Shear strength and creep settlement properties of municipal solid waste at the Chong Qing Landfill, China

ZHAO Yanru
(Department of Civil Engineering, ChongQing University, ChongQing 400045)

Abstract: This paper presents experimental results on geotechnical properties of municipal solid waste (MSW) at different biodegradation phases. The shear strength of fresh and landfilled municipal solid waste was determined by large direct shear tests (LDS). For fresh samples, the cohesion was increased from 0kPa to 19.89kPa, and the friction angle decreased from 27.84°to 14.41° as biodegradation degree increased from 0 to 63.83%.. For the triaxial tests under the consolidation drained (CD) condition, the shear strength of cohesion and friction angle for degraded samples presents a continuous increasing when the defined axial strain is increased from 5% to 20%, and the cohesion is vary from 35.90kPa to 66.42kPa, the drained friction angle ranged from 29° to37°. A narrow range for organic content and temperature that better for biodegradation and creep settlement were found in the creep tests, and it was ranged from 21.9% to 36.47%, 22° to 41°, respectively. The test results are useful for assessing the stability and creep settlement of landfills located in ChongQing city, in China.

Keywords: Municipal solid waste; Shear strength; Biodegradation; Creep settlement; Leachate

0 Introduction

Increasingly affluent life styles and population, continuing industrial and commercial grow in many countries around the world over the past decade has been accompanied by rapid increases in both municipal and industrial solid waste production. As the economical disposal way of MSW, 52%,90%,95%,54.3%and 83%of urban wastes production are landfilled into regulated centers, respectively, in Korea, Poland , Taiwan, USA, and China. (L.Di Palma et al., 2002;US EPA,2009；Tony L.T.Zhan,2008). However, with the continuous increasing of height and volume in the landfills, significant landfill slides have been triggered. For example, the largest Maine Slop failure in the United states happened in the 1996, march 9(Eid et al.,2000); and The Payatas landfill slide in Quezon City, Philippines, it was triggered by the extremely heavy rains from two typhoons, and at least 278 people were killed in this disasters(Merry.S.M,et al., 2005).

Consequently, assessing the stability of landfill is becoming one of the major concerns for engineering designers. And the Shear strength is required as the primary factors for calculation. Numerous studies has been conducted on it at field and laboratory tests.（Edil et al.,1990；Landva and Clark, 1990；Howland and Landva,1992；Jessberger and Kockel, 1993；Wall, D.K.& Zeiss,1995；Grisolia et al.,1995；Houston et al.,1995；Kavazanjian et al.,1995；Kockel and Jessberger,1995；Edincliler et al.,1996；Van Impe,1998； Thomas et al.,1999； Pelkey et al., 2001； Caicedo et al.,2002；Vilar and Carvalho, 2004；Gomes et al., 2005；Itoh et al., 2005；Feng, 2005；O.M.Vliar, 2005；T.L.T.Zhan et al.,2008; Dixon et al., 2008； Reddy,2008；Reddy,2009a；Reddy, 2009b； Reddy, 2011；）.It is believed that the degradation of organic matter in the waste could resulted in the changes of the particle sizes and composition of MSW, and the shear strength properties and moisture content in the waste could be also changed (Reedy et al.,2011).However, shear strength values reported in previous literatures varied widely (the cohesion varied from 0.5kPa to 71kPa, and inter friction angle ranged from 17.8° to 34°), and little studies focused on determining the change in properties of MSW due to the biodegradation under aerobic and anaerobic condition, therefore, further studies are needed to better understand the effect of decomposition on the shear strength. However, it is difficult to identify the shear strength

Brief author introduction: Zhao Yanri, ph.d. E-mail: zhaoyanru54022@163.com

properties because of its heterogeneous nature and biodegradation degree, and it has been becoming one more important thing for engineering designers to evaluate the stability of landfill by using the suitable shear strength value of MSW at different biodegradation levels.

Information on the creep settlement is also required to evaluate the total settlement and stability in the landfill, Numerous researches have been studied on it (Sowers,1973；Yen and Scanlon,1975；Tan et al., 1991；Rao and Oweis, 1977； Gabr et al., 2000；Hossain and Gabr., 2005；Hettiarachchi et al., 2003,2005,2009；Marques, 2001,2003；Elagroudy, 2008；Bareither,2008; Machado, 2002, 2008；Sivakumar and Babu, 2009；).An additional factor is the change of proportion of creep settlement in the total settlement due to the organic degradation. Coduto and Huitric.(1990) pointed out that the secondary compression settlement can be enlarged by the creep settlement due to the biodegradation. Pump.(1998), M.S wati and Kurian Joseph.(2008) indicated that the secondary settlement caused by the natural biodegradation reached to 40% ,and even reached to 49% of total settlement by using the recirculation of leachate. However, little research has been conducted on investigation the effect of biodegradation and temperature on the creep settlement due to the biodegradation in the landfill.

This paper describes a comprehensive laboratory study on Chong Qing landfill in China. The borehole samples collected at the different depth are shredded at the laboratory before the tests, and the shear strength properties of MSW samples were estimated using a series of larger direct shear tests (LDS) at the different biodegradation phases. The effect of organic content on shear strength of MSW due to the biodegradation was also identified in this study. Through the three axial shear test under consolidation drained (CD) condition, the correlation between shear strength of landfilled sample with the different shear strain of axial (5%, 10%, 15%, 20%) were clarified, and the effect of temperature on the degradation was clarified too. Unless stated otherwise, creep settlement tests were performed under the no precipitation condition during tests, and all of the experiments were carried out in accordance with the standard procedures established by the China Society of standard for soil test method (GB-T/50123-CSTM 1999).

1 Sample collection and characterization

Fresh and landfilled sample were prepared, which collected from the shallow of 1-3 meters layers and the depth of 25m, respectively, in Chong Qing landfill. Composition of the MSW was determined and grouped into different friction (organic friction, inorganic friction, cinder and others).

During the shear tests, The fresh and landfilled of shredded samples were prepared and all the samples were shredded before the drained direct shear tests. The shredded sample was dried and gradation was determined using sieves (size of sieves: 100,50,20,10,5mm) analysis in accordance with (GB-T/50123-CSTM 1999), the typical gradation of MSW was shown in fig 1. It is observed that approximately 95.3% particle sizes of shredded MSW are less than 10 mm.

In order to investigate the effect of degradation on the shear strength of fresh MSW, and 45 fresh shredded samples (organic content is 45.95 %) and 28 shredded partially degradable samples were prepared for the lager direct shear test.

