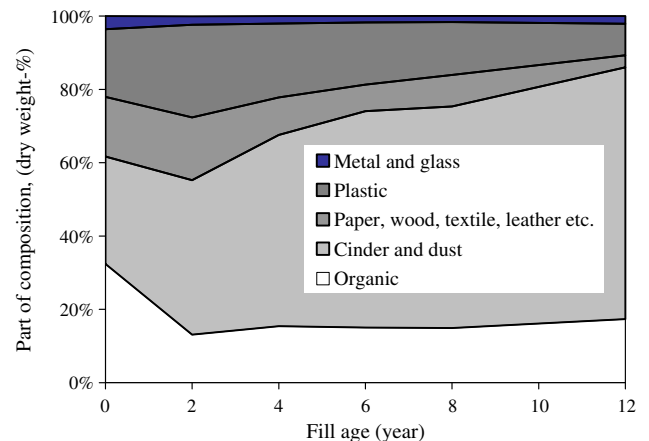


Fig. 4. Variations of MSW composition with its fill age.



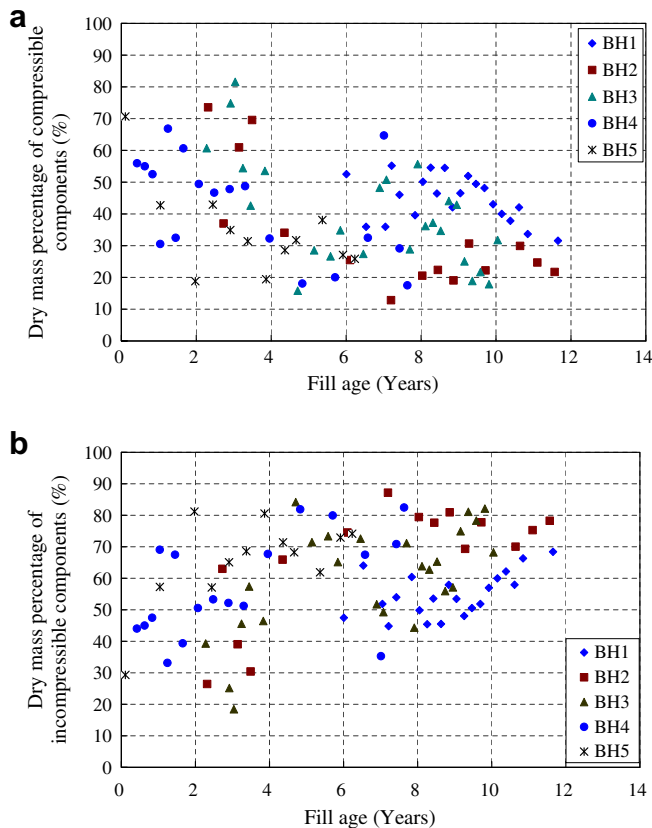


Fig. 5. Variations in content of compressible and incompressible components with fill age: (a) compressible components and (b) incompressible components.

#### 4.2. Unit weight

The self-weight of the MSW is related to the unit weight of the material. Self-weight provides the principal means of load that subsequently compresses the landfill. Measurements on the unit weight of the MSW are helpful in interpreting compressibility. The unit weight of the MSW is also required for other engineering analyses related to landfill performance, including settlement, slope stability and landfill capacity evaluation. Fig. 6 shows the variation in unit weight with depth for samples taken from the five boreholes (BH1–BH5). A typical profile of unit weights suggested by Zekkos et al. (2006) for American landfills is also shown in Fig. 6. It can be seen that most of the data fall within the range from 5 to 15 kN/m<sup>3</sup>. As anticipated, the values for unit weight generally increase with an increase in depth in the landfill. The data points can be best-fit through the use of a bi-linear line. The increased rate of unit weight at shallow depths (i.e., less than a depth of 22 m) is greater than that at depths exceeding 22 m. As compared with the typical profile suggested by Zekkos et al. (2006), most values for unit weight at the Qizhishan landfill are lower at shallow depths but greater at depths exceeding 25 m. The lower unit weights at shallow depths are likely attributable to the low-level of compaction effort executed in the waste disposal practice before 2007. The greater unit weights at depths exceeding 25 m are likely related to the high cinder contents in the MSW collected during the years between 1993 and 1996.

