Influence of composition and degradation on the shear strength of municipal solid waste

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Influence of composition and degradation on the shear strength of municipal solid waste

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ABSTRACT

This study aimed to evaluate the shear strength of municipal solid waste (MSW) of different landfilling ages exhumed from disposal sites in a subtropical humid environment. Wastes which had been landfilled from ages of 2 up to 25 years were characterized using physical, chemical and biochemical tests and were tested in a large scale direct shear device. The results indicate that the tested wastes older than five years had reached similar decomposition stages, but showed different compositions in terms of soft plastics, incompressible material and reinforcing elements. Different composition was also noticed between less degraded and more degraded samples. In the former, the soil-like materials, that is the particles smaller than 19 mm, are essentially reinforcing components while in the later it is formed mainly by incompressible components. Although MSW composition did not vary significantly throughout the years, some difference in the originally landfilled waste could account for the observed variations. However, they are mainly the result of exhuming and preparation methods, whose influence is discussed in the paper, as well as the waste degradation state. The reinforcing components, rather than the soft plastics content, correlated well with cohesion intercept increase, both for the less and more degraded waste samples. The results also indicate that as MSW degrades the waste material evolves from an initially highly cohesive material to one that loses cohesion yet gains in shear strength angle over time.

1. Introduction

Landfills continue to be a key component of municipal solid waste (MSW) management. These engineered structures demand careful design especially in areas related to slope stability. Determining the shear strength of waste, an unusual construction material, is achieved through back analysis of failed slopes and by performing field and laboratory tests. As far as laboratory tests are concerned, MSW stress-strain behavior obtained from triaxial tests is usually strain hardening so no clear sign of failure is observed for the common range of strain attained in these tests. This behavior is credited to the mobilization of reinforcing elements usually present in MSW, such as plastics. In direct shear tests the stress-strain behavior is also usually strain hardening, yet some stress-displacement curves concave downwards and depending on the displacement range reached in the test a peak shear stress can be attained. The mobilization of reinforcing elements is believed to be less intensive in these tests, as the main reinforcing components are parallel to the shearing plan due to sample compaction.

For the interpretation of both tests shear strength parameters are commonly derived utilizing the Mohr Coulomb shear strength criteria and strain compatibility with other elements of the structure. Reported values of MSW shear strength parameters determined from direct shear tests are friction angles (φ) ranging from 0 to 50° and cohesion intercept (c) values ranging from 27 to 41 kPa (Bray et al., 2009). This large range may be due to waste's heterogeneous nature, difficulty in recovering and testing representative waste samples and a lack of standardized testing procedures designed specifically for waste materials. In addition, climate, landfill operation practices and waste composition are known to influence the geotechnical behavior of landfill masses, which makes comparing results from different sites even more challenging.

The decomposition of biodegradable components of MSW to CH_4 and CO_2 in landfills is well documented (Barlaz et al., 1989; Christensen and Kjeldsen, 1995). However, the changes to MSW shear strength because of its compositional and structural evolution over time are still largely unknown and remain a controversial subject (Bray et al., 2009; Stoltz et al., 2009). For instance,

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Turczynski (1988), Caicedo et al. (2002), Gabr et al. (2007a,b), Varga et al. (2011), Hossain and Haque (2009) and Reddy et al. (2009a) found that MSW shear strength diminishes as MSW gets "older". Zhan et al. (2008) concluded just the opposite, while Reddy et al. (2011) and Koerner and Koerner (2015) stated that MSW starts as a high friction material and evolves into a material that loses friction yet gains cohesion over time. On the other hand, Zekkos (2005) concluded that there is no significant change in MSW shear strength over time Bareither et al. (2012) argued that the initial waste composition and subsequent changes to that composition are more relevant to MSW shear resistance than the state of decomposition itself.

Sometimes the terms MSW age and MSW degradation are interchangeably used. However, the fact that a waste has been buried for more time does not imply that it is more degraded than waste that has recently been deposited. A number of factors limit the decomposition of biodegradable components in landfills, including environmental conditions such as moisture, pH, and temperature (Barlaz et al., 1990), as well as initial waste composition and operational conditions of the disposal site, such as compaction efforts and leachate and gas drainage efficiency.

This paper presents the results of large-scale direct shear tests performed on MSW samples of different landfilling ages, exhumed from disposal sites in São Carlos, Brazil, and addresses the influence of the sample collection method and sample preparation procedure on the final composition of the tested specimens and on waste shear strength.

This study aimed to investigate the effects of waste degradation on MSW shear strength of selected samples that typify the waste streams, landfill operation conditions and climate of the Southeast states of Brazil, where humid subtropical conditions prevail and where organic waste is the largest fraction of the delivered waste. Because the entire degradation history and the initial composition of the wastes tested are not precisely known, chemical and biochemical tests were performed to characterize the state of degradation of the exhumed waste.

2. Materials and methods

2.1. Sample collection

Six samples with different landfilling ages were studied in this investigation. They were exhumed from three different disposal sites: an experimental landfill, a dumpsite and a sanitary landfill located in São Carlos, in southeastern Brazil, and were named per their landfilling year: S1988, S1995, S2001, S2004, S2007 and S2011. Shallow samples were collected in trenches and deeper samples were collected using hollow stem augers. The drill bit diameter of the auger was 35 cm or 29 cm, depending on the borehole.

The landfilling year was determined both from the site history obtained from site personnel, official documents and aerial photos and from dates still available on some of the exhumed packages. Table 1 summarizes the landfilling age and the recovery characteristics of the studied samples.

The gravimetric composition of MSW through the years can be appreciated in Table 2, which presents two surveys: one performed with waste from the experimental landfill, corresponding with sample S1988 and the other from the sanitary landfill, performed in 2006.

2.2. Sample preparation and characterization tests

Waste samples were exhumed and thoroughly mixed. The components longer than 200 mm were weighted and discarded from the sample during field work. After the first removal, the samples were quartered and subdivided. Thirty to 50 kg were extracted to determine the waste gravimetric composition. Fig. 1 summarizes the subsample extraction steps performed in this study.

The subsamples extracted for determining the waste gravimetric composition were screened through a 19 mm screen (wet sieving) and the retained components were separated by hand into the following categories: soft plastics, hard plastics, wood, tissues, metal, stones, rubber, paper, glass, other. The components that passed the 19 mm screen were aggregated into a single waste category and called "soil-like" material. All the components were then dried to constant weight at 60 °C and weighted. The gravimetric composition was calculated based on the dry weight.

About 300–500 kg of each exhumed sample were separated for the direct shear testing program. Based on the recommendations of Bray et al. (2009) and Athanasopoulos (2011) and owing to the dimensions of the direct shear testing device, the maximum particle size allowed for testing was 85 mm. Therefore a second hand sorting was performed on these subsamples to remove the particles that were longer than 85 mm. In samples S2001, S2004 and S2007 about 72–74% of the recovered waste remained to be tested after sample preparation procedures, while in samples S1988, S1995 and S2011 these percentages were 57%, 57% and 47% respectively.

Four kilo of each sample prepared for mechanical tests were extracted for the grain size analysis, which was performed after drying the waste at 60 °C. 3 kg of the soil-like material were extracted for chemical and biochemical tests. The remaining waste was used for mechanical tests.

The chemical and biochemical tests performed to quantify the degradation of the waste samples were loss on ignition (LOI), total organic carbon (TOC), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) and dissolved organic carbon (DOC). Abreu and Vilar (2016) presented the details of these characterization procedures, which are summarized here.

TOC and LOI tests were performed on solid samples, with measurements completed in triplicate on each waste. To perform the LOI tests the following non-biodegradable components were hand sorted and excluded from the sample: plastics, metals and stones. For the LOI test subsamples weighting between 50 and 100 g were dried until constant weight at 60 °C for one hour and then burned

Table 1
Landfilling age of the tested samples, operational conditions of the disposal site, method and depth of recovery.