Table 1* Typical components of MSW of research areas

Category	Organic						Inorganic (I)				Other type
Waste type	Cooking and Garden waste	Bones	Paper	Textiles	Plastic	Wood	Metal	Brick and tile	Glass	Cinder	
Percent(%)	22.82	1.55	5.39	2.84	11.82	1.53	1.16	3.01	2.19	17.21	30.48
Total (%)	45.95						23.57				30.48

Table 2* Range and representative value of MSW's natural water content

Waste type	Cooking and Garden waste	Bones	Paper	Textiles	Plastic	Wood	Metal	Brick and tile	Glass	Cinder
Percent(%)	50~80	5~20	4 ~10	6~15	1~4	15~40	2~4	6~12	1~4	6~12
Typical Percent（%）	70	15	6	10	2	20	3	8	2	6

*Table 1 and 2 dates were afforded by eco-environment science research institutes of Chong Qing.

The effect of moisture content on the shear strength of the landfilled MSW(older than 10 years) was conducted through the Drained Large direct shear test (DLDS).In order to avoid the particle sizes effect, landfilled samples were shredded and reconstructed at different moisture contents.

During the LDS tests, the borehole samples were initially subjected to a confining pressure of 40kPa and a vertical pressure of 30kPa and rest for 24 h before the tests. Latterly, the shearing was done at a low constant strain rate (0.1mm /min) under different normal stress conditions (50, 100, 200, 300, 400kPa). The shear strength was defined at 15% horizontal deformation and was used to establish the Mohr-coulomb shear envelopes. The tests stopped when the horizontal placement exceeds 6mm. The LDS tests were repeated for the other shredded landfilled samples.

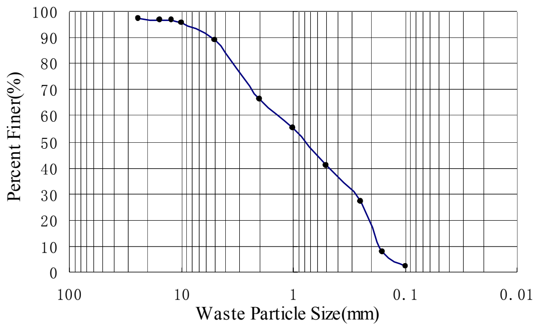

Fig.1 Grain size distribution curve of landfilled waste

Creep settlement tests were performed to investigate the changes of settlement properties of MSW due to the physics-chemical reaction and biodegradation. A special apparatus with a dimension of 500mm and 500mm in diameter (Fig.2) was prepared in the tests and which is completed sealed to simulate the anaerobic condition, and no precipitation was used during the tests. Five groups of shredded fresh MSW (each group have five samples) with varying moisture contents (10%,20%,35%,50%,65%,100 %)were prepared and then compacted into odometer (the sample is 480mm inside diameter and 480mm longer). Creep test was performed under the normal temperature environment. During the 350 days surveyed, the values of leachate production (ml/days) and creep settlement (mm/days) were recorded elaborately.

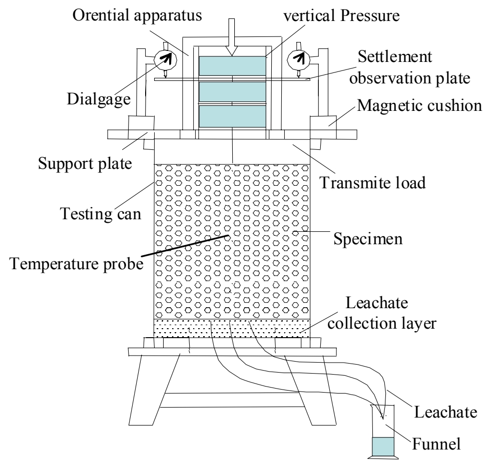

Fig 2 Compressive and Creep Settlement Test Apparatus

2 Testing methods

Tchobanoglous, et al.,(1993) Pointed out that the biodegradation could be completed during one or two years, and the drained direct shear tests are considered to be suitable way to achieve the shear strength parameters, and the value of shear strength should be better used for analyzing the stability of MSW (Hossain et al.,2009). A larger shear box (300 inside diameters and 200mm height) were used during the tests in order to eliminate the effect of shredding and test apparatus size on specimens.

2.1 Drained LDS tests for the shredded fresh Sample

Drained LDS tests were performed on the fresh shredded specimens. The dry density of MSW is varied from 610 to 630 Kg/m^3, and the organic content of specimen is 45.95%. the tests were performed according to (GB-T/50123-CSTM 1999).The fresh sample were initially subjected to a confining pressure of 40kPa and a vertical pressure of 30kPa, and it saturated by carbon dioxide before taking the tests .Each month, one group of five degraded samples were taken to shear at a constant shear strain rate (0.1mm/min) and sheared under the normal stress of 50,100, 150,200,250,300,400kPa. Based on the Mohr-coulomb failure criterion, the shear strength at 15% horizontal deformation was selected to determine the shear strength properties in order to make a comparison with other literatures.

2.2 Drained LDS tests for the shredded Landfilled Sample

Drained LDS tests were performed to study the effect of moisture contents on the shear strength (cohesion and the angle of internal friction) of landfilled MSW. The borehole samples were collected (at the depth of 25m and older than 10 years) and reconstructed with different moisture contents (25.2%, 26.7%, 29.2%, 30.6%, 33.6%, 37.2%, 41.1%). Specimens were compacted in the larger direct shear boxes (300 mm inside diameters and 200mm height) in laboratory. The average dry unit weight of specimens is 947Kg/m^3, and the proportion of particle sizes less than 10mm approximately 95.3% (Fig.1). Shear tests were performed at a constant strain rate of 4mm under three different normal stress conditions: 100, 200, 300kPa. Based on the Mohr-coulomb failure criteria, the shear strength (cohesion and inter friction angle) was obtained at 15% Horizontal deformation.

2.3 Consolidated drained (CD) shear strength

Triaxial testing under CD condition was performed (accordance with GB-T/50123-CSTM

1999) to study the changes of shear strength properties of landfilled MSW at the different axial strain level. The borehole was drilled by using a bucket auger that was 110mm in diameters and 600mm long, and the borehole samples were collected from a depth of 25m by using a inside diameter of approximately 96mm and 200mm height of torque(the filled age was determined more than 10 years old). The borehole samples were carefully transferred to the laboratory and placed in the triaxial chamber. No trimming was used to avoid disturbing the structure of each sample. The average dry unit weight of the specimens was 1022Kg/m^3. Before the tests, The sample was initially subjected to confining pressure of 30kPa, and then four specimens were consolidated under 100,200,300,400kPa confining pressure and sheared at a constant strain rate of 1mm/min. Based on the Mohr-coulomb failure criteria, the shear strengths (cohesion and inter friction angle) were determined at 5%,10%,15%,20% axial strain, respectively. The tests' results will be further studied later in this paper.