#### 4.3. Void ratio

Void ratio is defined as the ratio between the volume of voids and the volume of solids for a unit volume of porous medium. The

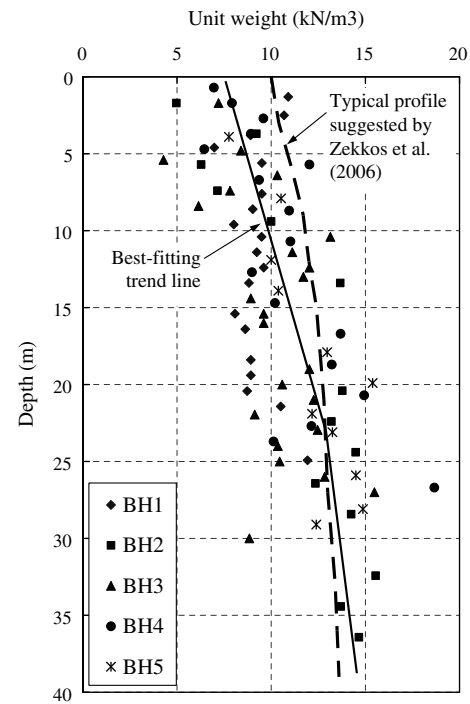


Fig. 6. Variations of unit weight with depth.

MSW is a porous media with a high void ratio. The compressibility of MSW is significantly influenced by the initial void ratio. The initial void ratio is related to waste placement and compaction methods as well as the *in situ* overburden pressure. Fig. 7 shows the variation in void ratio with the depth from which the samples were taken in the five boreholes (BH1–BH5). Almost all data points fall into the range between 1 and 4. There appears to be a general decrease in void ratio with depth as illustrated by the best-fit line. The significant scatter of the data points is related to the heterogeneous nature of MSW. Some of the scatter may also be due to sample disturbance and localization effects associated with the borehole sampling. The decreasing trend of void ratio with depth shown in Fig. 7 is basically consistent with the experimental data reported by Zornberg et al. (1999). However, the data of void ratio reported by Zornberg et al. (1999) for American landfills is located within a narrower range between 1.2 and 2.0. This indicates that the MSW in the Qizhishan landfill at shallow depths is significantly looser than those found in American landfills. The plot of void ratio versus depth shown in Fig. 7 is basically consistent with the profile of unit weights shown in Fig. 6. The void ratios shown in Fig. 7 provide the initial state conditions required for a landfill settlement analysis. The measured void ratios also assist in interpreting the compression behavior of the MSW samples.

Fig. 8 shows changes of void ratio with the effective overburden pressure for the samples taken from the Qizhishan landfill. The values of effective overburden pressure were calculated from the measurement of unit weights on the borehole samples in conjunction with the field measurements of water (or leachate) pressure in the boreholes (Chen and Zhan, 2006). The values of void ratio decrease with an increase in the effective overburden pressure. The best-fit line has an inclination of 1.14, which is slightly greater than the value of 0.99 reported by Zornberg et al. (1999). The inclination is similar to the measured primary compression index,  $C_c$ . However, the inclination shown in Fig. 8 also accounts for the compression of MSW related to mechanical creep and biological degradation.

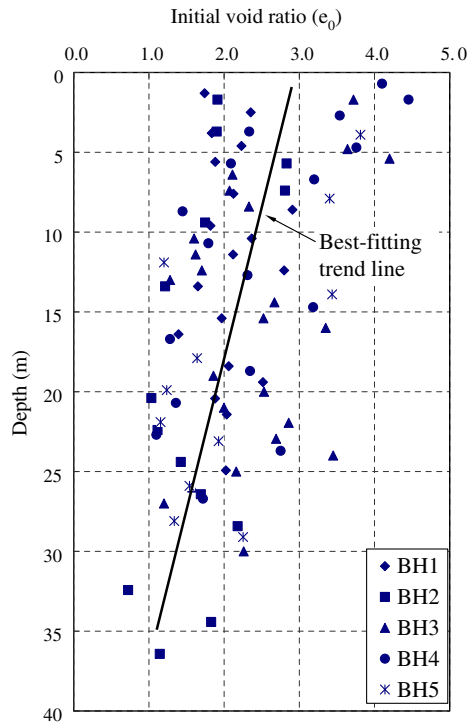


Fig. 7. Variations of void ratio with depth.

