A Study on the Effects of MSW Fiber Content and Solid Particles Compressibility on its Shear Strength Using a Triaxial Apparatus

Sandro Lemos Machado, Mehran Karimpour-Fard

Abstract. It is commonly accepted that the shear strength of Municipal Solid Waste (MSW) is enhanced by the reinforcement effect of its fibrous constituents. However, most papers in the technical literature do not systematically evaluate the effect of the MSW fibers on its stress-strain-strength response. This paper presents results of a series of laboratory triaxial tests performed to evaluate the effect of the MSW fiber content and solid particle compressibility on its mechanical behavior. The variation in the MSW shear strength and shear strength parameters with fiber content and axial strain are analyzed, the effective parameters obtained from CD and CU tests are compared and the applicability of Terzaghi's equation for MSW materials discussed. Test results were used to calculate the Factor of Safety, FS, for some slope geometrical configurations and the results were used to create some charts relating FS, fiber content and the slope geometry. The authors believe this subject could be of interest to landfill management companies, especially considering the new trend in plastic material recycling for energy recovery purposes.

Keywords: MSW, MSW fibers, solid particles compressibility, shear strength, triaxial tests, slope stability.

1. Introduction

The stress-strain-strength response of Municipal Solid Waste (MSW) is a matter of concern for the design and operation of landfills as well as when post-closure behavior and re-use or mining of old landfills areas are considered. It is commonly stated that MSW can stand very high values of shear stress due to the reinforcement effect of the fibrous materials it contains (Kavazanjian *et al.* 1999, Athanasopoulos *et al.* 2008). However, the number of papers that have systematically evaluated the effect of the fibrous waste components on the MSW mechanical response of MSW is limited.

Landava and Clark (1990), as a part of their extensive work, performed direct shear tests using a large apparatus with horizontal dimensions of 434 x 287 mm. According to their findings, the shear strength of old waste is clearly higher than that of fresh waste. They concluded that the low strength of fresh waste, which was shredded, was because fibrous and elongated particles have been found to align themselves in a horizontal direction, which is coincident with the shearing plane in direct shear tests. The presence of these sliding planes led to a reduction in the MSW shear strength. In the case of natural and old waste, there is no preferential alignment of the fibers which results in higher shear strengths.

Kölsch (1995) stated that triaxial and direct shear tests do not describe adequately the MSW shearing behavior, because in these test arrangements the anisotropy of waste is not sufficiently recorded. To quantify the tensile strength of MSW and evaluate the reinforcement characteristics of MSW materials, he developed an equipment for tensile test which was enable to apply tensile stress to MSW samples by pulling one half of the box and increasing the horizontal deformation slowly until the applied tensile force reaches a maximum. Typical results of tensile tests on MSW samples can be visualized in Fig. 1. In this figure the slope of the envelopes represents the angle of internal tensile forces. The higher this angle, the higher the reinforcement component in shearing behavior of MSW. As can be observed in this graph, the angle of internal tensile forces in the case of fresh waste is lower than aged waste, which could be attributed to the higher fiber content in old waste due to decomposition processes.

Zekkos (2005) performed large triaxial tests on the MSW materials from San Francisco bay and showed that the effect of the waste composition on the stress-strain-strength response of the MSW materials is significant. He also reported the results of large direct shear tests performed on the same materials by (2005) and showed that the type of mechanical response of MSW materials is dependent on the shear mechanisms. According to Georgiopoulos (2005), the direction of the fibers inside the samples could affect the mechanical response of these materials during shearing. In the case of samples in which the direction of the fibers were perpendicular to the shear plane, the response was similar to the samples sheared in triaxial apparatus, showing an upward concavity in their stress-strain

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curves due to the reinforcement effect of the fibrous material (Fig. 2).

In a similar work, Athanasopoulos *et al.* (2008) performed several large direct shear tests on MSW materials with varying fiber directions and concluded that the optimum angle of fiber which leads to a higher shear strength is 60 degrees, taking the horizontal plane as reference (Fig. 3).

Despite these valuable contributions, the number of experimental works focusing on the effect of the fiber content on the mechanical response of MSW remains incipient. One of the first attempts in this field was performed in the Geo-environmental Laboratory at the Federal University of Bahia (GEOAMB) by Karimpour-Fard (2009) using a large triaxial apparatus which is presented in the following sections.

2. Materials, Apparatus and Experimental Work

The MSW samples used in this research were collected at the disposal front of the Metropolitan Center Landfill, MCL, located approx. 20 km from Salvador. The results of the composition analysis of the MSW in the MCL according to the reports represented by GEOAMB in March 2010, are presented in Table 1.

As can be observed, the main elements which could act as a reinforcement element, plastic and textiles, make up about 25% of all the waste (dry basis). Other planar elements such as paper and cardboard, sometimes referred to as the fiber elements in the literature, in this research were assumed paste material as as having a negligible influence on MSW reinforcement.

This is justified by the high water content found in this material (around 100%, dry basis) which leads to a loss of tensile strength of such waste components. All the samples used in this work can be considered as fresh waste with a negligible soil content. Considering the data presented in Table 1 and the considerations made above, the maximum fiber content used in the compacted samples was assumed to be 25% by dry weight.

The water content of samples used in this work varied from 115 to 125%. Particles larger than 5 cm were removed from the waste or were reduced in size. Figure 4 illustrates the stages of sampling and treatment.

Considering a maximum fiber content of 25%, intermediate fiber contents of 12.5, 6.25 and 0 percent were chosen to compact the samples. To reach the desired value of fiber content in each sample the first step was to remove all the plastics and textiles from the MSW. After that, the desired amount of fibers was added to the waste, which was mixed and homogenized in order to obtain the samples to be used in the tests.

Figure 5 shows the apparatus used and the preparation steps of the sample. As can be seen, a large triaxial test apparatus was used to evaluate the mechanical behavior of the MSW materials. This apparatus includes a loading frame with a capacity of 300 kN and a set of hardware and software to perform stress/strain controlled triaxial tests. The

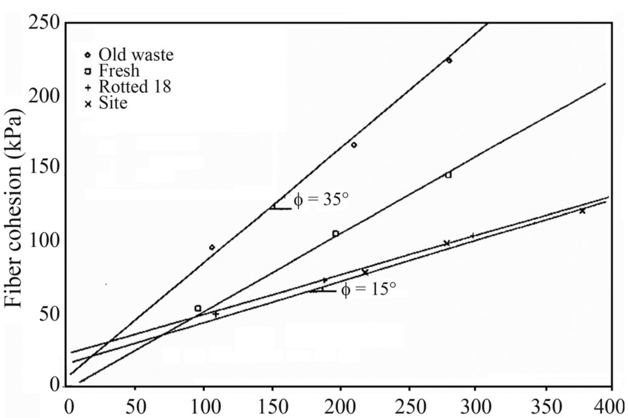

Figure 1 - MSW cohesion due to fiber reinforcement effect. Kölsch (1995).