Sample	Landfilling age (years)	Sample depth (m)	Sample wet mass (kg)	Recovery method	Operational conditions of the disposal site
S1988	25	1.0–1.5	900	Trench	Experimental landfill. Cover: 40 cm clayey sand + hypalon membrane + 30 cm clay layer; Drainage: gas and leachate;
S1995	16	0.7–1.5	1500	Trench	Dumpsite. Cover: 40 cm clayey sand
S2001	11	16–19	530	Borehole	Controlled landfill. Cover: compacted clayey sand; some gas and leachate drainage system
S2004	8	11–14	500	Borehole	
S2007	5	7–9	520	Borehole	Sanitary landfill. Cover: geomembrane + compacted clayey sand; gas and leachate drainage system
S2011	2	1.0–1.3	600	Trench	

Table 2
Gravimetric composition of MSW collected in São Carlos in 1988 and in 2006.

Category	Gravimetric composition survey (% of wet mass)	
	Gomes (1989)	Frésca (2007)
Organics	56.7	59.1
Paper	21.3	7.4
Plastics	8.5	10.5
Metals	5.4	1.3
Glass	1.4	1.7
Others	6.7	20.0

at 600 °C for two hours. Mass loss was reported in relation to the dry mass after burning at 600 °C. For the TOC test a subsample of 30 g of the soil-like material that passed the 1.0 mm openings sieve was used. The test was performed through dry combustion at 900 °C with the subsequent detection of CO_2 by infrared spectrometry. The spectrometer was a Shimadzu TOC-V_{CPH} SSM-5000A.

For the BOD_5, COD and DOC tests, solubilization was performed with components smaller than 9.5 mm and according to the Brazilian standard for waste characterization. After quartering and removing visible plastics, stones, glass and metals by hand sorting, 250 g of waste were placed in contact with distilled water in a 1000 ml flask, stirred for 5 min and then let to rest for seven days. After resting, the eluate of the material was separated from the solid portion by filtration using a 0.45 μm filter paper. The DOC, BOD_5, COD and pH measurements in the filtered extract were performed according to the Standard Methods for Water and Wastewater Analysis – 22nd Edition (APHA, 2012).

After performing the direct shear tests 40 kg of each sample were used for determining the gravimetric composition of the tested waste, considering the same categories and separation criteria used for the classification of the collected waste. Results were reported in terms of the dry mass of each component.

Another 2 kg (dry weight) of the soil-like material of each sample were used for a detailed description of this fraction. They were sieved in a 4.76 mm mesh and the retained material was softly ground with a mortar, in order to separate soil particles that adhered to other components, especially soft plastics. After that the whole subsample was sieved once more in a 4.76 mesh and

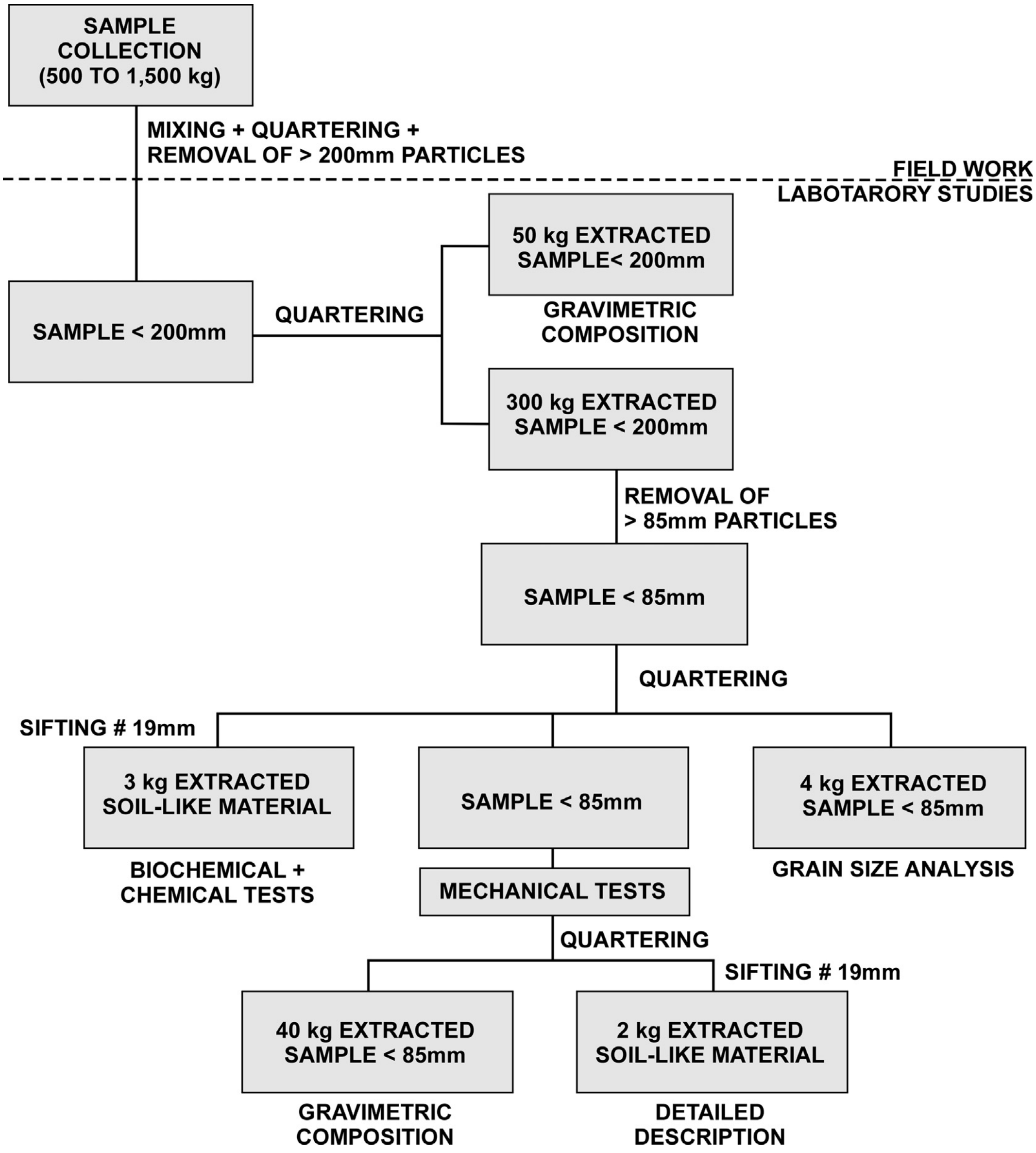

Fig. 1. Subsample extraction steps performed in this study.

the components larger than 4.76 (and smaller than 19 mm) were hand sorted into two categories: a) soft plastics and tissues and b) others. All the categories were weighted and the composition was reported in terms of the dry mass of each component.

2.3. Large-scale direct shear tests

A large-scale direct shear testing device was built especially for this investigation and is presented in Fig. 2. The shear box is 500 mm × 500 mm in plan view and 500 mm high. It has a load capacity of 250 kN in both horizontal and vertical directions. The displacement rate can be controlled between a minimum of 0.2 mm/min to a maximum value of 2 mm/min. In this study, the tests were strain controlled and a displacement rate of 1 mm/min was selected taking into account the consolidation properties of the tested wastes. A perforated plate was installed at the bottom of the specimen and liquid could drain from an outlet port at the center of the base of the lower half of the shear box during compression and shearing.

The equipment can maintain a constant vertical load. Two load cells were used for automatic acquisition of vertical and horizontal load data. The vertical displacement of the specimen top cap was measured with an encoded transducer. Data on normal and shear stresses and vertical displacements was acquired every 0.1 s.

A total of 18 large-scale specimens were tested at normal stresses of 50 kPa, 150 kPa and 250 kPa. This maximum value corresponds to approximately 20 m depth in the São Carlos sanitary landfill. Three tests with different normal loads were conducted on each waste. Some of the testes were repeated to check the repeatability of the results.

The specimens were prepared in the shear box in five layers and were statically compacted using the vertical loading system until the desired initial specific weight was achieved. Table 3 presents the characteristics of the molded specimens, which were prepared following the average values for MSW in-place unit weight and moisture content measured by Abreu et al. (2016) in São Carlos landfill. Specimens from samples collected at shallow depths were compacted to about 9.0 kN/m^3 and specimens from samples collected bellow 11 m depth were compacted to unit weights varying from about 14.0 to 15.0 kN/m^3. The moisture content varied from 39.0 to 45.0% for the shallower samples and from 49.0 to 53.0% for the deepest samples.