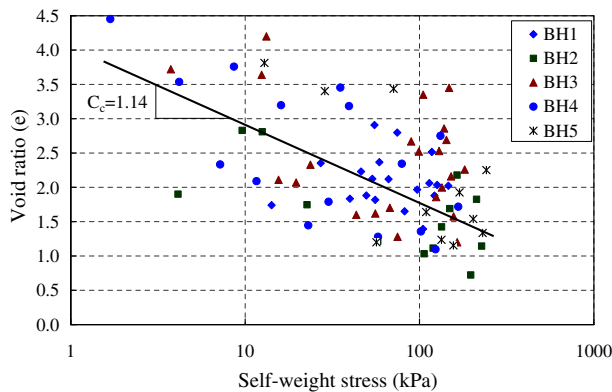


Fig. 8. Changes of void ratio with effective overburden pressure.

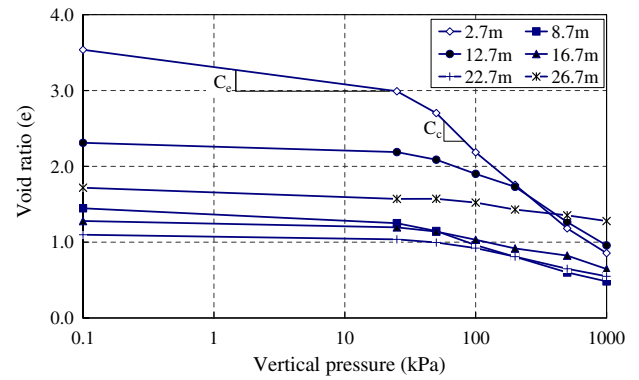


Fig. 9. Compression curves obtained from the six samples taken at different depths in borehole BH4.

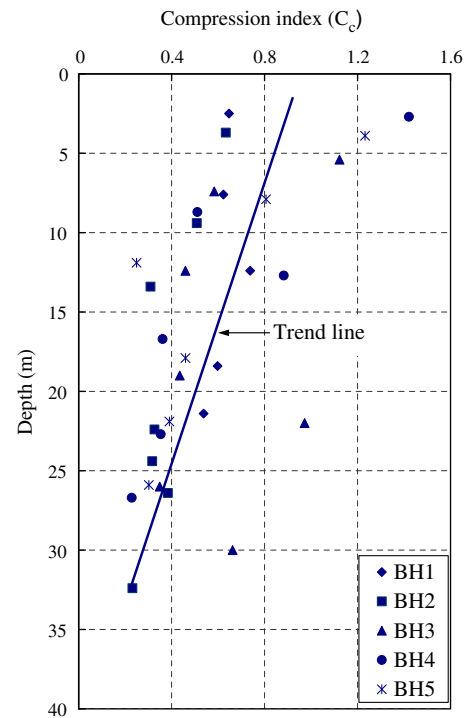


Fig. 10. Variation of compression index with depth.

#### 4.4. Coefficient of primary compression

Thirty-one compression tests were conducted on samples taken from the five boreholes (BH1–BH5). The test results are presented in Table 1 and Figs. 9–12. Fig. 9 shows the compression curves obtained from six samples taken at different depths in borehole BH4. The compression curves are shown using a semi-logarithm plot and the curves exhibit a bi-linear shape. The pressure corresponding to the inflection point is defined as a pseudo-yielding stress. The pseudo-yield stresses for the samples taken at different depths seem to fall within a relatively narrow range from 25 to 50 kPa. The inclination of the post-yielding curve is defined as the primary compression index,  $C_c$ . The primary compression index is commonly used in engineering practice to characterize the compressibility of a porous medium. The values of  $C_c$  obtained from all the 31 specimens ranged from 0.2 to 1.4, and the results are listed in Table 1. The inclination of the pre-yielding curve is assumed to represent the elastic compression index,  $C_e$ . The values for  $C_e$  for the

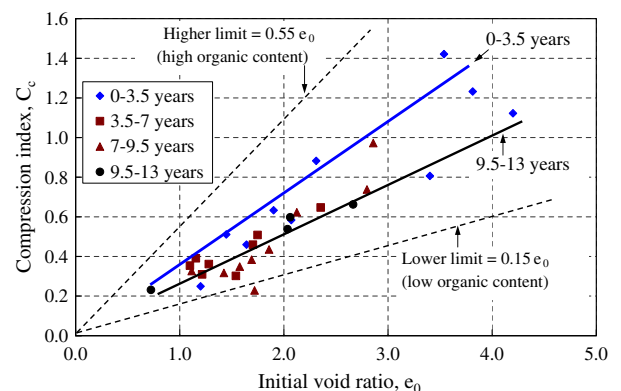


Fig. 11. Relationship between compression index and initial void ratio for the samples of different fill ages.