2.4 Static Creep testing

Creep settlement plays an important role in secondary compression settlement in the landfill after it was closed. In addition, with the growth of organic matters in the waste, the value of creep settlement grows due to the biodegradation and which represented an increasing proportion of total settlement. (Watts et al,(2002). However, because of the variations of the physics-chemical reaction and biodegradation and effect of temperature in the waste, and all of these made it difficult to accurately predict landfill settlements.

Machado et al.,(2002) pointed out that it is essential to acknowledge the creep settlement properties under the co-effect of stress, biodegradation and temperature for predicting the total settlement of waste. Haandel et al., (1994) take the leachate production as a calculate parameters to assess the biodegradation degree. Numerous previous literatures have been conducted and mainly focused on analysis the composition of leachate, gas production and the quality changes of MSW. However, little research has been conducted on the co-effect of stress, biodegradation and temperature on the creep settlement .In order to investigate the creep settlement properties under the anaerobic condition, shredded fresh samples at different organic content (at:10%,20%,35%, 50%, 65%,100%) were prepared and then were compacted into the specially designed apparatus. A special confining pressure of 40kPa and an initial vertical pressure of 30kPa were given for all the samples during the tests, the leachate production, creep settlement and the volume change were measured carefully.

2.5 Temperature effect

Significant amounts of heat are generated in municipal solid waste due to decomposition and phy-chemical reaction in the waste (Yesiller et al.,2003; J.L. Hanson,2005). Numerous literature were reported about the temperature distribution in the landfill .(Rigo and Cazzuffi, 1991；By T. G. Townsend,1996； J.L. Hanson, 2005；J.J.Bowders and C.M.Mitchell,2005； Yesiller et al., 2003,2005) and previous studies concluded that the temperature was varied from 15 to 60° at a large ranged of depth in the landfill. Rigo and Cazzuffi (1991) concluded that the high temperature could accelerate biodegradation of organic matters in the waste. However, little researches have been done to study the mutual effect on temperature and biodegradation systematically. Therefore, Special apparatus were used in the creep tests (Fig.2) and the correlation between temperature and organic degradation was identified. Through temperature sensors fixed in the body of specimens, the change of temperature with the varying time was recorded elaborately during the creep settlement tests.

3 Results and discussion

3.1 Drained direct shear strength result of shredded fresh MSW

Drained shear direct test were performed during 9 months to determine the shear strength properties at different biodegradation phase. The shear strength parameters calculated from Fig.3 are summarized in Table 3, The Mohr-Coulomb shear strength envelopes for direct tests at different months are presented in Fig.4.

Fig.3 shows (t=5months) the strain-stress curves exhibited a typical strain-hardening behavior of MSW, and the shear stress increased continuously with horizontal displacement without reaching any peak values, The similar trend could be observed for other samples at different biodegradation conditions. Table 3 shows that the cohesion of MSW was increased from 0kPa to 21.50kPa and the friction angle decreased from 27.84°to 21.69°due to the biodegradation. An increase in cohesion and decrease in friction angle was clearly observed through the tests, and the tests results were consistent with the work reported by Edincliler (1996).

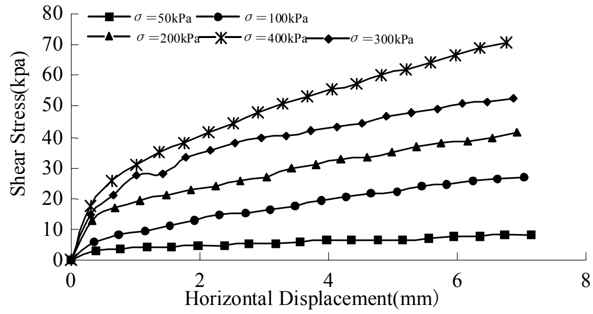

Fig.3 Direct shear test results for shredded fresh MSW at t=5 months

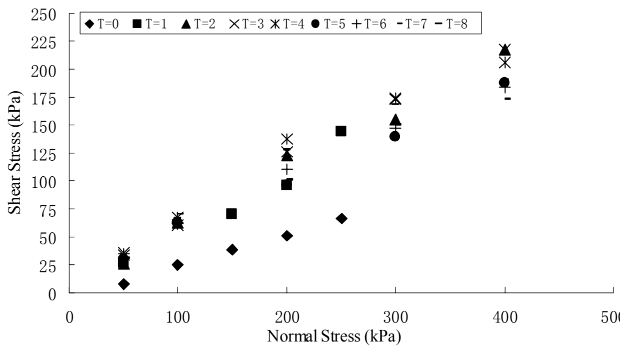

Fig 4 Mohr-Coulomb failure criteria for fresh shredded MSW at different times(T= months.)

The composition of samples after each test (every month) was determined and found that organic content was decreased from 45.95% to 16.6% during 9months of biodegradation. This finding was consistent with the results reported by Reddy, et al.,(2011). The comparison results between current and previous literatures were shown in Fig.5. M.A.Gabr.(2007)and M.S.Hossain.(2009) take the extent of refusing decomposition for characterized by the cellulose plus hemi-cellulose to lignin ratio(C+H)/L, and finding the measured friction angle decreased from 32 to 24°as (C+H)/L decreased from 1.29 to 0.25. With biodegradation, the proportion of un-degraded composition like plastic and fiber was increasingly play a predominant role in the waste and acted as a reinforcement during the shearing test, which resulted in a strain-hardening behavior of MSW (Klosch, 1995,1997；Machado et al.,2002；Reddy,et al.,2009b).However, the current tests results were contrary to literatures (Langer,2005; Hossain,2002; Howland and Landva,1992,Tony Z.T,2008), Analyzing the results we concluded that the wide variation in shear strength may be contributed to the composition and biodegradation level of MSW. And the current tests results only representative the variation of shear strength due to the biodegradation in the short-term (350days). The change of shear strength with the biodegradation after one or two years need enhance research to identify.