During the consolidation phase the specimens compressed significantly immediately after loading. In less than 60 min all specimens showed a steady and less pronounced consolidation rate, which was attributed to secondary compression. Some of the specimens were let to consolidate for up to 9 h, to check the influence of secondary compression on specimen unit weight. After analyzing the behavior of the specimens in some preliminary tests a consolidation phase of 4 h was deemed adequate for the experiments, since in this time span primary compression was complete and negligible secondary compression was noticed.

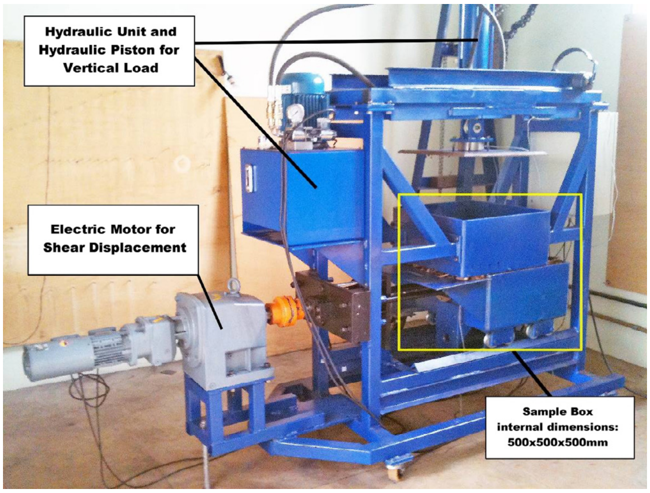

Fig. 2. large-scale direct shear testing device used in this study.

3. Results and discussion

3.1. Sample degradation state

The results of the chemical and biochemical tests performed on the wastes are presented in Table 4. Sample S2011 stands out with markedly higher results, which indicates that it is composed of less degraded waste. Its BOD_5/COD ratio is 0.58, its COD is 15,580 mgO_2/l and the pH of its eluate is 6.0. These results suggest that this sample was subjected to the early phases of methanogenesis (unstable methanogenesis) when exhumed. Its LOI is 80%, which is consistent with the values ranging between 52 and 89% reported by Bareither et al. (2012), Reddy et al. (2009b) and Machado et al. (2010) for fresh waste.

Regarding the other five samples, no clear tendency between landfilling age and the degradation of the samples could be established and they were grouped as "well degraded waste". They showed BOD_5/COD ratios ranging between 0.14 and 0.22, the pH of their eluates ranged between 7.8 and 8.1 and their COD varied from 212 to 461 mgO_2/l, which suggests that they were undergoing stable methanogenic conditions when exhumed. The LOI varied between 11 and 29% for these samples. These values agree with those reported by Machado et al. (2010) (16–29%) for old waste from Salvador, in northeast Brazil, with those reported by Carvalho (1999) (12–27%) for another landfill in São Paulo state and with the values ranging between 11 and 27% reported by Zekkos et al. (2010) for a sanitary landfill in California, USA.

3.2. Effect of sample collection and preparation methods on specimen composition

During the early stages of this research it became clear that the sampling method and the subsequent specimen preparation procedures could alter MSW composition, specially the amount of reinforcing components. Therefore, the gravimetric composition of the wastes was determined in various stages of the research.

Table 5 shows the quantities removed in each hand sorting stage and the remaining sample amount. The first removal of components in the field was low when the sample was collected using a hollow stem auger, ranging from 2 to 6% of the total sample wet weight. These figures increase when the trench method is considered since it allows for recovering components of all sizes, shapes and material types. This suggests that trenches are probably the most representative sample collection method for buried waste. These results also suggest that auger drillings cannot retrieve stiff larger components, which obviously did not need to be removed from the samples during the first removal stage, which explains the large amounts of remaining samples at the end of the preparation stages.

Fig. 3 illustrates the gravimetric composition of the as-recovered waste samples or the waste without the removal of large particles, and the gravimetric composition of the tested samples, that is the composition of the samples after the first and second particle removals.

The composition of the as-recovered waste shows that soil-like components predominate in all samples, followed by soft plastics,

Table 3
Characteristics of the specimens when molded.

Specimen	Normal stress (kPa)	Moisture content (%)	Wet unit weight (kN/m^3)	Dry unit weight (kN/m^3)	e	S$_r$ (%)
Shallow waste						
S1988-50	50	44.5	9.1	6.3	2.73	39
S1988-150	150	43.0	9.1	6.4	2.70	38
S1988-250	250	45.5	9.1	6.3	2.76	40
S1995- 50	50	43.3	9.6	6.7	2.51	41
S1995-150	150	42.6	9.1	6.4	2.69	38
S1995-250	250	41.6	9.3	6.6	2.58	39
S2011-50	50	45.0	8.1	5.6	1.81	40
S2011-150	150	39.0	9.0	6.5	1.42	44
S2011-250	250	42.5	9.0	6.3	1.48	46
S2007-50	50	43.0	9.7	6.8	2.47	42
S2007-150	150	45.0	10.3	7.1	2.31	47
S2007-250	250	43.0	11.0	7.7	2.06	50
Deep waste						
S2004-50	50	52.0	13.8	9.1	1.59	78
S2004-150	150	53.0	14.1	9.2	1.55	82
S2004-250	250	49.0	14.8	9.9	1.37	86
S2001-50	50	49.0	15.1	10.1	1.32	89
S2001-150	150	52.0	15.2	10.0	1.35	92
S2001-250	250	52.3	14.9	9.8	1.40	89

Table 4
Results of the chemical and biochemical tests.

Parameter	Sample					
	S1988	S1995	S2001	S2004	S2007	S2011
BOD$_5$ (mgO$_2$/l)	100	52	51	49	45	8956
COD (mgO$_2$/l)	461	284	328	356	212	15,580
DOC (mgC/l)	197	218	145	154	104	5275
LOI (%)	26	29	11	16	15	80
TOC (%)	7.6	9.5	3.3	5.4	3.8	19.3

Table 5
Percentage of sample wet weight removed during each stage of sample preparation.

Stage	Sample					
	S1988	S1995	S2001	S2004	S2007	S2011
Recovery method	Trench	Trench	Auger	Auger	Auger	Trench
As recovered (%)	100	100	100	100	100	100
Removed during field work (%) (components larger than 200 mm)	34	25	2	2	6	31
Removed in the laboratory (%) (components smaller than 200 mm and larger than 85 mm)	9	18	26	24	22	22
Tested material (%)	57	57	72	74	72	47

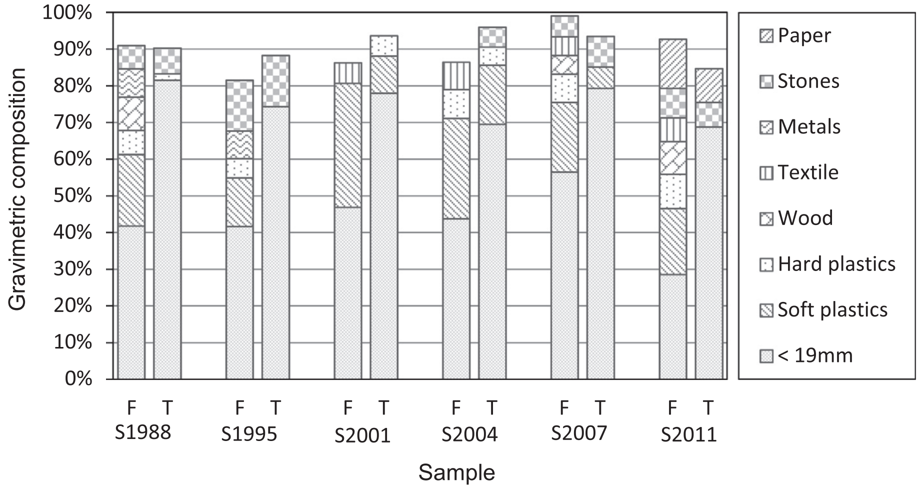

Fig. 3. Gravimetric composition of the waste samples (dry basis). Only components with more than 5% are presented. F = as recovered; T = as tested.

the second most abundant component, varying from 13.2 to 27.3%. Both components show no trend regarding landfilling age.