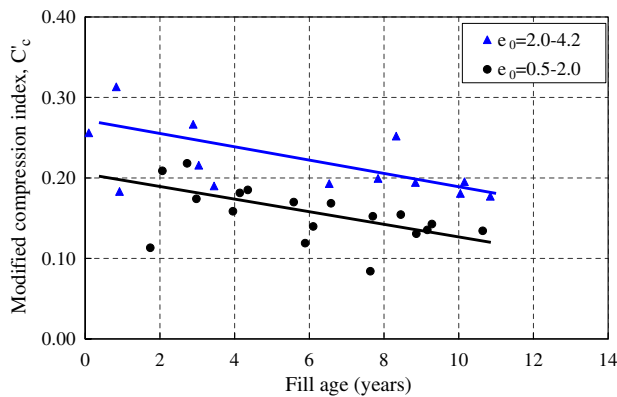


Fig. 12. Relationship between compression index and the fill age for the samples with different initial void ratios.

31 samples vary from 0.05 to 0.5 (see Table 1). A comparison between  $C_e$  and  $C_c$  shows that the ratio ( $C_e/C_c$ ) is close to 1/3 for most of the specimens.

Fig. 10 shows a plot of compression index,  $C_c$ , versus depth for all 31 samples taken from the five boreholes (BH1–BH5). Almost all data points fall within the range of 0.3–1.0. Although the data points show scatter, there is a general decreasing trend of  $C_c$  with depth. As the depth increases, the MSW samples contain more cinder content and less compressible materials. The MSW therefore becomes denser and more uniform, resulting in a lower compressibility. The experimental data shown in Fig. 10 allows an engineer to be able to calculate the settlement of the existing landfill taking into account the surcharge loading associated with vertical expansion of landfill. The above results suggest that the current practice of using a single value of  $C_c$  for settlement calculation could be improved upon in engineering practice.

Fig. 11 shows a plot of compression index versus initial void ratio,  $e_0$ , for all the samples of different fill ages together with the boundaries suggested by Sowers (1973). The fill age of each sample was identified from the borehole logs and the landfill operation records. It can be seen that all the data points fall within the boundaries provided by Sowers (1973). The higher limit for the data points (i.e.,  $C_c = 0.4e_0$ ) are lower than the limit provided by Sowers (1973) (i.e.,  $C_c = 0.55e_0$ ). The values of  $C_c$  increase in a nearly linear manner with an increase in initial void ratio. For a given void ratio, the older MSW samples generally exhibit a lower compressibility. The lower  $C_c$  is related to the absence of the compressible components (see Fig. 5).

Fig. 12 shows a plot of the compression index modified to take the initial void ratio into account ( $C'_c = C_c/(1 + e_0)$ ). It was observed that the relationship between the  $C'_c$  value and the fill age of MSW was still related to the extreme variations in void ratio. The data points shown in Fig. 12 can be divided into two groups corresponding to two different ranges of initial void ratio (i.e.,  $e$  from 0.5 to 2.0 and  $e$  from 2.0 to 4.0). For each group, the value of  $C'_c$  decreases with an increase in the fill age of MSW. A linear relationship can be obtained by best-fitting the data points within a particular range of void ratios. The above experimental results appear to be inconsistent with those reported by Hossain et al. (2003), which showed that the modified compression index,  $C'_c$ , increased with an increase in the degree of decomposition. Hossain et al. (2003) used the cellulose, (C) plus hemi-cellulose, (H) to lignin, (L) ratio to quantify the degree of decomposition. It was found that the modified compression index,  $C'_c$ , increased with a decrease in the [(C + H)/L] ratio. The reason for the above difference in the observed test results is not completely clear. There are several differences between the research undertaken by Hossain et al. (2003)

and this study. The main differences between the two research studies involves the sample composition, sample size and specimen preparation methods. Shredded and remolded specimens with a size of 63.5 mm diameter and 19 mm thick were used by Hossain et al. (2003). In this study the borehole samples with different fill ages also have significant differences in composition.