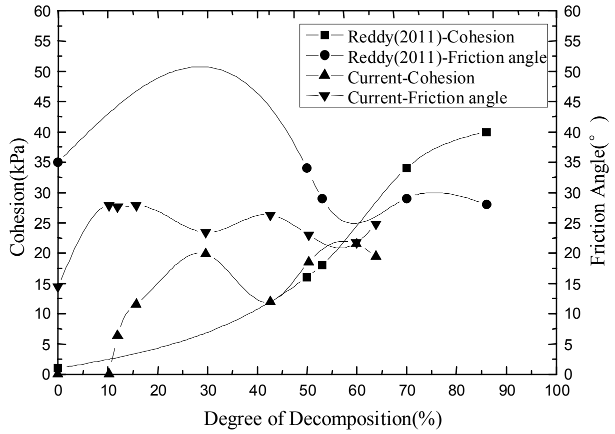

Fig. 5 Variation of cohesion and friction angle with degree of Decomposition

The effect of organic content on the shear strength of the fresh MSW was also studied in the tests, the fresh shredded samples were prepared at different initial organic contents (10%, 20%, 35%,50%,60%),and the test was performed under the normal stress at 50,100,150,200,250,300, 400kPa. The shear strength was defied at the 15% horizontal deformation and the shear strength parameters were calculated based on the Mohr-Coulomb failure criteria from Fig.6 and it was presented in Table 3. Based on the analysis of the date shown in Table 3, the cohesion of shredded fresh MSW was calculated and it varied from 4.90kPa to 18.58kPa, the friction angle decreased from 24.44 to 14.12°.

Fig 7 shows that neither the cohesion nor the inter friction angle demonstrated any correlations with the organic content, and no correlation between shear strength with the moisture content was found (Reedy, 2009a). Pelkey et al.,(2001) point out that the waste is a complex matters and the Shear strength is co-effected by the biodegradation ,stress level, inter structure and other factors.

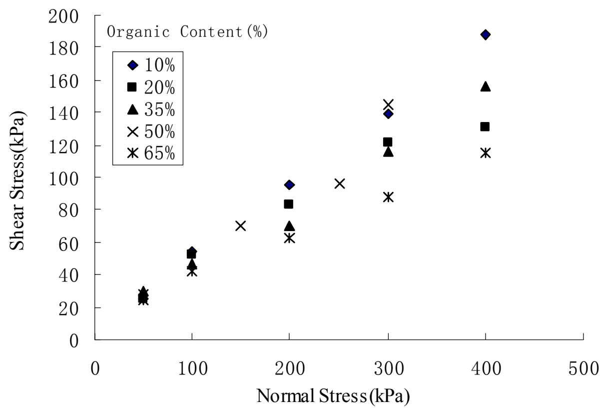

Fig 6 Mohr-Coulomb failure criteria for fresh shredded MSW at different times(T= months.)

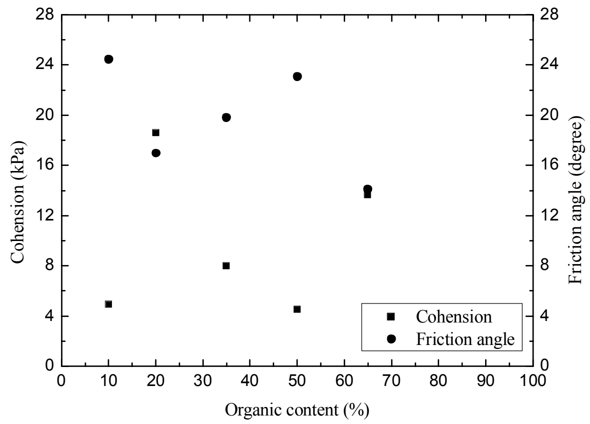

Fig 7 Variation of fresh shredded MSW at different initial Organic Content

3.2 Drained direct shear strength result of Landfilled sample

Fig.8 shows the direct shear test results for landfilled MSW at an in-situ moisture content of 25.2%, Similar trends were observed from the tests conducted with samples at other moisture content. The landfilled specimens exhibited a strain-hardening and contractive behavior when the horizontal deformation well in excess of 15% of the apparatus diameters. In the absence of specimens reaching any peak strength, shear strength at 15% horizontal deformation was used to establish the Mohr-Coulomb shear strength envelopes(Fig.9), and the shear strengths of samples at different water content (wet gravimetric content: 25.2%，26.7%，29.2%，30.6%，33.6%，37.2%，41.1%)are presented in Table 3. It is concluded from Table 3 that the cohesion of landfilled MSW is very small and varied in a narrow ranged from 0kPa to 8.4kPa and the drained friction angle ranged from 36.38 to 41.38°. Neither the cohesion nor the drained friction angle demonstrated any correlation with the moisture content. This finding is consistent with previous results reported by Reddy et al. 2009a).Through analysis the composition of landfilled MSW, we found that the organic content is close to zero after 10 years degradation.

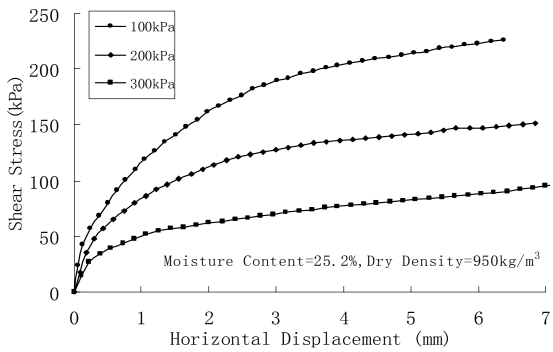

Fig 8. Direct shear test results for unshredded landfilled MSW

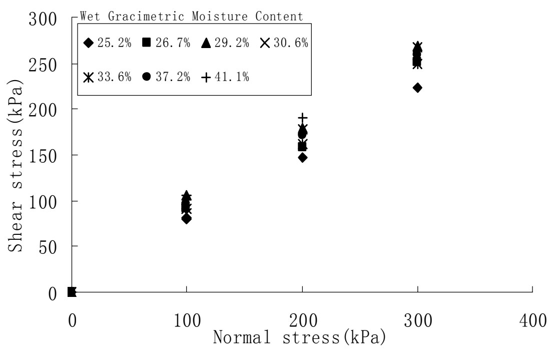

Fig 9.Mohr-Coulomb failure envelope for shredded landfilled MSW at different moisture content under the large Direct tests

Table 3

Drained shear strength properities of specimens on the larger direct shear testing