The amount of paper in sample S2011 is 13.4% and stands out when compared to the other samples, which is another indication that this sample is not very degraded and corroborates the results of the chemical and biochemical tests presented in the former section.

Considering the composition of the tested specimens, Fig. 3 shows that the soil-like material accounts for over 68% of all samples. No tendency regarding landfilling age could be established. Stones were the second most abundant components in samples S1988, S1995 and S2007. Paper was still an important component in sample 2011 accounting for 9.2%. Soft plastics were no longer a significant component in samples S1988, S1995, S2007 and S2011, but accounted for a considerable part of the dry mass in samples S2001 and S2004.

Table 6 and Fig. 4 illustrate the composition of the soil-like material in the various samples. The smaller than 4.76 mm components accounted for 64.9–80.8% of the soil-like material dry mass and were visually similar to sand grains. Sample S2011 was an exception to that as those components were mainly plant parts, such as leaves, seeds, twigs and fruit peelings.

Table 6 also showed marked differences. In sample S2011 the material sized between 4.76 and 19 mm was composed of plant parts and significant amounts of paper, while in the other samples it was composed of glass, wood, hard plastics, metals and stones. Large quantities of soft plastics were also present in samples S2001, S2004 and S2007.

All in all, samples S1988 and S1995 resembled a sandy soil with hard components. Samples S2001, S2004 and S2007 resembled a sandy soil with hard and soft components. Sample S2011 did not resemble a soil. These features indicate that degradation, collection method and the steps of sample preparation affected the tested waste composition.

Fig. 5 presents the composition of the tested samples according to the classification system proposed by Dixon and Langer (2006), which suggests that MSW components should be classified as compressible, incompressible or reinforcing materials. The components of the wastes tested in this investigation were classified based on the role they are expected to play in direct shear testing of waste and they were assigned to one of those three groups. Therefore, soft plastics, hard plastics, paper, wood, textile and metals were reinforcing components, rubber was classified as a compressible component and all other components were classified as incompressible. For samples S1988, S1995, S2001, S2004 and S2007 the fraction smaller than 4.76 mm was considered "incompressible". For sample S2011 this fraction was considered "reinforcing", because it did not meet the definition given by Dixon and Langer (2006) of regularly 3D shaped particles, according to the visual description of the material discussed before (Fig. 4), even though it was the smallest fraction in the sample.

The sample preparation method used in this study caused a depletion of reinforcing components and an enrichment of incompressible components for the more degraded waste samples (S1988, S1995, S2001, S2004 and S2007). For the less degraded wastes the effect of sample preparation inverted the results, there

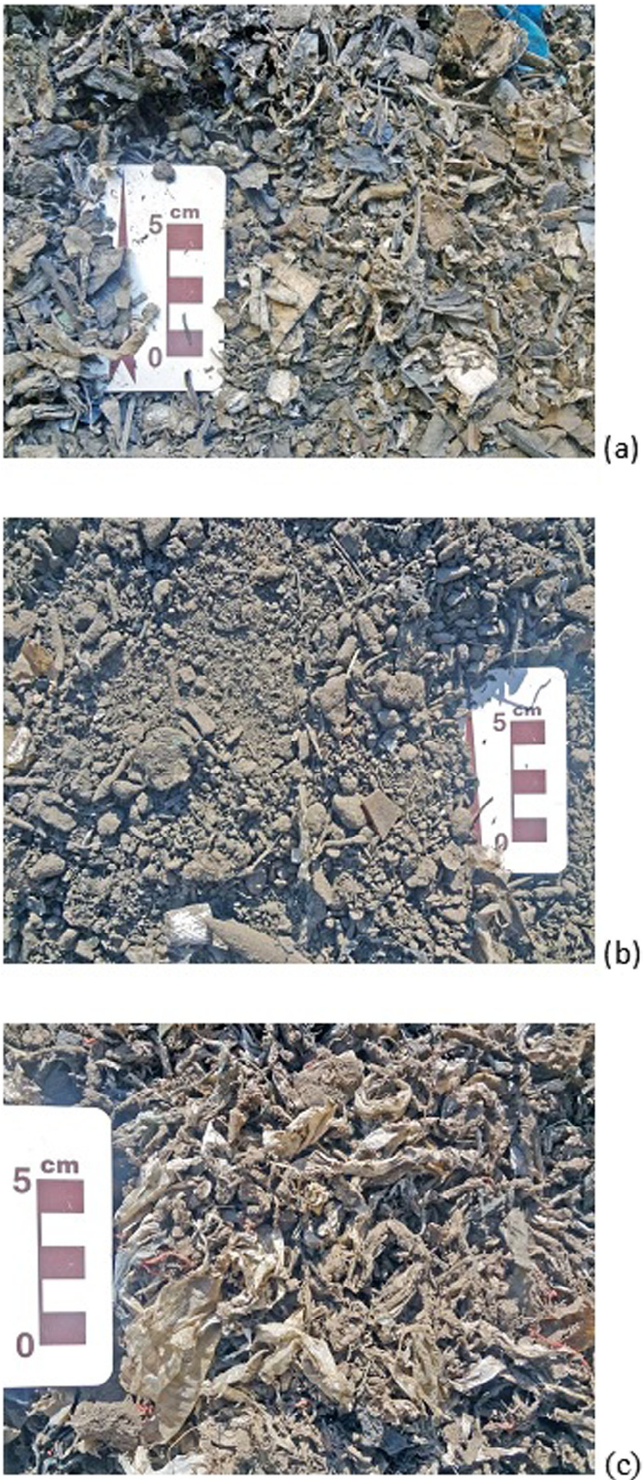

Fig. 4. Typical aspect of the soil-like material (a) sample S2011 (b) sample S1988 (c) sample S2001.

Table 6
Composition of the soil-like waste fraction (percentage of dry weight).

Category	Sample					
	S1988	S1995	S2001	S2004	S2007	S2011
<4.76 mm	70.3	72.5	80.8	74.4	75.2	64.9
Soft plastics and tissues	0.1	0.4	11.3	17.5	5.5	1.0
Other components	29.6	27.1	8.0	8.1	19.3	34.1

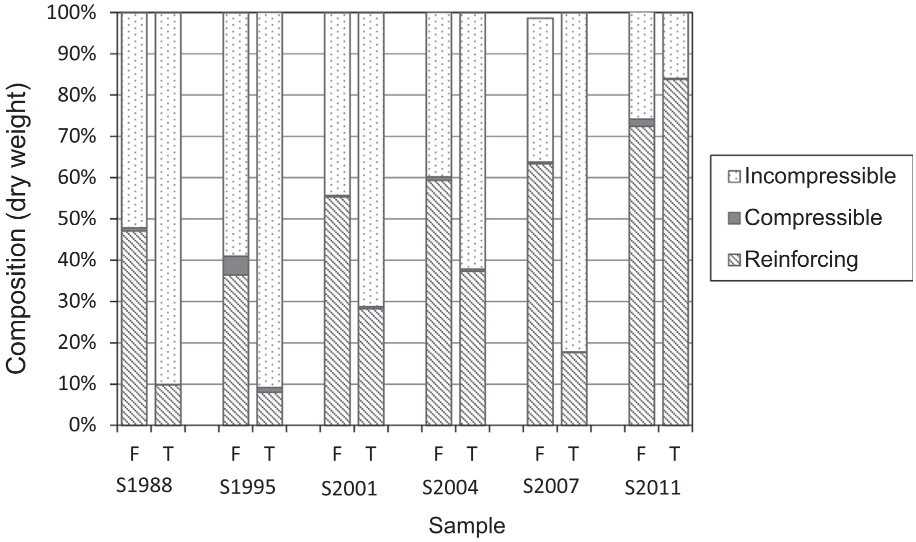

Fig. 5. Composition of the tested wastes considering the groups proposed by Dixon and Langer (2006) (percentage of dry weight). F = as recovered; T = as tested.

was an increase in reinforcing components and a decrease in incompressible components.

Fig. 6 shows the grain size distribution of the samples tested. Samples S1988, S2001, S2004 and S2007 show similar results: 25–28% gravel sized particles and 68–69% sand sized particles, considering that sand corresponds to particles sized between 0.075 and 4.75 mm and gravel corresponds to particles larger than 4.75 mm.