Fig. 13 compares the modified primary compression indices reported in other research literature with the ranges obtained in this study. Further information on how each of the data was obtained is presented in Table 2. It can be seen that the range in compressibility obtained from the borehole samples is comparable to those reported in the research literature. The mid-range values of  $C'_c$  for all the 21 sets of data fall within the range between 0.1 and 0.3, with two exceptions. The secondary compression indices representing the compression associated with mechanical creep and biological degradation are also presented in Fig. 14. Most of the data sets show the value of secondary compressibility ranging from 0 to 0.05. These figures provide a database for selecting appropriate compressibility parameters for MSW at the preliminary design stage of landfills.

## 5. Discussion on effect of sample size on the experimental results

The size of the borehole samples used in this study was smaller than that desirable for a material, which is as heterogeneous as MSW. However, the experimental results presented appear to be reasonable and consistent with the results of other studies. Most of the data are consistent with typical ranges reported in the research literature. It is acknowledged that some researchers have succeeded in obtaining large-size borehole samples (e.g., 1 m in diameter) for the measurement of unit weight (Matasovic and Kavazanjian, 1998; Zekkos et al., 2006). The large samples are more representative of the MSW composition, and therefore are of increased value for the characterization of the engineering properties. However, the procedure required to retrieve large-size samples is costly and time-consuming. It may be difficult to enforce the retrieval of large-size samples for routine engineering practice. It should also be noted that the samples collected from large-size boreholes was usually in a disturbed state. As compared with the large-diameter borehole samples, the more conventional small-diameter borehole samples have the advantage of being able to retrieve a more “intact” samples with respect to the density and fabric. It is suggested that further research be undertaken to establish the significance of sample size to the reliability of the measured engineering properties. In other words, it would be of value to have a comparison of MSW properties measured on the small-diameter “intact” samples and those measured on large-diameter disturbed samples.

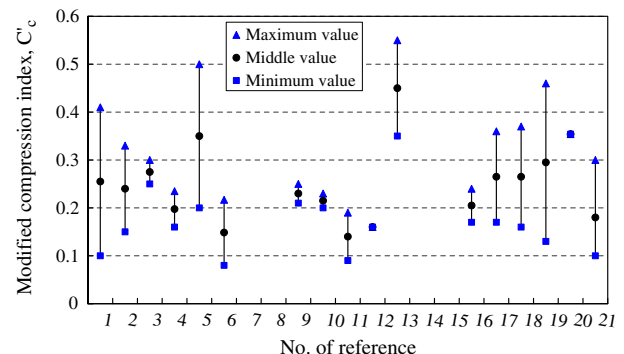


Fig. 13. Comparison of the modified primary compression index.