Source	Time (month/years)	Organic content(%)	Cohension kPa	Friction angle (degrees)	Gravimetric moisture content (%)
Current study: Fresh shredded MSW, Appratus size 300mm diamater, shear strength defined at 15% strain, the initial orgnanic content is 45.95%, mositure content is 43.17%, Dry density =620KN/m3, maximum particle size is less than 30mm.	0	45.9	0	14.413	not tested
	1	41.2	0	27.84	
	2	40.4	6.396	27.664	
	3	38.7	11.566	27.856	
	4	32.3	19.889	26.262	
	5	26.3	11.934	23.432	
	6	22.8	18.509	22.962	
	7	18.4	21.497	21.688	
	8	16.6	19.365	24.83	
Reddy et al.(2011) Fresh synthetic MSW, 63.5mm diameter shear box, shear strength defined at 15% strain, initial moisture content is 50%, Bulk unity weight varied from 11.2 to 16.2KN/m$^{3.}$	Fresh to Partialy degraded	57.5	1	35	83
		40.2	16	34	68.8
		38.9	18	29	77.9
		28.6	34	29	84.3
		15.5	40	28	53.9
Current study: Landfilled shredded MSW, Appratus size 300mm diamater, shear strength defined at 15% strain, the orgnanic content is 0, Dry density =947kN/m$^{3.}$	≥10 years	0	2.22	36.38	25.2
			2.38	39.28	26.7
			6.29	41.38	29.2
			0	41.6	30.6
			3.01	39.26	33.6
			3.64	40.42	37.2
			8.4	41.33	41.1
Reddy et al. (2009b) partially decomposition shredded MSW, 63.5mm diameter shear box, shear strength defined at 15% strain, maximum particle size less than 40 mm and approximately 80% of the waste consisting of particles ranging from 10 to 20 mm.	1.5 years	41.8	12	32	44
			63	31	60
			34	35	80
			56	32	100
Gabr et al.(2007) 100mm diameter and 50mm height shear box, the shredded sample is composited by paper, partially decomposed refuse, and plastics. the particle size of fresh paper particle size is 10 mm by 20 mm. shear strength defined at 10% strain, R=(C+H)/L. — Initial stages of decomposition	24 days	R=1.29		32	
accelerated methane production phase	53 days	R=0.73		27	
decelerated methane production phase	84 days	R=0.38		25	
Stable methane production phase	127 days	R=0.25		24	
Reddy et al.(2009a) Fresh shredded MSW, 63.5mm diameter shear box, shear strength defined at 15% strain.	Fresh	55.1	46	30	44
			64	26	60
			32	28	80
			31	30	100
Current study: Fresh shredded MSW, Appratus size 300mm diamater, shear strength defined at 15% strain,	Fresh	10%	4.9	24.437	23.08
		20%	18.58	16.977	35.78
		35%	7.97	19.829	39.83
		50%	4.53	23.098	51.59
		65%	13.628	14.122	56.95
Caicedo et al. (2002), unshredded waste,, 900mm diameter diameter shear box, shear strength defined at 6.7% strain.	1 years		78	23	67
Reddy et al. (2008) 0.9m diamaterand, and 1.5m long, the incoming waste component is 70% MSW, 17% contrustion and demolition debris, 11% soils, and 2% others. the waste components included 8% papers, 11% plastics, 12% wood, 4% glass, 4% metal and others. shear strength defined at 15% strain, Dry density of landfill msw was 515Kg/m^{3}.	Fresh	24	47	29	43.7
Hossain et al.(2009), 100mm diameter shear box, Shredded and processed MSW. R=Maxmium particle size/shear box size.	Fresh	R=0.5		32	0.55
		R=0.25		27	0.55
Gabr and Valero (1995), 63.5 mm diameter, 23mm thick, 33% Ash, soil and rock, 23% textiles, 13% plastics, 10% metals, Dry unit weight=10-12.1kN/m^{3}, shear strength defined at 10%, 20% strain respective.	15-30 years	0	no	20-39	
			0-28	no	
Landva and Clark (1990), Shredded sample, 434×287mm, 20-55% Paper products, 5-42% food waste, 4-20% garden waste, 6-15% metal, 2-15% plastic.	Fresh	0	23	34	
Kavazanjian et al. (1995), 457mm diameter shear box, Shredded sample, waste recover from the depth of 35m, and also conducted the direct shear simple testing(460mm), particle larger than 100mm was removed, unit weight: Ground face: 10-13kN/m3, depth 30m: 13-16kN/m3, depth 60m: 14-17kN/m3, shear strength defined at 15% strain.	11-35 Years	0	43	31	7.5%-41.2%

3.3 Shear strength Based on Triaxial (CD) tests

In geotechnical engineering, CD tests results might be considered as a suitable way to analysis and evaluate the stability of landfill, because it can be better simulate the drained situation in the waste. Four groups of unshredded ladfilled samples (Each group have four samples and the average dry unit weight is $1022kN/m^3$， and the average moisture content is 41%) were collected from a depth of 25m and the consolidated drained (CD) triaxial tests were performed under the confining pressure at 100,200,300,400kPa.

Fig.10. shows the representative stress-strain tests results, the peak value of shear strength was not gained even the horizontal deformation well in excess of 20% axial strain and the strain-stress curves of CD tests exhibited a typical strain-hardening behavior of landfilled MSW. Similar trends were also observed by other researchers (Grisolia et al.,1995; Machado et al.,2002; Feng, 2005; O.M.Vliar et al.,2005; T.L.T.Zhan et al.,2008).

Currently, no standard cut-off displacement value is appropriate to define MSW shear strength, and it is customary in geotechnical engineering to define strength at 10% to 15% axial strain in the event of continuous shear strength gain (T.L.T.Zhan et al.,2008). To identify a possible correlation between shear strength with shear strain in the waste of different fill age, CD tests were performed and the results were compared with the published literatures. Based on the Mohr-coulomb failure criteria, The shear strength (cohesion and inter friction angle) in this tests was determined at 5%,10%,15%,20% axial strain, respectively. And the comparison of previous literature with current tests results was shown in Table 4.