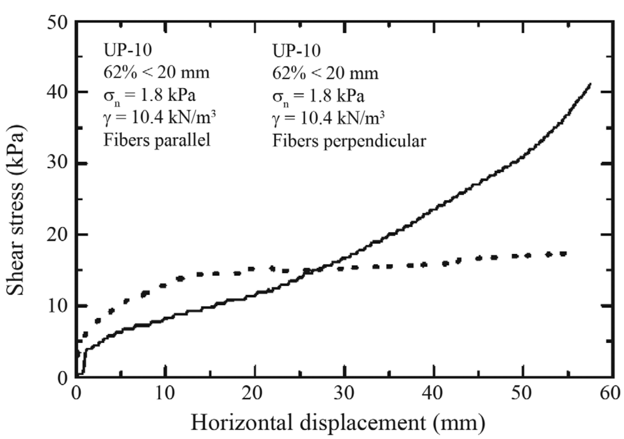

Figure 2 - The effect of the direction of the fibers on the mechanical response of MSW materials Georgiopoulos (2005).

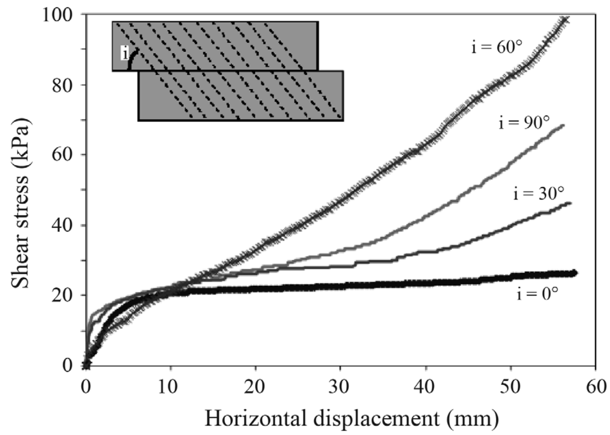

Figure 3 - Changing the shear strength of MSW materials with variation in the direction of the fibers, Athanasopoulos *et al.* (2008).

Table 1 - The composition of fresh MSW material in MCL (Machado *et al.*, 2010).

Component	Average composition – dry basis			Average composition – wet basis		
	Average (%)	S.D. (%)	Cov.	Average (%)	S.D. (%)	Cov.
Wood	5.92	3.04	0.51	5.19	3.39	0.65
Stone/Ceramic	10.89	6.56	0.60	5.88	3.84	0.65
Textile	3.66	1.78	0.49	4.19	2.25	0.54
Rubber	0.44	0.45	1.01	0.29	0.27	0.95
Plastic	20.11	4.92	0.24	18.74	3.99	0.21
Glass	3.78	1.55	0.41	1.65	0.75	0.46
Metal	2.90	1.59	0.55	1.49	0.71	0.48
Paper/Cardboard	17.12	5.17	0.30	19.70	4.27	0.22
Paste	35.18	6.64	0.19	42.86	7.27	0.17

S.D. : Standard Deviation, Cov. : Coefficient of variance.

size of the triaxial chamber and the nominal size of the samples were 50x100 and 20x35 cm, respectively. Samples were compacted statically to reach a nominal density of 8 kN/m^3 similar to that obtained in field after waste disposal. The loading frame was used to compress the samples to the height of 30 cm. Samples were left pressed for 2 h and then released to rebound. The height of the samples at the end of the process was about 35 cm.

A test program was scheduled based on the short and long term behavior of MSW materials so both drained and undrained tests were carried out to evaluate the effect of the fiber content on the waste shear strength. Table 2 lists the tests performed.

Samples were saturated with water. The saturation techniques used were upward flow (using an effective confining pressure of 10 kPa) and back-pressure. The flow stage lasted for a minimum of two hours until stationary flow was reached. The back-pressure technique used confining pressure increments of 50 kPa and a minimum value of $B = 0.9$ was adopted.

After saturation, the samples were consolidated until a negligible rate of volume change was observed. To correct the cross section of the samples after consolidation, a non-isotropic deformation assumption was used (Eq. (1)),

Figure 4 - Sample preparation (a) Sampling (after quartering, particles larger than 5 cm were removed) (b) removing plastic and textiles (c) and (d) cutting and processing the particles larger than 5 cm.

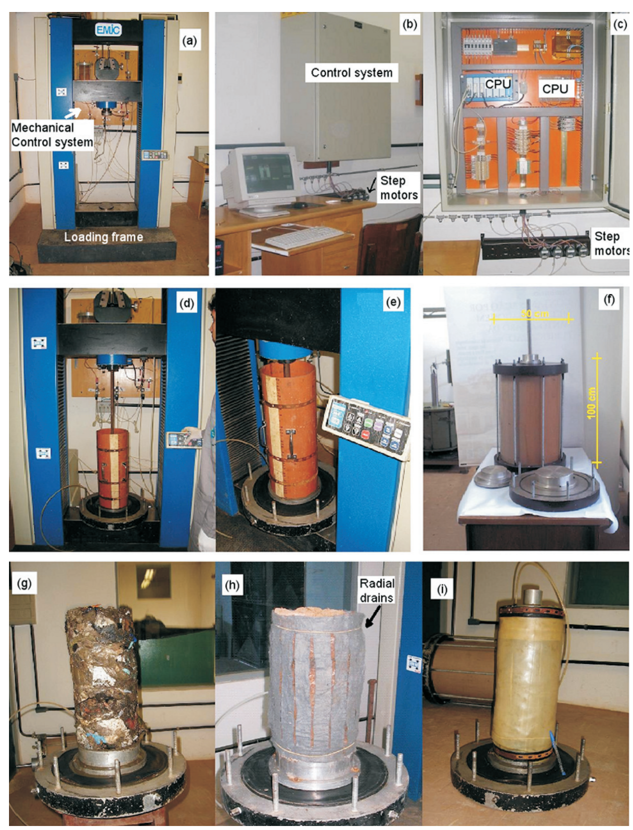

Figure 5 - (a) Loading frame (b) and (c) control system (d) and (e) compacting the sample (f) triaxial chamber (g) sample after compaction (h) Radial geotextile drains (i) sample before test.

Table 2 - List of performed tests.