Sample S1995 was coarser than previously cited samples due to the abundant presence of stones that were heavy large components. Differently, the coarser grain size of sample S2011 is explained by the composition of the soil-like material, which was formed from components relatively less dense than the mineralized components of the more degraded samples. This is clearly related to the composition, or more precisely the specific gravity of the soil-like material, since yard trimmings and wood have a specific gravity of 0.97 and 1.59, respectively, while mineralized components, the main components of the soil-like fraction of the other five samples, have specific gravities of around 2.6 (Wong, 2009).

3.3. Large-scale direct shear testing program results

3.3.1. Consolidation phase

During the consolidation phase the specimens compressed significantly, as illustrated in Figs. 7 and 8, and some of them expelled water, so that immediately prior to shearing the specimens characteristics were as presented in Fig. 9.

Fig. 9 illustrates the specific unit weight of the specimens prior to the shearing phase and shows that it depends on the applied normal force. Moreover, the samples can be grouped according to their composition. Sample S2011 always showed the lowest specific unit weight prior to shearing. Samples S1988 and S1995 can be grouped as an intermediate situation and samples S2001, S2004 and S2007 can be grouped as the composition that showed the highest unit weight before shearing.

3.3.2. Stress-displacement behavior

In this investigation the direct shear stress–displacement response of all the specimens was strain-hardening, as shown in Fig. 10. In all tests the mobilized shear stress continued increasing

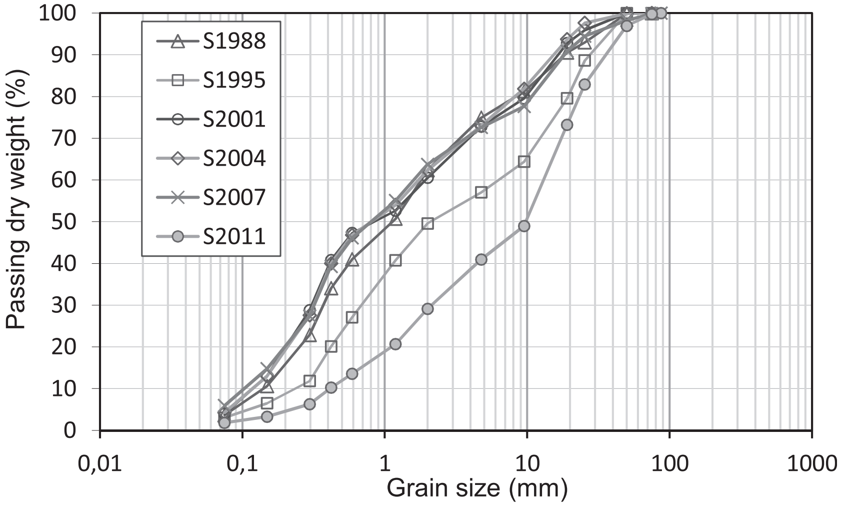

Fig. 6. Grain size of the tested samples.

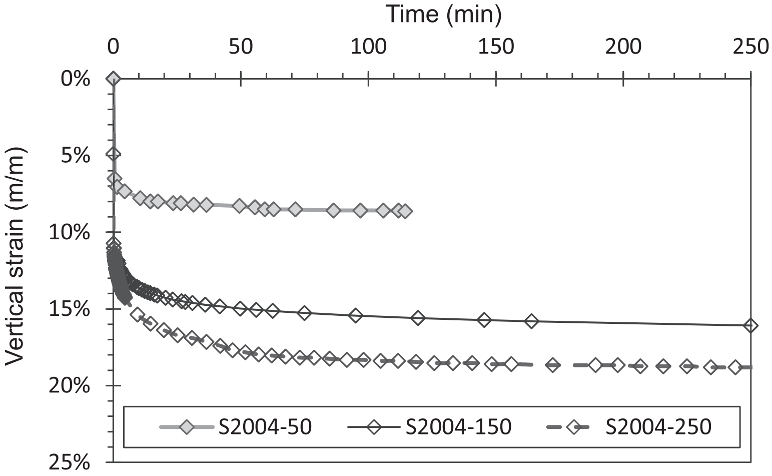

Fig. 7. Compression phase – sample S2004.

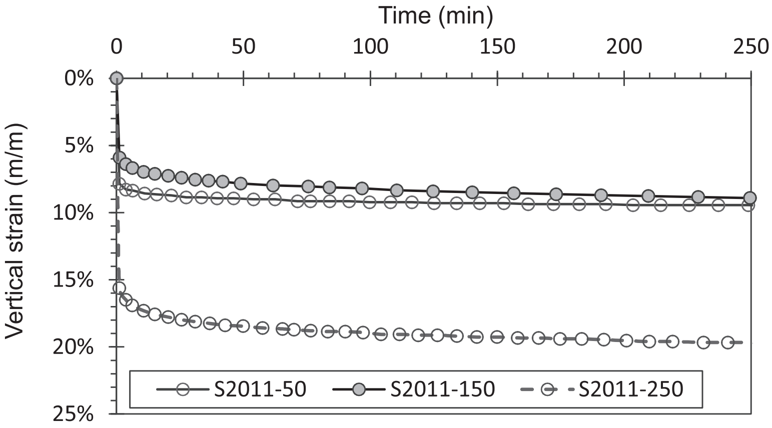

Fig. 8. Compression phase – sample S2011.

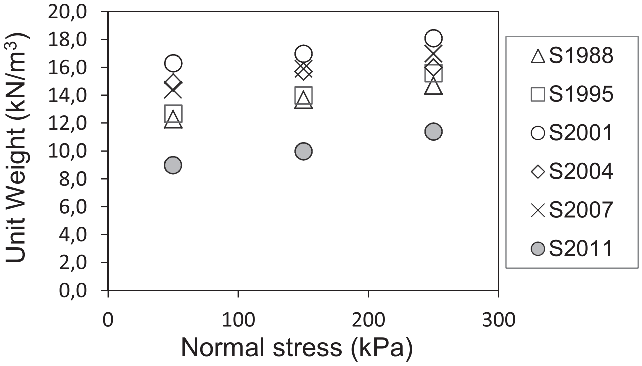

Fig. 9. Wet unit weight of the specimens at the beginning of shearing.

until reaching a horizontal displacement of 150 mm, which is the maximum displacement of the testing device and therefore the test needed to be interrupted. All the curves showed a downward concavity. Only the curves for specimens S2007-150 and S1995-150 developed a tendency to reach an ultimate stress toward the end of the direct shear test. All tests showed a contractive vertical to horizontal strain behavior, illustrated in Fig. 11.

This behavior is comparable to those reported by Gotteland et al. (2001), Gabr et al. (2007a,b), Singh et al. (2009), Zekkos et al. (2010), Reddy et al. (2009a,b, 2011) and Bareither et al. (2012) for direct shear tests on MSW with the long-axis of reinforcing particles oriented in the direction of shear.

The shear stresses for the direct shear tests conducted at low normal stress (50 kPa) reached about the same range for the more and the less decomposed samples. However, higher shear stresses were measured for the more decomposed wastes compared with sample S2011 at both higher normal pressures (150 and 250 kPa). These observations suggest that shear resistance is higher for more decomposed waste. They also demonstrate that, according to Fig. 9, the specimens from the more degraded wastes were sheared with higher initial unit weights, which is a consequence of their composition.

3.3.3. MSW shear resistance

MSW shear resistance parameters were calculated using the Mohr-Coulomb envelope. An average linear failure envelope was fitted to shear strength versus normal stress for each sample to obtain φ and c. As none of the stress-displacement curves reached peak shear strength values, the parameters were calculated for horizontal displacements of 25, 50 and 100 mm, which are equivalent to a horizontal displacement of 5, 10 and 20% of the specimen length, respectively. All failure envelopes had $R^2 > 0.88$, indicating that a linear representation of the strength envelope was reasonably accurate in the stress range (50–250 kPa) evaluated in this investigation. Fig. 12 presents the best fit Mohr-Coulomb failure envelopes for samples S2004 and S2011.