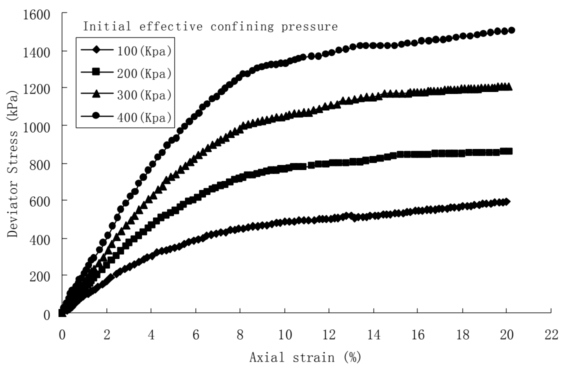

Fig.10 Stress-strain relationships obtained from five samples under drained CD test for the landfilled MSW

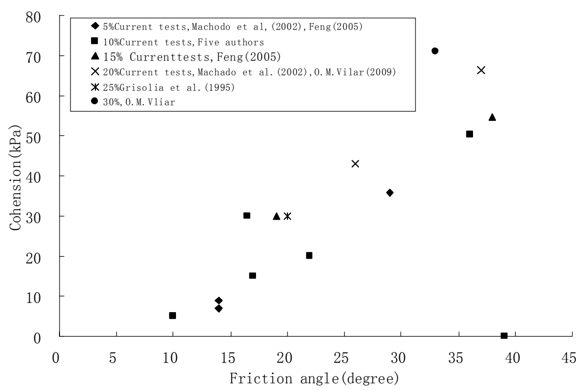

Fig.11 The comparison between Triaxial compression under CD condition test result for landfilled MSW and previous literatures

Table 4Shear strength properties of MSW based on triaxial consolidated drained (CD) testing

Source	Age (years)	Appratus size(mm)	Shear Strain(%)	Cohension (kPa)	Friction angle (degrees)
Current study	≥10 years	300mm diameter	5	35.9	29
			10	50.2	36
			15	54.63	38
			20	66.42	37
Grisolia et al.(1995)	1～3	600×300mm	10	5	10
			25	30	20
Machado et al.(2002)	15	200×400mm	5	9	14
			10	30	16.5
			20	70	27
Feng(2005）	5	300×600mm	5	7	14
			10	15	17
			15	30	19
T.L.T.Zhan et al.(2008）	1.7	100mm diameter	10	23.3	9.9
	11			0	39
O.M.Vliar et al.(2005）	Fresh	400mm diameter	10	20	22
			20	43	26
			30	71	33

Table 4 shows the cohesion of landfilled MSW increased correspondingly from 35.9kPa to 66.42kPa and the drained friction angle increased from 29°to37° when the defined shear strain increased from 5% to 20% of axial strain.

Machado et al. (2002) conducted CD tests on the unshredded 15-year-old MSW from Sao Paulo, Brazil and the resulting shear strength properties increased from 0kPa to 70kPa and 14° to 27°when the shear strain was determined at the 5%;10%,20% axial strain ,respectively. As it is shown in Table 4, the shear strength (cohesion and friction angle) was also began to increase with the increasing of shear strain, and the trend for the shear strength is consistent to the literatures reported(Grisolia et al., 1995;O.M.Vliar,2005;Feng, 2005), but even the shear strain excess of 30% axial strain, the shear strength peak value were not found (Reddy et al. 2009b). T.L.T.Zhan et al.(2008), through the comparison of shear tests results between 1.7years and 11 years fill age MSW, found that the cohesion is decreased from 23.3kPa to 0kPa and the friction angle was varied from 9.9 to 39° due to the biodegradation. However, the shear strength at the different strain level were not drawn.

It is evident from Table 4 that the cohesion and drained angle of friction of MSW reported by previous literatures were increased from 0 kPa to71kPa and 9.9° to38°,respectively.Although the shear strength properties were varied in a large areas, a slight increase trend in shear strength can be observed with the increasing of shear strain and deviator stress. And the current test results is more close to O.M.Vliar.(2005) results.

The results of tests concluded that landfilled shear strength increased with the varying of axial strain, and identified that shear strength was stress level depended, and the suitable axial strain should be defined to gain the shear strength of MSW.

3.4 Static Creep Settlement test results of MSW

The creep settlement tests were performed at the different organic contents (10%,20%,35%, 50%,65%,100%) of shredded MSW. As the biodegradation, the change of leachate production, settlement and the time were recorded elaborately .The calculated results were shown in Table 5.

Table 5Laboratory test result information

Column	Organic content	Leachate(ml)/ Settlement(mm)	Stage			Range of values		Average value	Peak value	
			First	Second	Third	Days	ml / mm	ml	ml or mm	days
No.1	10%	L	First			0-90	0-41	8.41	41.00	1
				second		90-322	1-86	26.27	86.00	204
		S	First			0-83	0-1.37	0.69	1.37	62
				second		83-322	0.16-3.67	1.30	3.67	134
No.2	20%	L	First			0-103	0-48	16.64	48.00	6
				second		103-322	0-229	39.05	229.00	200
		S	First			0-94	0-3.70	1.13	3.70	17
				second		94-322	0.67-4.56	1.87	4.59	204
No.3	35%	L	First			0-99	0-63	32.45	63.00	16
				second		99-322	0-139	34.26	139.00	171
		S	First			0-74	0-4.136	1.81	4.14	18
				second		74-322	0.34-3.85	1.31	3.85	205
No.4	50%	L	First			0-99	0-133.47	49.88	133.47	18
				second		99-322	0-104	27.78	104.00	205
		S	First			0-85	0-5.95	2.20	5.95	18
				second		85-322	0.34-2.42	1.01	2.42	204
No.5	65%	L	First			0-94	0-210	62.50	210.00	18
				second		94-322	0-84	30.19	84.00	171
		S	First			0-80	0-7.73	2.71	7.73	17
				second		80-322	0.19-1.44	0.58	1.44	100
No.6	100%	L	First			0-14	0-98.25	38.78	98.25	4
				second		14-88	7.75-76.75	22.16	76.75	46
					third	88-249	2.63-27.75	9.20	27.75	99

Fig.12 shows the typical curves of leachate production(ml/day), settlement(mm/day) and biodegradation degree versus time at 50%organic content. It is observed that the settlement is divide into three stages:(Initial compression phase that included physical compression due to waste particles distortion, bending, crushing, re-orientation(0~30days); Primary compression phase that include the consolidation involving both waste skeleton and the migration of small particles in to voids among large particles(30~90days) Secondary compression phase that included the Physics-chemical reaction and biodegradation reaction due to the organic matters and leachate (after 90 days).The same trend for other curves of settlement and leachate production at different organic content is presented in Fig.13.

According to the time that the peak value of the leachate appeared, the biodegradation was divided into two phases: aerobic and anaerobic phase, and the first stage represented “V” type, the second stage represented “M” type.

Of course, the leachate production was also divided into two phases depend on the biodegradation. In the first phase, leachate was produced mainly due to the dropping of pore water and the water in the organic compounds as the result of mechanical compression as the decomposition degree is below the 2.15%,this process will continue for 60 days or so. Table.5 shows leachate is quickly increased with an increase of organic content from 10% to 65% in the first phase. With the depletion of oxygen in the waste, the aerobic phase was transformed to anaerobic phase, methane, carbon oxygen, and other bio-gas were produced.