No.	Test type	F.C. (%)	$\Delta\sigma_3$ (kPa)	γ_0 (kN/m^3)
1	TX-CD	0	50	8.4
2	TX-CD	0	150	8.55
3	TX-CD	0	300	8.32
4	TX-CU	0	50	8.32
5	TX-CU	0	150	8.42
6	TX-CU	0	300	8.15
7	TX-CD	6.25	50	8.26
8	TX-CD	6.25	150	8.23
9	TX-CD	6.25	300	8.38
10	TX-CU	6.25	50	8.44
11	TX-CU	6.25	150	8.48
12	TX-CU	6.25	300	8.46
13	TX-CD	12.5	50	8.05
14	TX-CD	12.5	300	8.41
15	TX-CU	12.5	50	8.32
16	TX-CU	12.5	300	8
17	TX-CD	25	50	7.83
18	TX-CD	25	300	8.1
19	TX-CU	25	50	8.52
20	TX-CU	25	300	8.12

TX. Triaxial Test, CD. Consolidated-Drained. CU. Consolidated-Undrained, F.C. Fiber Content. $\Delta\sigma_3$. Consolidation stress, γ_0. Initial density.

as suggested by Shariatmadari *et al.* (2009) who used samples collected at the same place.

The recorded volume changes during the consolidation phase were used in conjunction with the changes in the sample height (measured using the free length of the loading ram) to calculate the sample radial strain and the sample cross section prior to shearing. According to the authors, the ratio of axial to radial strain (which should be equal to one in isotropic materials) varied from 1.65 to 3.48, with an average of 2.4. This means that the assumption of isotropic deformation leads to a smaller cross section and therefore to higher values of axial stress and shear strength. In Eq. (1) ε_r, ε_a and ε_v are the radial, axial and volumetric strains, respectively.

$$\varepsilon_r = 1 - \sqrt{\frac{1-\varepsilon_V}{1-\varepsilon_a}} \tag{1}$$

The apparatus shown in Fig. 5 had two different chambers to measure volume change. The rst chamber (chamber No. 1), common in triaxial apparatus, measures the changes in the volume of water inside the samples (or the changes in the volume of the samples, in the case of saturated specimens with incompressible particles). The second one, chamber No. 2, connected to the conning stress water supply line, was used to measure the overall sample volume change (please refer to Fig. 6).

In the case of the second chamber, the measured volume values were corrected in order to take into account the triaxial cell deformation. Triaxial cell deformation was small compared to the volume change of the samples even for low conning pressures. Chamber 2 always showed higher volume changes than chamber 1 and this difference was believed to be due to the compressibility of the waste particles.

Tests were performed using a loading rate of 0.8 mm/min. The shearing phase lasted until the sample reached 30% of axial strain. Tests were performed according to procedures suggested by Head (1986) and ASTM D4767 (2004).

3. Results and Analysis

Figures 7 and 8 present the results of the triaxial tests performed using confining pressures of 50 and 300 kPa. As can be observed, almost all the curves are concave upward, without presenting any evidence of rupture, which is in agreement with the results presented by researchers such as Grisolia & Napoleoni (1995), Jessberger & Kockel (1993), Carvalho (1999), Machado *et al.* (2002, 2008), Towhata *et al.* (2004), Zekkos (2005), Nascimento (2007) and Karimpour-Fard (2009). With increasing fiber content, the MSW shear strength increased in both drained and undrained tests. Although not shown in this paper, even in the case of the use of the maximum obliquity criteria, $(\sigma'_1/\sigma'_3)_{max}$, it is not possible to detect failure of the MSW samples.

Analyzing Fig. 8b it is possible to observe that the pore water pressure at the end of the shearing phase is almost equal to the confining stress. These results are similar to those obtained by Carvalho (1999) and Nascimento (2007). On the one hand, this means that if the effective stress equation proposed by Terzagui is used, the effective confining stress will approach zero. Despite this, however, the samples continue to present strain hardening, and absolutely no evidence of liquefaction can be found in the tests results. On the other hand, the use of the Terzaghi equation in such conditions leads to very high friction angles and almost null cohesion intercepts which is physically contradictory with the ability of the samples to sustain high deviatoric stress levels in almost unconfined conditions.

Shariatmadari *et al.* (2009) analyzed the results obtained from drained and undrained triaxial tests and concluded that the compressibility of the MSW particles leads to a contact area that is not negligible compared to the total cross section area of the samples, which is the most important assumption of Terzaghi's effective stress equation. According to the authors, instead of the effective stress equation proposed by Terzaghi, Eq. (2) originally proposed