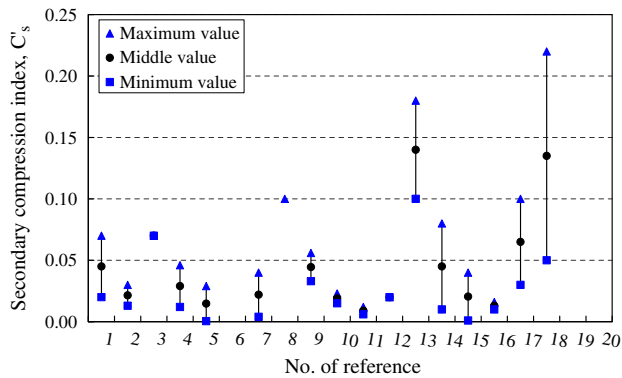
**Table 2**

List of research literature reporting compressibility values

No.	Reference	$C'_c$	$C'_d$	Remarks	$e_0$ or $\gamma$
				Composition	
1	Sowers (1973)	0.1–0.41	0.02–0.07	P: 20–40%; C: 0–15% R1: 16–40%; R2: 11–31%	$e_0 = 2–15$
2	Zoino (1974) <sup>a</sup>	0.15–0.33	0.013–0.03	Nil	Nil
3	Converse (1975) <sup>a</sup>	0.25–0.3	0.07	Nil	Nil
4	Rao et al. (1977)	0.16–0.24	0.012–0.046	Nil	Nil
5	Landva et al. (1984)	0.2–0.5	0.0005–0.029	Nil	Nil
6	Oweis and Khera (1986)	0.08–0.22	–	Nil	Nil
7	Bjarnagard and Edgers (1990)	–	0.004–0.04	Nil	Nil
8	Fassett et al. (1994)	–	<0.1	Nil	Nil
9	Wall and Zeiss (1995)	0.21–0.25	0.033–0.056	P: 21%; C: 17% R1: 54.5%; R2: 7.5%	
10	Gabr and Valero (1995)	0.2–0.23	0.015–0.023	P: 0%; C: 33% R1: 47%; R2: 20%	$e_0 = 1–3$
11	Boutwell and Fiore (1995)	0.09–0.19	0.006–0.012	Nil	Nil
12	Stulgis et al. (1995)	0.16	0.02	Nil	Nil
13	GeoSyntec (1996)	0.35–0.55	0.10–0.18	From back analysis for OII landfill in USA	
14	Green and Jamenjad (1997)	–	0.01–0.08	Nil	Nil
15	Oweis and Khera (1998)	–	0.001–0.04	Nil	Nil
16	Landva et al. (2000)	0.17–0.24	0.01–0.016	P: 0–6%; C: 24–66% R1: 25–62%; R2: 0.8–6%	$\gamma = 7.6–10.4$
17	Qian et al. (2001)	0.17–0.36	0.01–0.1		
18	Hossain et al. (2003)	0.16–0.37	0.05–0.22		$e_0 = 2–2.8$
19	Liu Rong et al. (2003)	0.13–0.46	–	P: 25%; C: 8–47% R1: 23–53%; R2: 0.8–12%	$e_0 = 3.5–5$
20	Chen and Ke (2003)	0.354	–	P: 17–27%; C: 44–57% R1: 20–23%; R2: 2–6.3%	$e_0 = 3.8$
21	This study	0.1–0.3		P: 17–32%; C: 29–69% R1: 12–35%; R2: 2–4%	$e_0 = 1–4$

Notes: P – putrescent organics; C – cinder and dust; R1 – plastic, paper, wood, textile, rubber, etc.; R2 – metal and glass;  $e_0$  – initial void ratio;  $\gamma$  – unit weight (kN/m<sup>3</sup>).

<sup>a</sup> From Wall and Zeiss (1995).

**Fig. 14.** Comparison of the secondary compression index.

## 6. Calculation of settlement caused by surcharge loading of expanded landfill

The above experimental results were used in the calculation of the anticipated settlements that might occur at the existing Qizhi-shan landfill as a result of the surcharge loading resulting from the vertical expansion (40 m in height). For the purpose of illustration, a cross-section with a length of 200 m was chosen for the settlement analysis (see Fig. 1). The thickness of waste along the cross-section ranged from 0 to 49 m. It was assumed that the deformation of the waste body could be described using a one-dimensional model.

As shown in Table 3, three series of compressibility values were selected for the settlement analyses. The three compressibility values are meant to demonstrate the effect of changing compressibility associated with the fill age of MSW. For Series I, a constant value of  $C'_c$  (i.e., 0.2) was selected as representing the mean value of the data obtained from this study. The same value was adopted for each of the waste layers (3 m in thickness). For the other two series, the variation of  $C'_c$  with depth was taken into account. The values for  $C'_c$  for each of the sub-layers were determined from the best-fit line shown in Fig. 10. For Series III, the elastic behavior

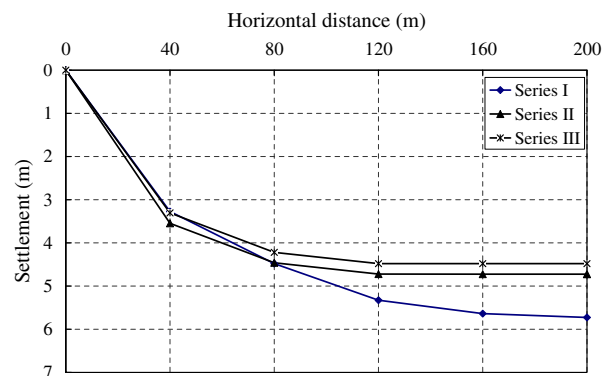
**Table 3**

Compressibility values used for settlement calculations

Series No.	Compressibility	Maximum settlement (m)
I	$C'_c = 0.2$ (constant)	5.73
II	$C'_c$ : deduced from the best-fit line shown in Fig. 10	4.72
III	$C'_c = C_e$ , $\sigma_v \leq 50$ kPa $C'_c$ : deduced from the best-fit line shown in Fig. 10, $50$ kPa $\leq \sigma_v \leq 1000$ kPa	4.48