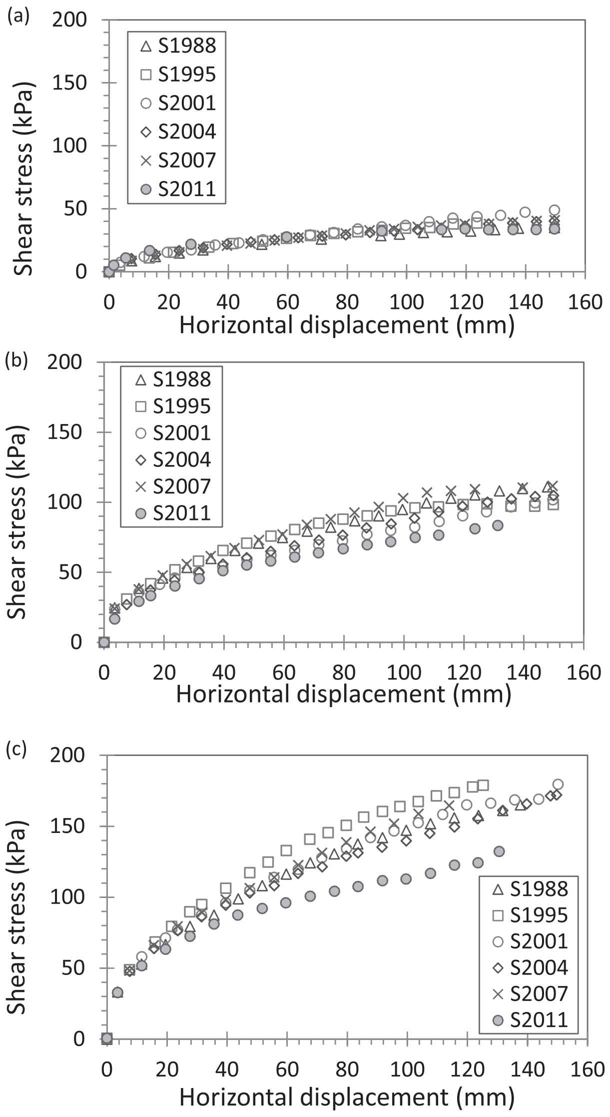

Fig. 10. Stress-displacement behavior of the tested specimens (a) 50 kPa normal stress (b) 150 kPa normal stress (c) 250 kPa normal stress.

Figs. 13 and 14 summarize the shear strength parameters calculated in this investigation. Sample S2011, which was comprised of less degraded waste, stands out for its higher cohesion (8–13.7 kPa) and its lower friction angle (14–22°), especially in larger horizontal displacements. The more degraded waste samples showed similar φ, starting with 17–19° for 25 mm displacement and practically the same increase rate, reaching φ = 28–33° for 100 mm horizontal displacement.

Regarding cohesion these samples can be divided into two groups: samples S1988 and S1995 showed an almost constant cohesion value for all horizontal displacement intervals (2.6–2.7 kPa for S1988 and 0.0–0.5 kPa for S1995) and samples S2001, S2004 and S2007 exhibited higher cohesion values for larger horizontal displacements. They started with 0.6–1.4 kPa for 25 mm displacement and reached 5.8–6.8 kPa for 100 mm horizontal displacement, with a similar increase rate.

These differences are explained by the different content of reinforcing materials in the tested specimens. Samples S1988 and S1995 contained between 0.3 and 0.9% soft plastic and only 6–8% reinforcing components, while samples S2001, S2004 and S2007 had larger percentages of soft plastics (5.8–16.1%) and reinforcing components (11–24%).

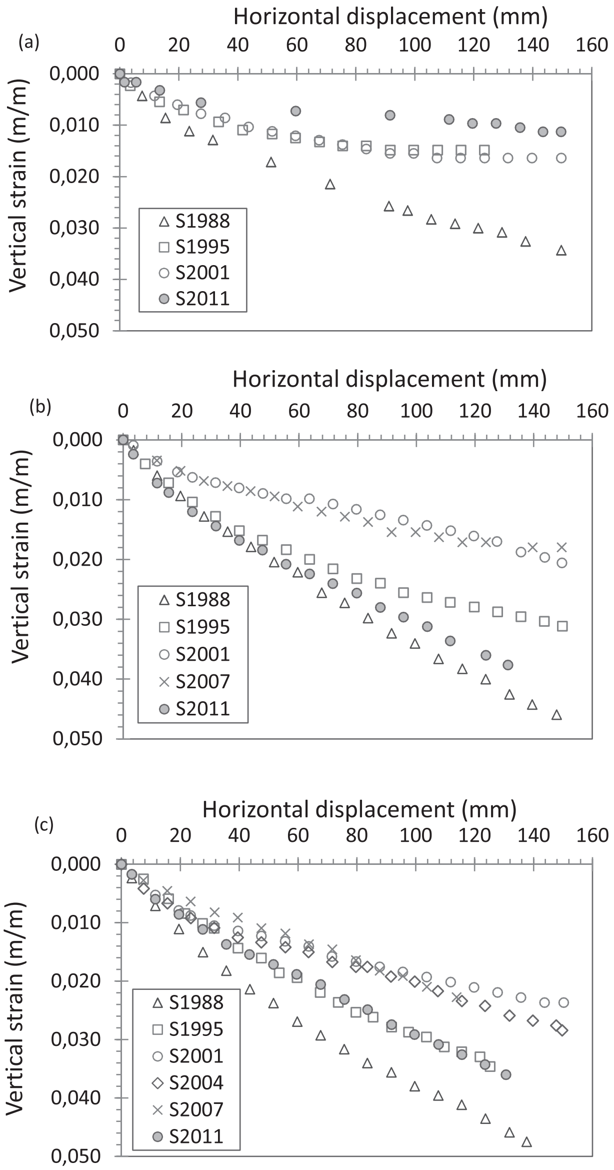

Fig. 11. Contractive behavior of the tested specimens for (a) 50 kPa normal stress (b) 150 kPa normal stress (c) 250 kPa normal stress.

Borgatto et al. (2009) and Shariatmadari et al. (2011) emphasize the importance of the soft plastics content on the direct shear MSW shear strength. However, in this investigation the percentage of soft plastics did not show a good correlation to cohesion, while the percentage of reinforcing components showed a positive correlation to cohesion, as illustrated in Figs. 15 and 16. The coefficient of determination for a linear fit in the latter case is 72% for 25 mm horizontal displacement, 87% for 50 mm horizontal displacement and 83% for 100 mm horizontal displacement (Fig. 16). The cohesion calculated for sample S2011 in this investigation increased with horizontal displacement increase, even though this sample only had 0.9% soft plastics. On the other hand, its reinforcing components content was 20.9%, which explains the progressive mobilization of cohesion in a waste with little soft plastics.

These results suggest that the reinforcing components content highly influence the shear-displacement behavior and shear resistance of MSW and, thus, they should be emphasized more in sample description, rather than the soft plastic content as an isolated reinforcing material.

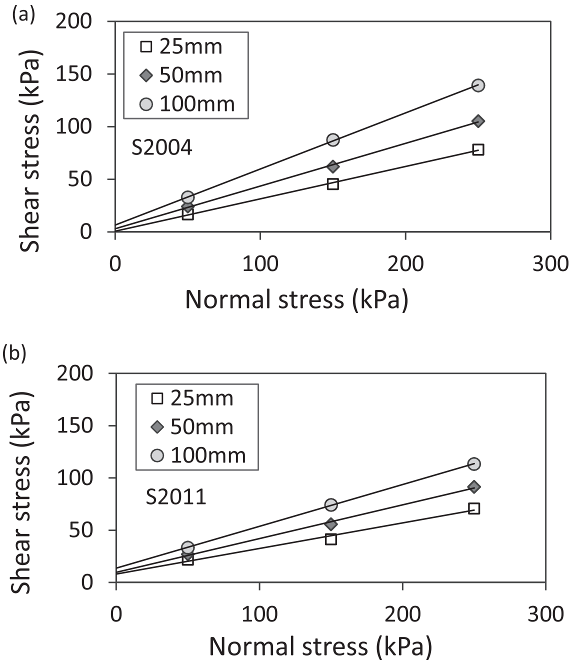

Fig. 12. Best fit Mohr-Coulomb failure envelopes for samples S2004 (a) and S2011 (b) considering 25, 50 and 100 mm horizontal displacement.