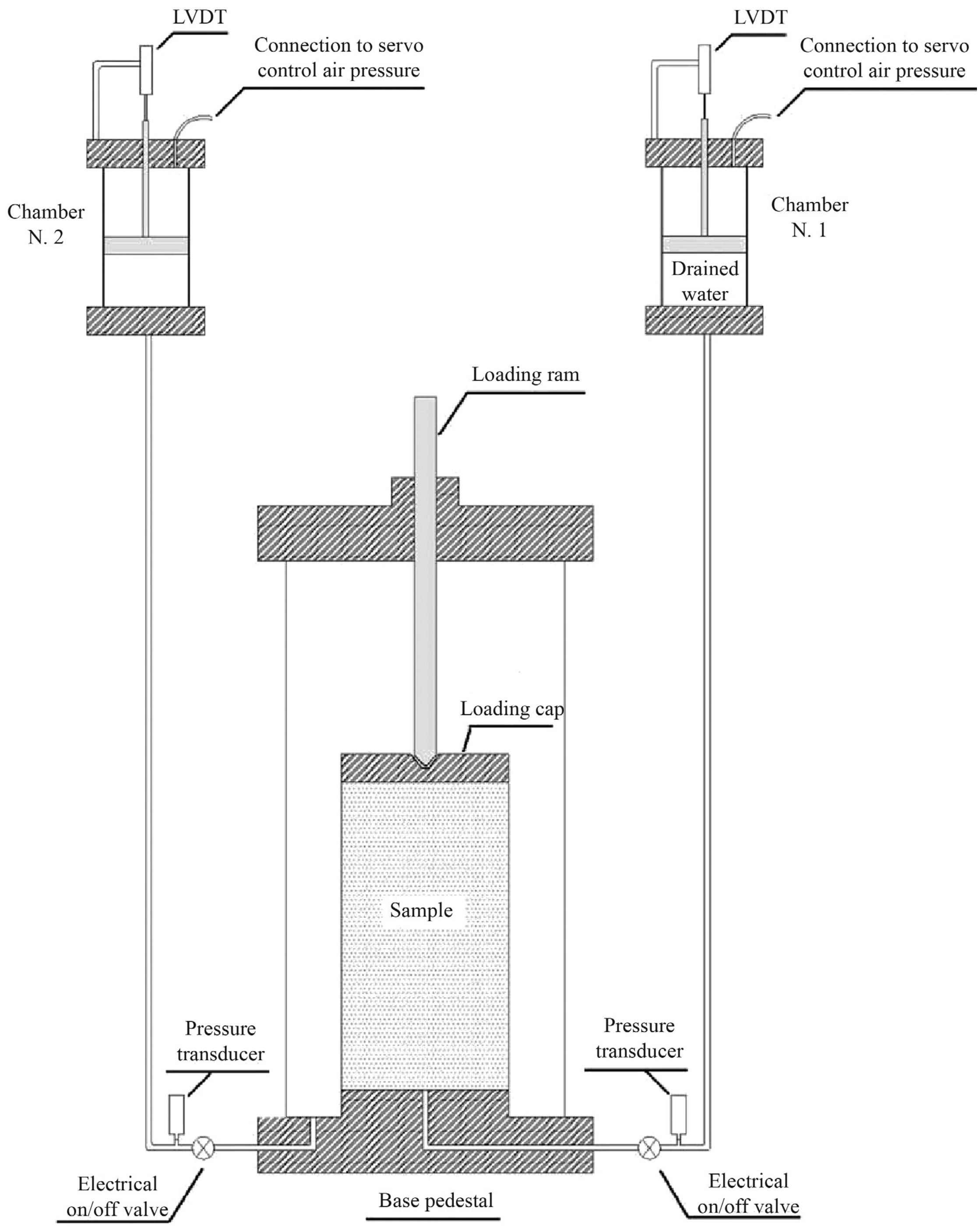

Figure 6 - A schematic view of triaxial apparatus used.

by Skempton (1961) should be used when analyzing the undrained behavior of MSW:

$$\sigma' = \sigma - Au \qquad (2)$$

where σ' and σ are the effective and total normal stresses. *A* is the pore pressure (*u*) reduction coefficient, a function of the ratio between the compressibility of MSW particles and the compressibility of the MSW as a whole (Eq. (3)).

$$A = 1 - \frac{C_s}{C} \qquad (3)$$

where C_s is the compressibility of the waste particles and C is the compressibility of the waste as a whole.

Figure 9 shows the variation of A with mean pressure (*p*) for MSW samples with different fiber contents. According to Shariatmadari *et al.* (2009) the use of the *A* factor to

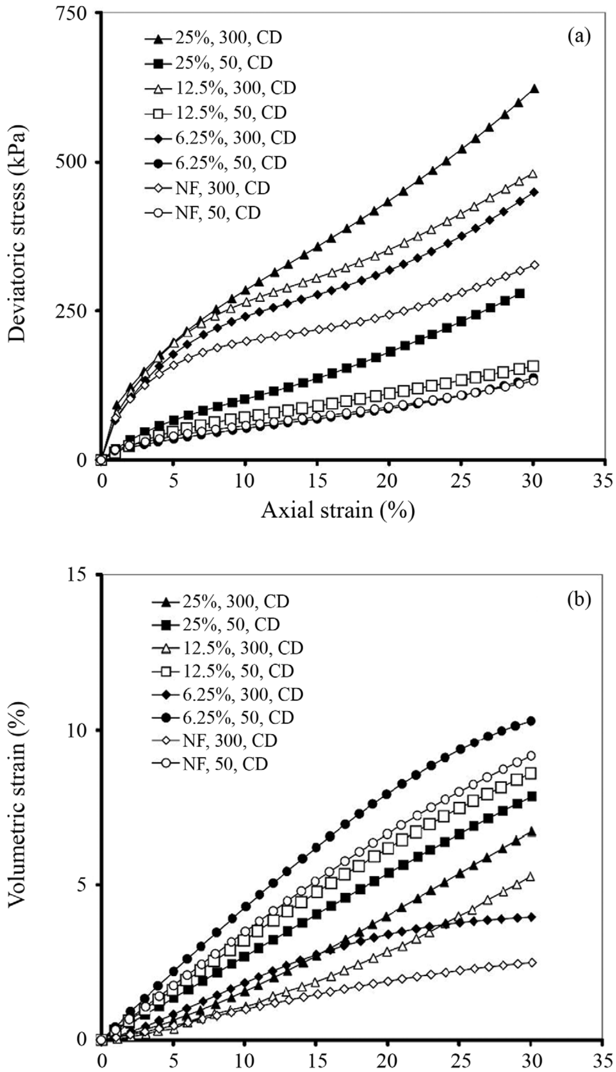

Figure 7 - Typical CD triaxial test results.

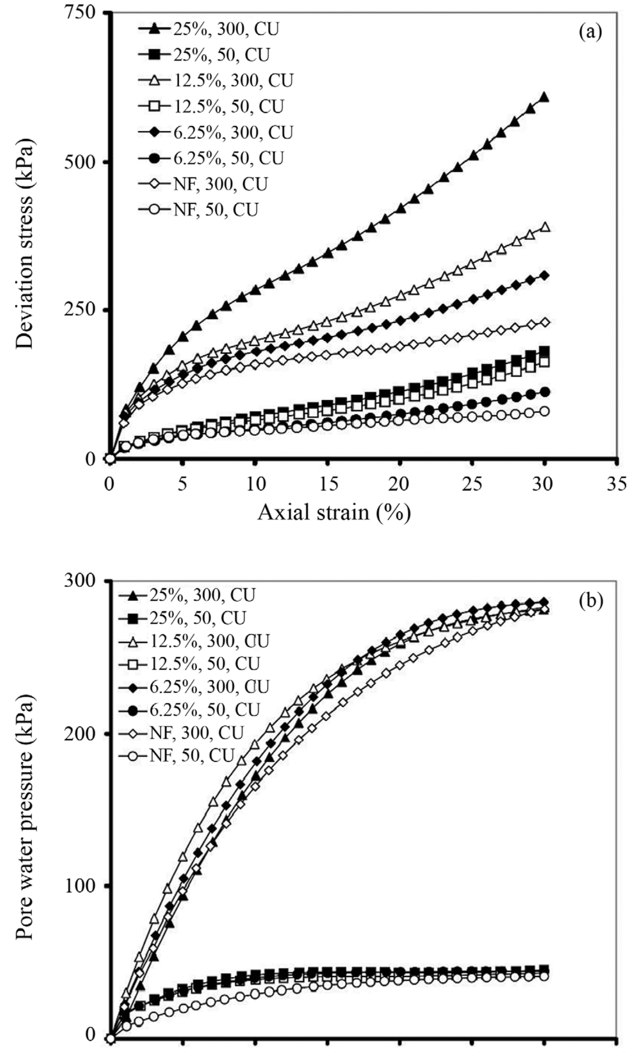

Figure 8 - Typical CU triaxial test results.

compute the pore water pressure contribution in the effective stress equation resulted in a signicant improvement in the compatibility between the effective parameters obtained from CU and CD tests.