along the compression curves was also taken into account. In other words, the rebound compression index ( $C_e = C'_c/3$ ) was used when the vertical stress was lower than the pre-consolidation pressure (i.e., 50 kPa). For all the three series, the plot of self-weight stresses with depth was calculated using the best-fit line shown in Fig. 6.

Fig. 15 shows a comparison of the calculation results obtained for the three series of analyses. It can be seen that the use of a constant value for  $C'_c$  in Series I results in much greater settlements than those from Series II and III. There is particularly more significant differential settlement over the considered 200 m long cross-section. Less differential settlement occurred when using the Series II and III assumptions. The reduced differential settlements are

**Fig. 15.** Settlements of the existing landfill caused by a surcharge loading associated with the expansion of the landfill.



related to the decrease in compressibility with an increase in depth (see Fig. 10). The above comparison indicates that the use of a constant value of compressibility parameter may result in a significant error in the prediction of landfill settlement. Giving consideration to the elastic portion of the compression curve (i.e., Series III) results in a slightly different calculation from that of Series II. The reason is that the pre-consolidation pressure of the MSW (i.e., 50 kPa) is relatively low when compared to the increment of extra loading (i.e., over 400 kPa).

The settlement curve corresponding to Series III shows that the surcharge loading of the expanded landfill can result in a differential settlement of about 4.5 m. The different settlement is primarily related to the waste thickness varying from 0 to 49 m. Further biological decomposition of the waste in the existing landfill will cause additional settlement as well as additional differential settlement. Further study on the secondary settlement behavior is undertaken for a complete understanding on the total post-expansion settlement of the existing landfill. Significant settlement will inevitably affect the serviceability of the intermediate liner system in between the existing and expanded landfills by tearing the sealing layer and/or altering the inclination of the leachate drainage layer. Further investigation on these adverse effects will be of great significance for a safe design of the expanded landfill.

## 7. Conclusions

Laboratory compression tests were carried out on 31 borehole MSW samples with different fill ages to measure the compressibility of municipal solid wastes. The laboratory study also included the determination of waste composition and volume-mass properties (i.e., unit weight, void ratio, and water content). The following conclusions are based on the laboratory test results:

- (1) The content of compressible components (i.e., organics, plastics, paper, wood, and textiles) decreased with an increase in the fill age of MSW. The content of incompressible components increased with the fill age of MSW. These changes are primarily the result of biological degradation within the landfill.
- (2) The void ratio of the MSW in the landfill was observed to decrease from 3.0 to 1.0 with an increase in depth from 0 to 37 m. The unit weights increased from 6.0 to 15.0 kN/m<sup>3</sup> with an increase in depth.
- (3) The changes in composition and void ratio of the MSW with depth resulted in a decrease in the primary compression index,  $C_c$ , from 1.0 to 0.3 with an increase in depth.
- (4) The modified primary compression index,  $C'_c$ , measured on the MSW samples from different depths (i.e., different fill ages), fell into the range between 0.1 and 0.3. These values are consistent with the ranges reported in the research literature. It was found the magnitude of  $C'_c$  decreased linearly with an increase in the fill age of MSW, and the linear relationship depended upon the range of initial void ratios. For a given fill age, MSW with a void ratio between 2.0 and 4.0 had a significantly higher value of  $C'_c$  than that with a void ratio between 0.5 and 2.0.
- (5) Settlement analyses on the existing landfill took different descriptions of the compressibility values into consideration. It was demonstrated that the variation of MSW compressibility with fill age or depth should be taken into account in the settlement prediction.

The experimental results presented in this paper were obtained from the borehole samples with a size of 80–100 mm in diameter and 200 mm in height. It is recommended that further research be

undertaken to assess the effect of sample size on the experimental results.

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