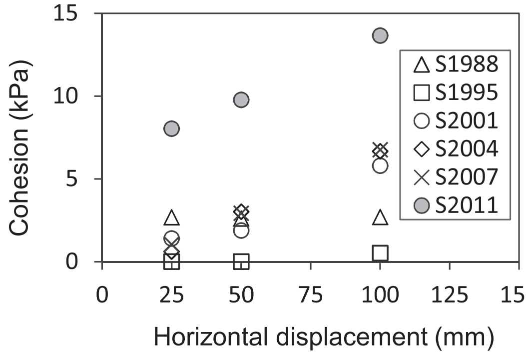

Fig. 13. Cohesion for the various samples determined for 25, 50 and 100 mm horizontal displacement.

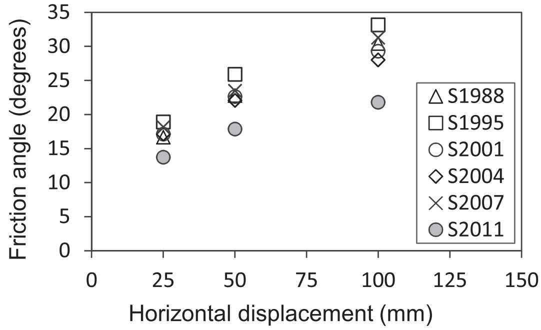

Fig. 14. Friction angles for the various samples determined for 25, 50 and 100 mm horizontal displacement.

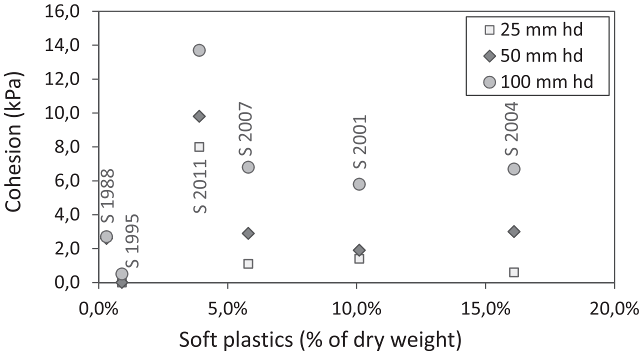

Fig. 15. Relationship between the fraction of soft plastics and the cohesion calculated for the tested wastes.

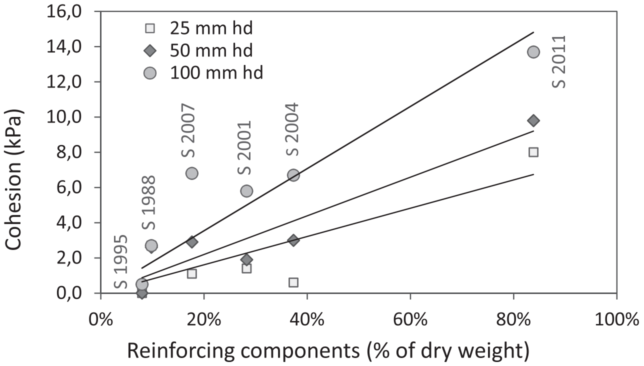

Fig. 16. Relationship between the fraction of reinforcing components and the cohesion calculated for the tested wastes.

An average failure envelope was calculated for the more degraded wastes: S1988, S1995, S2001, S2004 and S2007, considering 100 mm horizontal displacement. This failure envelope had a friction angle of 30°, cohesion of 4.4 kPa and R^2 of 0.98. It compares with the envelope proposed by Kavazanjian (2008) for traditional landfills located in all types of climatic conditions, as illustrated in Fig. 17. The envelopes recommended by Eid et al. (2000), Stark et al. (2009) and Zekkos et al. (2010) fall above the results of the tests performed in this investigation.

The well degraded wastes tested in this study have large fractions of incompressible components, including soil-like and larger than 19 mm components, and their average failure envelope shear strength parameters are comparable to the shear strength parameters typical of loose cohesionless soils such as sands and gravels, despite the fact that their stress-displacement behavior is strain hardening even for large horizontal displacements.

The less degraded waste tested in this study, namely sample S2011, showed smaller shear resistance in the normal stress range investigated in this research.

These results suggest that as MSW degrades the waste material transitions from an initially highly cohesive material to one that loses cohesion yet gains in friction angle over time, which would agree with the conclusions of Gabr et al. (2007a,b) and Zekkos et al. (2010). However, the sample collection and sample preparation methods imposed significant changes on the composition of the waste and the more degraded waste samples were depleted of reinforcing components and obtained shear strength parameters are expected to be conservative. The laboratory test results for sample S2011 may be closer to in situ MSW shear resistance than the results achieved when testing the more degraded samples, because the composition of the tested S2011 sample was more similar to the field composition of the recovered waste.

The results of the present investigation reaffirm that the composition of the tested specimen plays a fundamental role in determining MSW shear strength, which is in agreement with Bareither

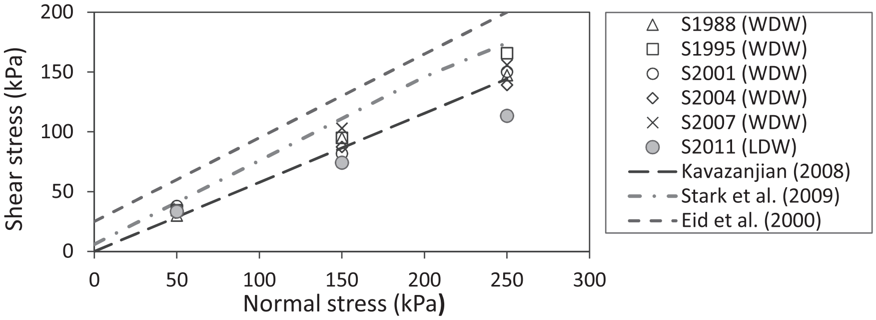

Fig. 17. Results from this investigation (100 mm horizontal displacement) compared to the envelope proposed by Kavazanjian (2008), Eid et al. (2000) and Stark et al. (2009). WDW = well degraded waste; LDW = less degraded waste.

et al. (2012), who presented a comprehensive review of literature data on MSW direct shear testing and argue that "there may not be a unique relationship between φ and waste decomposition and that changes in φ with decomposition depend on the initial waste composition and subsequent changes to that composition". However, more attention should be paid to the description of the soil-like material. In this investigation the soil-like material of less degraded waste was formed mainly from reinforcing components and the soil-like material of more degraded waste was formed mainly from incompressible components. The influence of this kind of difference in determining MSW shear strength needs to be further investigated.

4. Conclusion

This paper dealt with the shear strength of six Municipal Solid Waste (MSW) samples of landfilling ages varying between 2 and 25 years. Based on visual observation, physical and chemical tests it was possible to conclude that the sample that had been buried for only two years was clearly less degraded than the other five samples, which were 5 to 25 years old when exhumed.

Direct shear tests showed a strain-hardening and a contractive volume behavior during shearing. Stress–displacement curves were mostly concave downwards, with no stress peaks. The average failure envelope calculated for the more degraded wastes for 100 mm displacement had a friction angle of 30° and cohesion of 4.4 kPa. The failure envelope calculated for the less degraded waste for 100 mm displacement had a friction angle of 22° and cohesion of 13.7 kPa.

These results suggest that as MSW gets "older" the waste material transitions from an initially high cohesion material to one that loses cohesion yet gains in friction angle over time. However, the sample collection and sample preparation methods imposed significant changes on the composition of the waste and the more degraded waste samples were depleted of reinforcing components, while the less degraded waste sample was enriched in reinforcing components. The shear strength parameters developed in this investigation for the more degraded wastes are expected to be conservative, while the shear strength parameters developed for sample S2011 may be closer to in situ MSW shear resistance, as its composition is more similar to the composition of the exhumed waste.

Better sample description in terms of waste composition, especially for the soil-like material, is needed, so that research results can be adequately compared. The influence of each type of reinforcing component on MSW shear strength needs to be further investigated, but the results from this investigation suggest that the reinforcing components content as a whole should be emphasized in sample description and understanding of shear-displacement behavior and shear resistance of MSW, rather than the soft plastics content as an isolated reinforcing material.