Figure 10 presents the effective stress paths followed by the samples in CD and CU tests. In the case of the effective stress paths obtained in CU tests, two equations were used for effective stress calculation: one is the classic Terzaghi equation ($A = 1$) and the other is Eq. (2) ($A < 1$).

To evaluate the effect of the fiber content on the MSW shear strength parameters, the results were analyzed using the Mohr-Coulomb shear strength envelope. Because of the strain hardening nature of MSW (it was not possible to detect any trend of failure in the performed tests) the shear strength parameters were calculated for axial strain values of 5, 10, 15 and 20%.

The use of the Mohr-Coulomb shear strength envelope in MSW materials is a controversial. As presented by

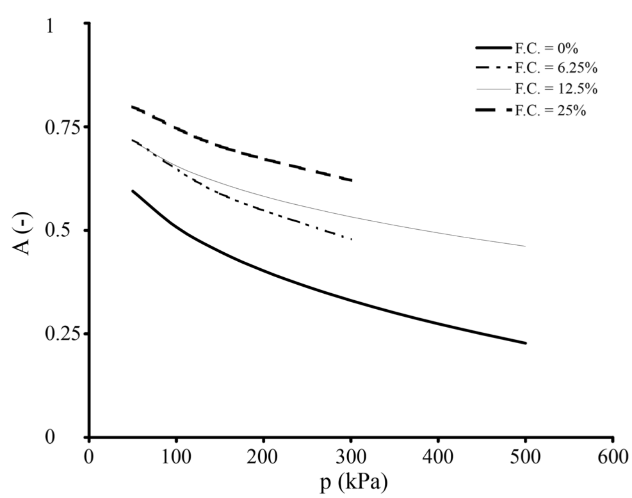

Figure 9 - Values of A parameter for varying fiber contents and mean stress.

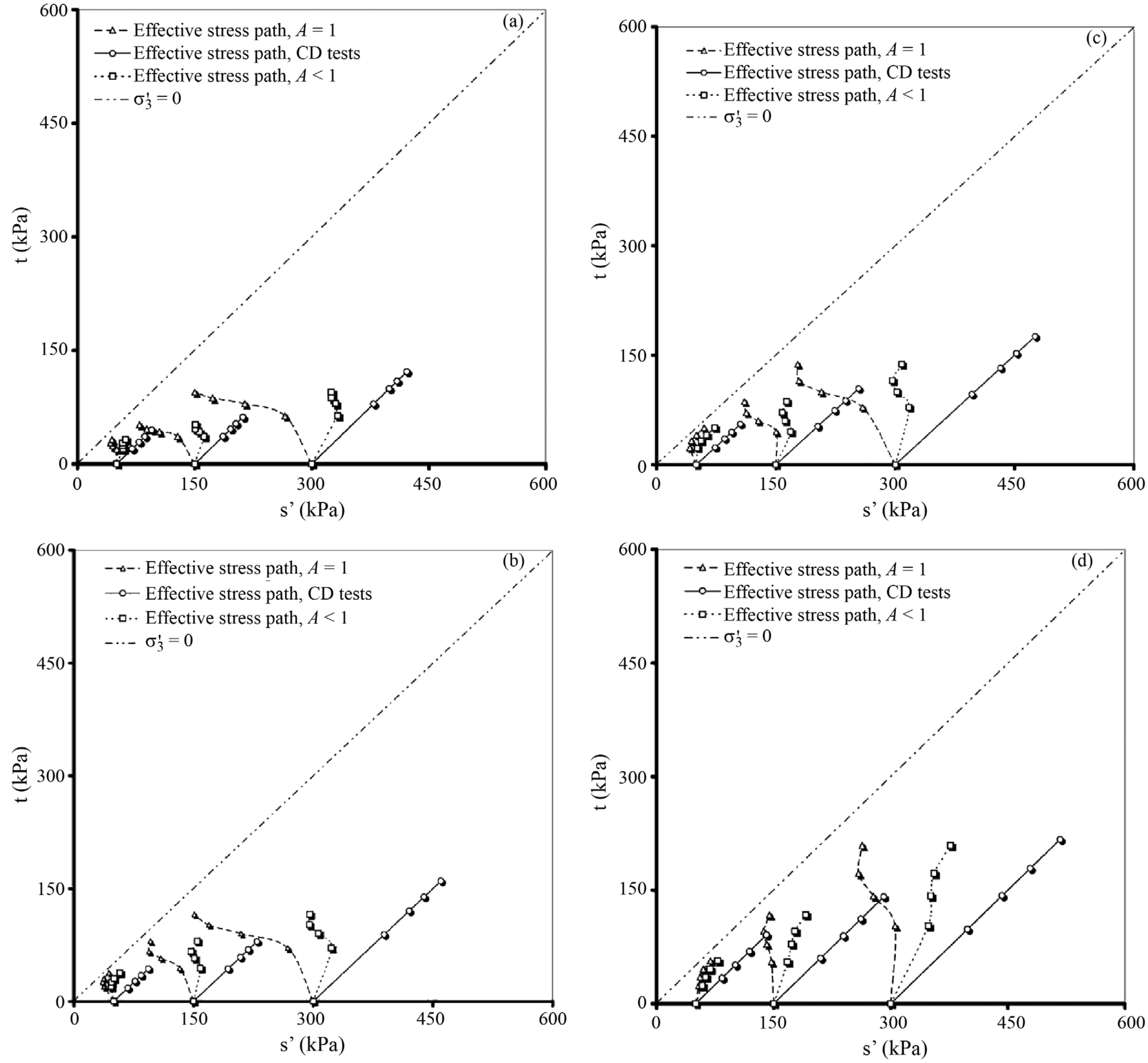

Figure 10 - Stress path of MSW samples with varying ber content (a) 0%, (b) 6.25%, (c) 12.5% and (d) 25%.

Machado *et al.* (2002) and Machado *et al.* (2008), MSW short and long term mechanical behavior can be modeled as a composite material of two phases each with its own constitutive model. However, the use of such complex elasto-plastic models is not possible in most of the available commercial slope stability software and these models require a number of parameters which is not usually available in the field. Besides this, the capacity of landfill structures such as gas and leachate collection systems and cover layers to sustain horizontal and vertical displacements without losing serviceability can be used to define maximum strain levels and thus makes it possible and defensible to use the Mohr-Coulomb shear strength envelope in slope stability analysis in landfills.