It can be concluded from Fig.12 that the addition settlement was caused mainly attribute to the pore water dropping due to the immediately compaction after placement (EI-Fadel and Khoury, 2000), and part of leachate production due to biodegradation (wall and zeiss, 1995;qian et al., 2002;Wall, D.K., C.,1995)during aerobic phase of 0~90days, as the degree of biodegradation is varied from 2.15 to 6.56%,

After 90days, the settlement come into the secondary compression phase which was caused by the Physics-chemical reaction and biodegradation reaction. And during this time, the decomposition degree is increased from 6.56 to 63.83%, and a positive correlation is found between settlement and leachate production due to the bio-chemical react. The relationship between biodegradation and organic content will be analysis in the later studied.

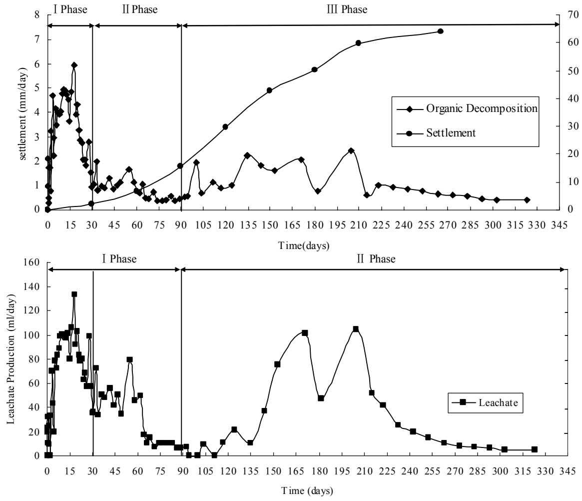

Fig.12 Different phases of the Leachate Production and Settlements vs time

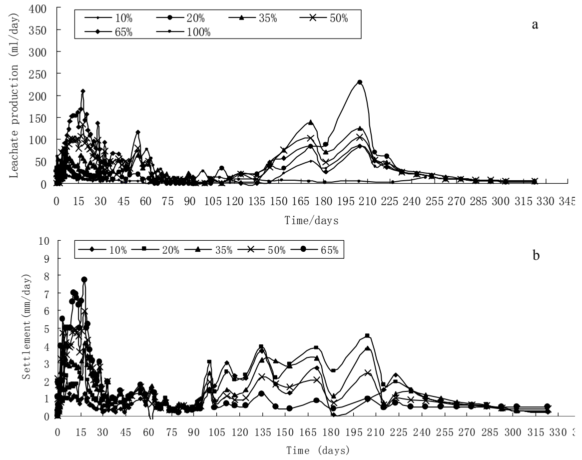

Fig.13 Variation of the Leachate Production and Settlements vs time

Table 5 shows the leachate production in the first stage increased as the increasing of organic content, and the corresponding peak value of leachate varied from 41 to 210 ml during the 0-18days. However, the time that the peak value of settlement appeared is clearly lagged behind the leachate, and varied from 1.37 to 7.73mm.during the 17-62days.With the biodegradation happening, the time that the peak value appeared for MSW settlement was advanced by 45days, and the time of peak value appeared for leachate production and settlement is more closely as the increase of organic content.

Primary compression settlement was observed during the 30~90days,and concluded that addition settlement was induced due to the applied load and the creep due to the crush of skeleton ,the migration of small particles in to voids among large particles to accommodate their stress situation better, and the same results has been reported by EI-Fadel and Khoury,(2000), Bareither et al.,(2008).Admittedly, further study need to be performed to identify the relationship between the stress and settlement.

As the time growing, secondary compression settlement plays a key role in the second phases. Table 5 shows that the peak value of the leachate production decreased from 229 to 76.75ml during 90-206days(the time appeared for the peak value of leachate at 100% organic content is 46days), and the settlement value also decreased from 5.49 to 1.44mm (100-205 days).

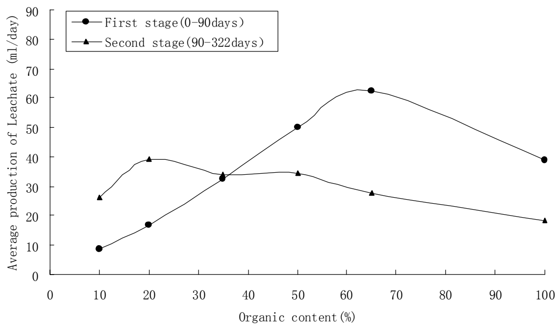

Fig.14 Variation of organic with the Leachate

Fig.14 shows during the first stage(0-90days) the peak value of leachate production due to the biodegradation can reach 210ml as the organic content increased to 65%. However, the average value of leachate production was decreased after the organic content excess the 65%.In the second stage(90-330days) the average peak value of leachate production reached 229ml when the organic content was 20% of MSW. After that, the peak value of leachate decreased from 229 to 76.75ml as the continuingly growing of organic content in the waste. Through the comparison of two phases, it can be concluded that the average value in the first stage is larger than second stage (33.93ml＞32.36ml), and the corresponding organic content in the waste was varied from 36.47 to 65% (Fig.14), the maximum value is appeared when the organic content was 36.47%.

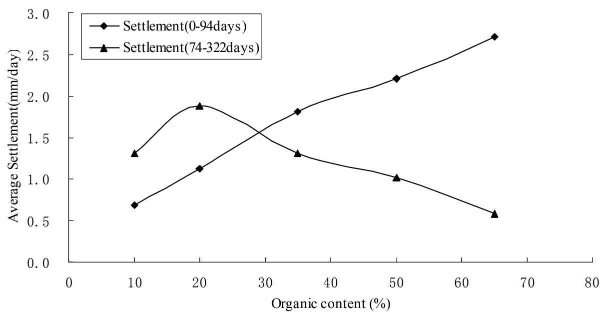

Fig.15 Variation of organic with the Average Settlement

Fig.15.shows the curves of relationship between creep settlement and organic content during the two stage,And it can be concluded From Table 5 that average value of settlement increased as the increase of the organic matter in the first stages (0-94days) and the peak value was 1.71mm. However, with the increase of organic content in the waste, the average value of settlement decreased from 1.71 to 1.21mm during the second stages(94-322days).Fig.15 shows the intersection point of two curves during the two stages appeared when the organic content is 29.1% during the two stages. And the value of creep settlement in the first phases is larger than the second (1.71mm＞1.21mm).

Using the Statistical methods, it can be concluded that most appropriate organic content zones for biodegradation and creep settlement is varied from 21.9%to 36.47% during the two stages.