Moreover, sample preparation methods that involve reducing components size and preserving the as-recovered mass proportion of the sample components seem to be more suitable for sample preparation than the large components removal method, as they tend to preserve the original sample composition.

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References

Abreu, A.E.S., Vilar, O.M., 2016. Accessing the biological stability of Municipal Solid Waste of different landfilling ages. J. Solid Waste Manage. Technol. 42 (3), 236–244.

Abreu, A.E.S., Gandolfo, O.C.B., Vilar, O.M., 2016. Characterizing a Brazilian sanitary landfill using geophysical seismic techniques. Waste Manage. 53, 116–127.

APHA, 2012. Standard methods for the examination of water and wastewater. Rice, E.W., Baird, R.B., Eaton, A.D., Clesceri, L.S. (Eds.), 22nd edition. American Public Health Association, America Water Works Association, Water Environment Federation, Washington, DC.

Athanasopoulos, G., 2011. Laboratory testing of municipal solid waste. In: Zekkos, D. (Ed.) Geotechnical Characterization, Field Measurement, and Laboratory Testing of Municipal Solid Waste. ASCE Geotechnical Special Publication 209, pp. 195–205.

Bareither, C.A., Benson, C.H., Edil, T.B., 2012. Effects of waste composition and decomposition on the shear strength of municipal solid waste. J. Geotech. Geoenviron. Eng. 138 (6), 1161–1174.

Barlaz, M.A., Ham, R.K., Schaefer, D.M., 1989. Mass balance analysis of decomposed refuse in laboratory scale lysimeters. J. Environ. Eng. 115 (6), 1088–1102.

Barlaz, M.A., Ham, R.K., Schaefer, D.M., 1990. Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. CRC Crit. Rev. Environ. Control. 19 (6), 557–584.

Borgatto, A.V.A., Mahler, C.F., Izzo, R.L.S., 2009. Influence of soft plastic on MSW geomechanical behaviour. In: 3rd Int. Workshop on Hydro-Physico-Mechanics of Landfills, Braunschweig, Germany, 1–10.

Bray, J.D., Zekkos, D., Kavazanjian, E., Athanasopoulos, G.A., Riemer, M.F., 2009. Shear strength of municipal solid waste. J. Geotech. Geoenviron. Eng., ASCE, New York 135 (6), 709–722.

Caicedo, B., Yamin, L., Giraldo, E., Coronado, O., 2002. Geomechanical properties of municipal solid waste in Dona Juana sanitary landfill. In: 4th International Congress on Environmental Geotechnics, Proceedings..., Rio de Janeiro, Brazil, vol. 1, pp. 177–182.

Carvalho, M.F., 1999. Mechanical Behavior of Municipal Solid Waste Doctor of Philosophy Dissertation. University of São Paulo, São Carlos, SP, Brazil (in Portuguese).

Christensen, T.H., Kjeldsen, P., 1995. Landfill emissions and environmental impact: An introduction. In: Christensen, T.H., Cossu, R., and Stegmann, R. (Eds.), Proc. Sardinia '95, Fifth International Landfill Symposium, Volume III, CISA, Cagliari, Italy, 3.

Dixon, N., Langer, U., 2006. Development of a MSW classification system for the evaluation of mechanical properties. Waste Manage. 26, 220–232.

Eid, H.T., Stark, T.D., Evans, W.D., Sherry, P.E., 2000. Municipal solid waste slope failure I: waste and foundation soil properties. J. Geotech. Geoenviron. Eng. 126 (5), 397–407.

Frésca, F.R.C., 2007. Analysis of Municipal Solid Waste Generation in São Carlos, SP, Considering Its Physical Characterization Master Dissertation. University of São Paulo, São Carlos, SP, Brazil (in Portuguese).

Gabr, M.A., Hossain, M.S., Barlaz, M.A., 2007a. Shear strength parameters of municipal solid waste with leachate recirculation. J. Geotech. Geoenviron. Eng. 133 (4), 478–484.

Gabr, M.A., Hossain, M.S., Barlaz, M.A., 2007b. Erratum for "Shear Strength Parameters of Municipal Solid Waste with Leachate Recirculation". J. Geotech. Geoenviron. Eng. 133 (9), 1181.

Gomes, L.P.G., 1989. Physical Characterization and Biodegradability of Municipa Solid Waste in Sanitary Landfills Ph.D Thesis. University of São Paulo, São Carlos, SP, Brazil (in Portuguese).

Gotteland, P., Gachet, C., Vuillemin, M., 2001. Mechanical study of a municipal solid waste landfill. In: Proc. Sardinia 2001, Eight International Landfill Symposium. Cagliari, Italy, pp. 425–433.

Hossain, M.S., Haque, M.A., 2009. The effects of daily cover soils on shear strength of municipal solid waste in bioreactor landfills. Waste Manage. 29, 1568–1576.

Kavazanjian, E, Jr., 2008. The Impact of degradation on MSW shear strength. In: Proceedings of GeoCongress '08: Geotechnics of Waste Management and Remediation. ASCE Geotechnical Special Publication 177, pp. 224–231.

Koerner, R.M., Koerner, G.R., 2015. On the Shear Strength of Municipal Solid Waste (MSW). GSI White Paper #33. Geosynthetic Institute, Folsom, 11p.

Machado, S.L., Karimpour-Fard, M., Shariatmadari, N., Carvalho, M.F., Nascimento, J. C.F., 2010. Evaluation of the geotechnical properties of MSW in two Brazilian landfills. Waste Manage. 30, 2579–2591.

Reddy, K.R., Gangathulasi, J., Parakalla, N.S., Hettiarachchi, H., Bogner, J.E., Lagier, T., 2009a. Compressibility and shear strength of municipal solid waste under short-term leachate recirculation operations. Waste Manage. Res. 27 (6), 578–587.

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

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

Shariatmadari, N., Karimpour-Fard, M., Keramati, M., Kolarijani Jafari, H., Naebi, A., 2011. Fiber content impact on the shear strenght of MSW materials in direct shear tests. In: Proceedings Sardinia 2011, Thirteenth International Waste Management and Landfill Symposium. Cagliari, Italy.

Singh, M.K., Sharma, J.S., Fleming, I.R., 2009. Shear strength testing of intact and recompacted samples of municipal solid waste. Can. Geotech. J. 46, 1133–1145.

Stark, T.D., Huvaj-Sarihan, N., Li, G., 2009. Shear strength of municipal solid waste for stability analyses. Environ. Geol. 57 (8), 1911–1923.

Stoltz, G., Nousheen Arif, K., Gourc, J.P., Olivier, F., Redon, E., 2009. Hydro-mechanical properties of MSW from laboratory tests following a deep drilling campaign. In: Proceedings Sardinia 2009, Twelfth International Waste Management and Landfill Symposium. Cagliari, Italy.

Turczynski, U., 1988. Geotechnical Aspects of the Construction of Landfills Doctor of Philosophy Dissertation. University of Freiberg, Germany, p. 96 (in German).

Varga, G., Imre, E., Czap, Z., Firgi, T., Telekes, G., 2011. Laboratory and in situ tests of a landfill. In: Fourth International Workshop "Hydro-Physico-Mechanics of Landfills" (HPML4) Santander, Spain. Disponível em: http://www.hpm4.unican.es/proceedings.html (Acessado em 09 de novembro de 2011). 10p.

Wong, W.W., 2009. Investigation of Geotechnical Properties of Municipal Solid Waste M.S. Thesis. California Polytechnic State University, San Luis Obispo, California.

Zekkos, D., 2005. Evaluation of Static and Dynamic Properties of Municipal Solid Waste Doctor of Philosophy Dissertation. Department of Civil and Environmental Engineering, University of California, Berkeley, California, USA.

Zekkos, D., Athanasopoulos, G.A., Bray, J.D., Grizi, A., Theodoratos, A., 2010. Large-scale direct shear testing of municipal solid waste. Waste Manage. 30, 1544–1555.

Zhan, T.L.T., Chen, Y.M., Ling, W.A., 2008. Shear strength characterization of municipal solid waste at the Suzhou landfill, China. Eng. Geol. 97 (3–4), 97–111.