Figure 11 presents the shear strength envelopes for each fiber content and drainage condition adopted in the experimental program (20% of axial strain). Tables 3 and 4 present the obtained MSW friction angle and cohesion intercept for the different levels of axial strain. Figure 12 summarizes the obtained results graphically.

As can be noted, there are different patterns of shear strength mobilization in the CU and CD tests. In the case of the CD tests, Fig. 12b and Table 4, fiber content affects cohesion intercepts much more than friction angles. Despite the 6.25% fiber content there is a decrease in the obtained value of cohesion. After 6.25% the effect of the fiber content on the friction angle seems negligible.

Table 3 - Evolution of the MSW shear strength parameters with axial strain for different fiber contents. CU tests.

Axial strain (%)	Fiber content (%)							
	0		6.25		12.5		25	
	ϕ	C (kPa)	ϕ	C (kPa)	ϕ	C (kPa)	ϕ	C (kPa)
5	9	9	10	9	10	10	14	6
10	11	9	12	12	12	16	17	10
15	11	11	13	15	13	20	20	14
20	12	14	14	21	15	26	22	17

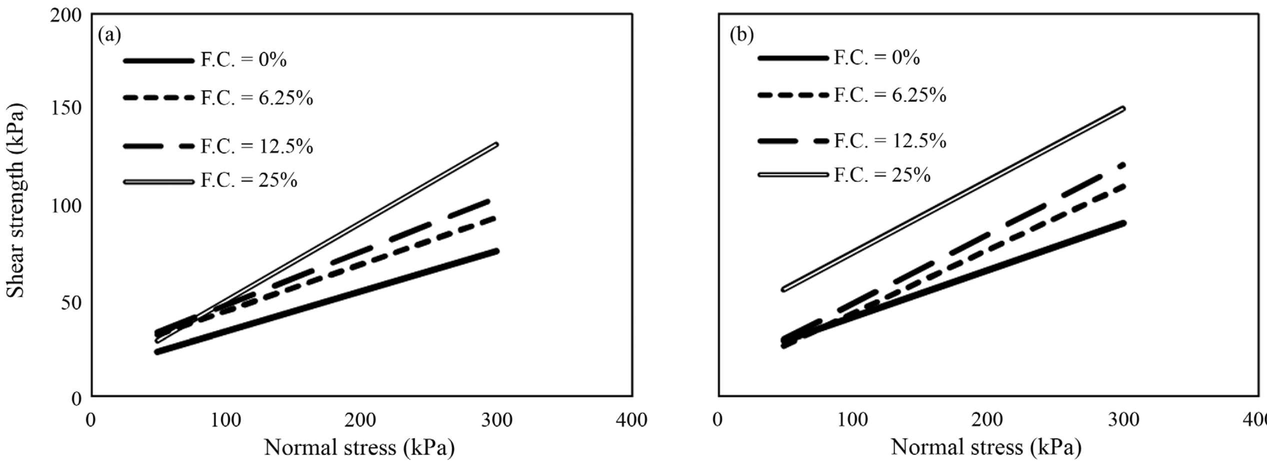

Figure 11 - The effect of the fiber content on the shear strength (a) undrained conditions (b) drained conditions.

In the case of CU tests, there is a monotonic increase in the friction angle with fiber content and the effect of the fiber content on the cohesion intercept seems to reach a maximum for a fiber content of 12.5%. One of the possible reasons for such behavior must be related to the high values of pore water pressure generated during the shear phase, which tends to reduce the anchoring conditions of the fibers inside the samples.

Figure 13 compares the effective stress results from CU and CD tests using Eq. (2) and Terzaghi's equation. In order to do this, shear strength envelopes were calculated for various levels of axial strain and fiber contents as well. Using the obtained shear strength envelopes and a 50 kPa of normal stress increments, shear strength ratios (β) for samples with the same fiber content were calculated as follows:

$$\beta = \frac{\tau_p}{\tau_r} \tag{4}$$

where τ_r is the shear strength based on stress analysis of CD test results and τ_p is the shear strength based on effective stress analysis of CU tests.

The log normal distribution was used to perform a statistical analysis of the β values. The mean (μ) and standard deviation (σ_β) were evaluated using the natural logarithm of strength ratio as follows:

Table 4 - Evolution of the MSW shear strength parameters with axial strain for different fiber contents. CD tests.

Axial strain (%)	Fiber content (%)							
	0		6.25		12.5		25	
	ϕ	C (kPa)	ϕ	C (kPa)	ϕ	C (kPa)	ϕ	C (kPa)
5	11	4	13	2	13	7	12	17
10	13	8	16	4	16	12	16	25
15	13	13	17	8	18	17	18	34
20	14	18	19	11	19	22	20	46