3.5 Analysis the effect of temperature on biodegradation

It is believed that the temperature can affect solid waste decomposition and could be enhanced by the phy-chemical reaction in the MSW. In order to investigate the relationship between temperature and biodegradation, the variation of temperature, leachate production and settlement during the 330days were recorded elaborately. Fig.16 shows that during the first phases, the leachate production per day varied from 8.41 to 62.50 ml/day, Corresponding temperature is ranged from 5.5 to 17.5°. As the times increased from 90 to 135 days, the temperature is varied from 12 to 24°.However, leachate production during this time is in a low level (Fig.16). When time increased from 135 to 240days, the peak value of leachate production for all the samples represented the "M" type, and varied from22.16 to 39.05ml/day, the temperature was also varied from 22 to 41°. After 240 days, the leachate production was decreased and close to stability.

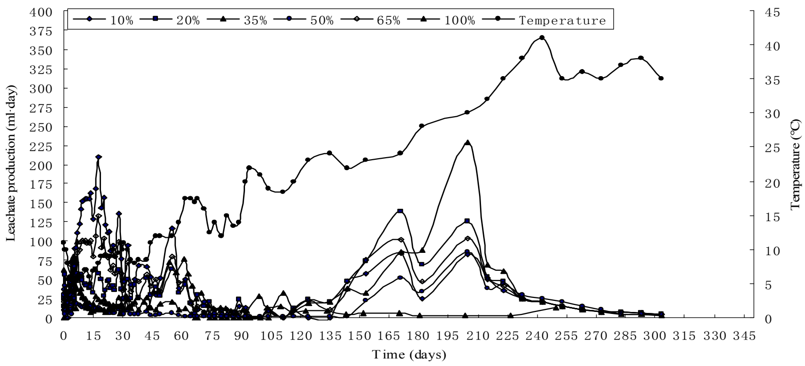

Fig 16.Variation of the Leachate and Temperature vs time

Fig.12 shows during aerobic phase of 0~90days, temperature is varied from 5 to12°, and the corresponding degree of decomposition is in a low level,So it can be concluded that the leachate was produced mainly because of the pore water dropping due to the immediately compaction after placement (EI-Fadel and Khoury,2000) and little part of leachate prodection due to the biodegradation(wall and zeiss,1995;qian et al., 2002;Wall, D.K., C.,1995),

During 90 to 135days, the production of leachate stayed in a low level, corresponding temperature was varied from 12 to 24°.after the time of 135 to 350days, the value of temperature was ranged from21 to 41°, the peak value of leachate production represented a"M"type(Fig.16). and concluded in the anaerobic phases, the temperature was increased from 20 to 41° due to the inner react of physico-chemical-biodegradation, and the leachate production was clearly increased too. So that ,It can be concluded that the optimum temperature between 20 and 41° is a suitable zones that enhanced the react of physico-chemical-biodegradation in the waste, and the tests result was consistent with the results reported by J.L.Hanson (2005), J.J.Bowders and C.M.Mitchell (2005), the tests results were slightly lower than 40-50°reported .By T. G. Townsend.(1996).

(Yesiller et al,(2003), Yesiller et al,(2005), Hanson et al, (2005) reported that the optimum temperature ranges for methane bacteria action involved in waste decomposition were reported to be 45 to 60°.However, Another temperature zones of 20° to 41° were find in this studied, which can accelerate the biodegradation during the anaerobic stages(135～330days). Of course, more date and information are needed to identify it.

4 Summary and conclusion

Fresh and landfilled MSW collected from Chong Qing landfill were tested for shear strength, and creep properties, and the effect of temperature on biodegradation also been clarified. The following conclusions can be drawn from the results of this study:

The shear strength of shredded fresh and landfilled municipal solid waste were determined by large direct shear tests(LDS), and the tests results for fresh samples shows that the cohesion was increased from 0kPa to 19.89kPa, and the friction angle decreased from 27.84°to 14.41° as the increase of biodegradation.

Based on LDS tests, the shear strength of shredded fresh sample at one month with different organic content and landfilled sample with different moisture content were determined and the tests results for shredded fresh sample show that the drained cohesion was varied from 4.9 to 18.58kPa, and the inter friction angle was ranged from 14.12 to 24.44°. The shear strength for shredded landfilled sample show that the drained cohesion was varied from 0 to 8.4kPa and the inter friction angle was ranged from 41.38 to 36.38°. With elaborate analysis, it was concluded that neither the initial organic content for fresh samples nor moisture content for landfilled samples demonstrates any correlation with shear strength of MSW during the LDS.

Three triaxial shear tests under the consolidation drained (CD) condition were performed and the results shows the shear strength for degraded samples present a continuous increasing when the defined axial strain is increased from 5% to 20%. The cohesion was varied from 35.90kPa to 66.42kPa, and the drained friction angle ranged from 29° to37°.

A narrow range for organic content and temperature, which could be better for helping the biodegradation in the waste was found and which ranged from 21.9% to 36.47%, 22° to 41°, respectively. However, due to the heterogeneous nature of landfills, more analysis with data from other landfill is needed and all of the tests results in this study should be properly utilized to assess the stability and settlement of Landfill, in China.

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垃圾土抗剪强度及蠕变沉降特性实验研究

赵燕茹

（重庆大学土木工程学院，重庆 400045）

摘要：本文基于大型直接剪切试验，三轴固结排水试验和静力蠕变沉降观测试验，对垃圾土的抗剪强度特性和蠕变沉降特性进行了研究，通过对重庆地区典型有机物含量为45.9%的垃圾土直剪试验，得到抗剪强度随降解在270天内的变化规律。随着降解的发生，垃圾土的粘聚力（c）从0增长到19.889Kpa，内摩擦角（φ）在27.840°～14.413°之间波动，有递减的趋势；通过直剪实验，得出新鲜垃圾土初始抗剪强度不受有机物含量的影响；通过三轴固结排水试验，以5%、10%、15%、20%作为应变标准，得出陈垃圾土的粘聚力随应变的增长，从0增长到66.423kPa,内摩擦角从29°增长到38°，呈现递增趋势，说明垃圾土的抗剪强度受应力水平以及应变大小的控制；直剪试验和三轴试验得到的不同埋龄垃圾土的应力应变曲线都呈硬化趋势，均无峰值强度出现；通过对不同有机物含量的新鲜垃圾土长达350天的静力蠕变观测实验，得出当有机物的含量在29.1～36.47%，有机物的降解对蠕变沉降的贡献最大；通过在实验过程中对试样内部温度场的监测，得出20～35°是能够加快有机物降解的一个温度区间。

关键词：垃圾土；抗剪切度；蠕变沉降；有机物降解；温度；渗滤液

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