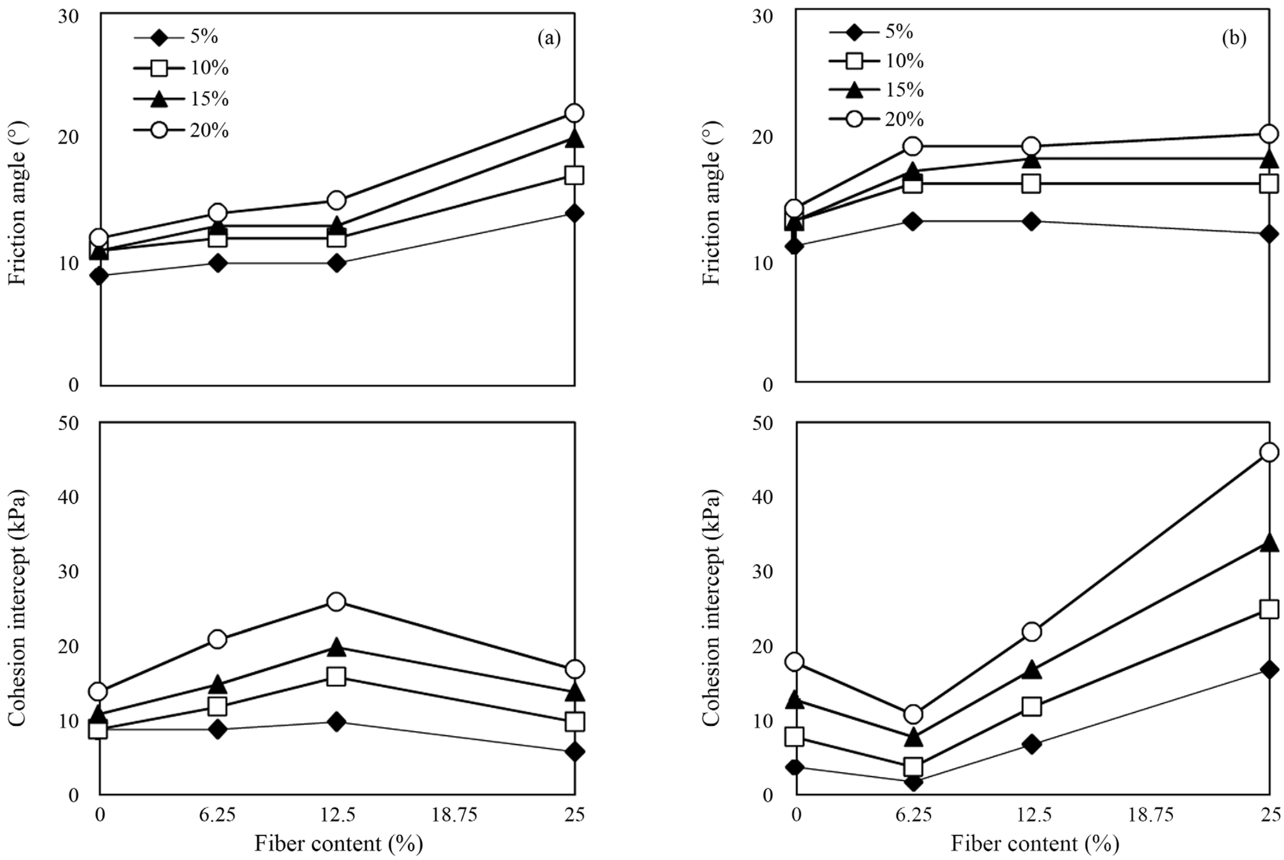

Figure 12 - Variation of shear strength parameter of MSW materials with varying fiber contents (a) undrained conditions (b) drained conditions.

$$\mu = \frac{1}{n}\sum_{i=1}^{n} \ln \beta_i \tag{5}$$

$$\sigma_\beta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (\ln \beta_i - \mu)^2} \tag{6}$$

the Log Normal distribution of the β values is given by

$$f(\beta) = \frac{1}{\sqrt{2\pi}\,\sigma_\beta\,\beta} \exp\left(-\frac{1}{2}\left(\frac{\ln(\beta)-\mu}{\sigma}\right)^2\right) \tag{7}$$

The function above produces a bell shaped distribution with a constant area, therefore increasing the peak value of $f(\beta)$ implies reducing the width and as a result the scatter of the prediction is lower. If the peak length is equal to 1, this means that the average value of shear strength is equal to unity or the average error is zero. If the peak length is greater than 1, the effective shear envelope derived from CU tests leads to an over estimation of shear strength compared to CD ones and vice-versa.

As can be seen in Fig. 13, the error analysis performed using the results of effective stress from the CU tests and assuming the results of CD tests as a reference showed that ignoring particle compressibility could cause an overestimation of up to 50% in the shear strength of MSW. Using Eqs. (2) and (3) this error was reduced to less than 15%.

In this paper, effective stress parameters were obtained using the results of CD tests. Although not the case in this paper, in the absence of CD tests, the authors suggest the use of Eq. (2) in order to obtain effective shear strength parameters from CU tests. The use of Terzaghi's equation may lead to an unacceptable overestimation of the MSW shear strength.

For illustrative purposes, some slope stability calculations were carried out to verify the effect of the fiber content on the factor of safety (FS) of some hypothetical slopes. The authors believe that this kind of information is worthwhile for designers as a preliminary approach to evaluate the effect of fiber removal on the MSW shear strength parameters and on the slope factor of safety. In this case only the shear parameters obtained for 20% of axial strains were used. Slopes were defined considering their height and inclination.

Due to the developments in computing, the use of several relatively new numerical methods for slope stability analysis are increasing in popularity. One such is the shear strength reduction technique (SSR). In this method, the factor of safety of one slope is computed by reducing the shear strength of soil, rock or any type of Geo-materials

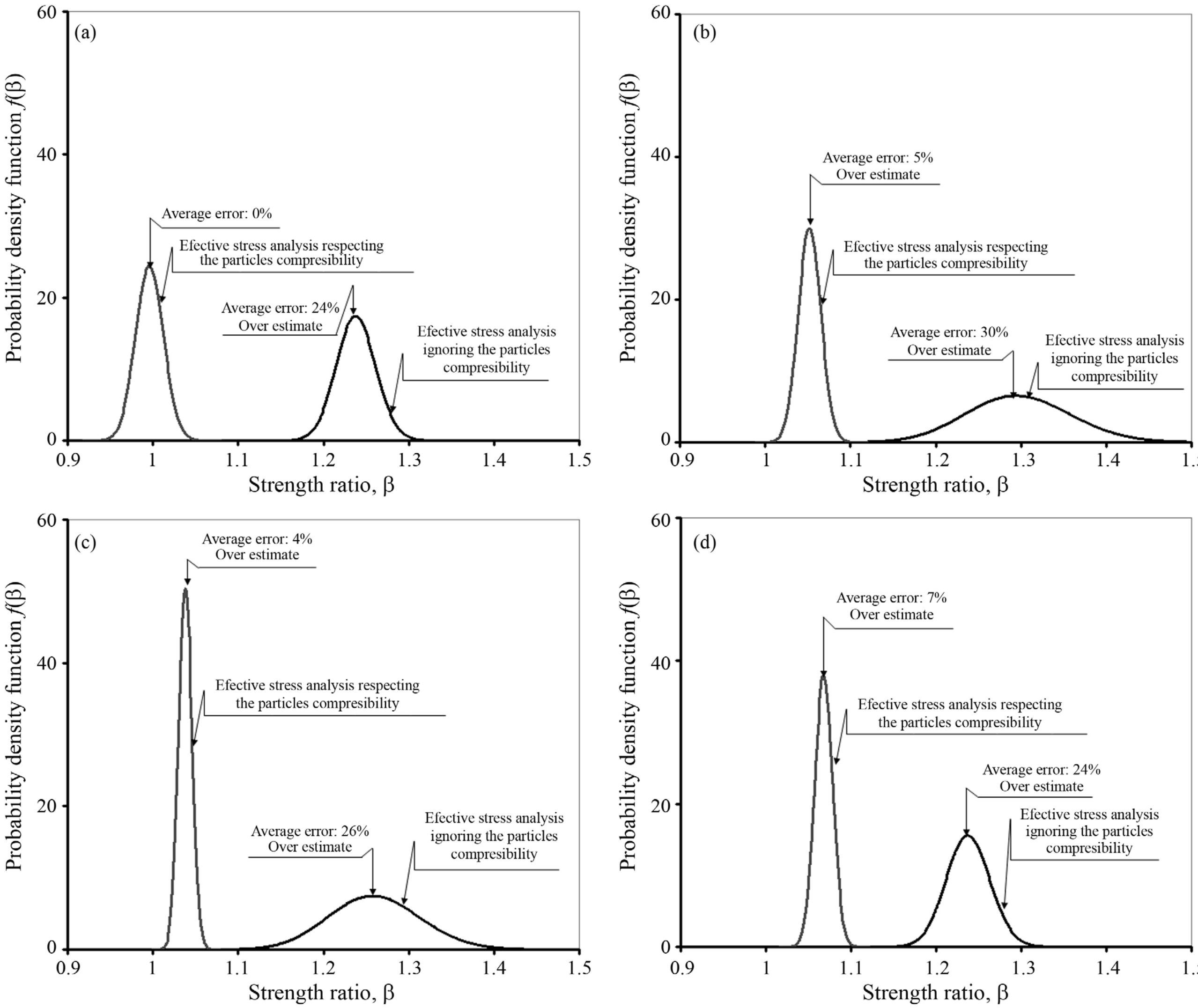

Figure 13 - Error analysis. (a) 0%, (b) 6.25%, (c) 12.5% and (d) 25% fiber content.

in stages, until the slope fails. For Mohr-Coulomb material shear strength is reduced by FS according to the equation:

$$\frac{\tau}{FS} = \frac{c'}{FS} + \frac{\tan(\varphi')}{FS} \tag{8}$$

Eq. (8) can be re-written as

$$\frac{\tau}{FS} = c^* + \tan(\varphi^*) \tag{9}$$

In this case, $c^* = c'/FS$ and $\phi^* = \arctan(\phi')/FS$ are the reduced Mohr-Coulomb shear strength parameters and these values can be input into an finite element or finite difference model and analyzed. For Mohr-Coulomb materials, the main steps for systematically searching for the critical FS, which brings a previously stable slope to the verge of failure, are described below:

Step 1: Develop a numerical model of a slope, using appropriated boundaries and the deformation and strength properties established for the slope materials. Run the model obtaining the values of stress and strain and recording the maximum total deformation in the slope.

Step 2: Increase the value of FS and calculate the reduced values of c’ and f ‘ as described above. Enter the new strength properties into the slope model and repeat Step 1.

Step 3: Repeat Step 2, using systematic increments of FS, until the numerical model does not converge with a solution (the displacement values become excessively high), *i.e.* continue to reduce material strength until the slope fails. The final FS value can be calculated as the one that leads to virtually infinite displacements. The FS steps must be reduced as the displacements become higher to approach an equilibrium limit situation.

The Finite Difference Method code FLAC (FLAC, 2000) enables the analysis of slope stability using the SSR technique. To evaluate the effect of fiber content on the slope stability using FLAC software, about 150 combina-

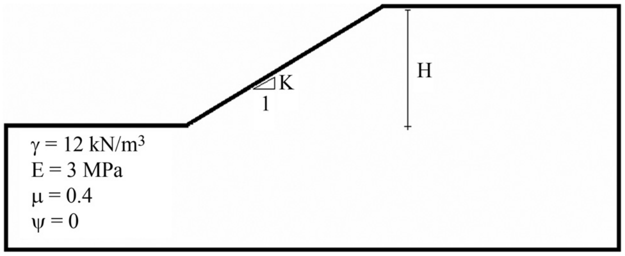

Figure 14 - Hypothetical slope section adopted for slope stability calculation.

tions of slope geometry and MSW shear strength parameters were used.

Figure 14 illustrates the general model of waste fill used for these analysis. It was assumed that the waste fill had been constructed on a foundation of waste materials of infinite depth (this is reasonable in the MCL case, as the cells are part excavated and part above the ground level). Besides this, critical surfaces (assumed as the regions of the mesh with higher displacements) were always located at shallow depths, passing near the toe of the slope. The model boundaries extend to the left and right far enough to have no effect on the values of the computed FS.

It was assumed that the leachate collection system works properly so that increasing levels of leachate (or gas pressure) inside the fill is not a matter concern. The authors believe that these are reasonable assumptions only in well managed landfills with the use of a compatible number of deep and superficial gas drains and an efficient leachate collection system. In slope stability analysis of waste fills, the authors suggest that the use of undrained parameters must be considered only in the absence of gas pressure or leachate level information.

According to the discussion presented above, only the results of the CD tests were used in the performed calculus. As said above, other values of strain may be chosen by the staff responsible for the landfill management, considering the interactions between the waste mass and the cover layer, drainage system, etc. Values of k were chosen in order to cover MSW slope inclinations normally found in the field for new and old MSW slopes. In the same way values of H cover most of the situations found in Brazilian landfills.

Table 5 presents the FS factors calculated by the software for various geometry and strength conditions. As can be observed, although most FSs are relatively high, there is a clear increase in FS values as the fiber content increases. The only exception occurs when comparing the results of the material without fibers with the results of the material with a fiber content of 6.5% for low slope heights. This can be explained by observing Figure 7 and Table 4. Samples without fibers presented higher cohesion and consequently higher shear strengths for low levels of confining stress. This is possibly due to this fact that in the absence of plastics, samples compact better (higher densities) resulting in better interlocking between particles which cause a higher strength at lower confining pressures.

In Table 5 FS values lower than 1.6 were highlighted in order to make clear that these values are considered unsatisfactory by the authors to guarantee to the overall stability of the MSW mass.

Fig 15 presents some charts with the variation of FS as a function of the slope height and fiber content.

4. Conclusions

The fibrous components of MSW play a key role in its mechanical behavior. The reinforcement action of these components and their effect on the shear strength is the main reason why the MSW shear-strain curves are concave upward and do not show evidence of failure even under high levels of stress and strain. Most of the fiber elements inside the MSW materials are plastics and most of these are plastic bags used by the population to provisionally store their MSW until it is collected by the refuse collection services from their residences.

The results clearly show that with increasing fiber content and/or plastic content the shear strength of MSW materials increases. This finding is compatible with the re-

Table 5 - Factor of safety of slopes with varying geometry and strength.

Fiber content (%)	*k*	*H* (m)						
		5	7	10	12.5	15	17.5	20
0	1	2.35	1.92	1.41	1.21	1.08	0.99	0.91
	2	2.94	2.33	1.86	1.64	1.49	1.37	1.28
	3	3.42	2.76	2.26	2.01	1.84	1.71	1.62
	4	3.90	3.17	2.63	2.38	2.19	2.06	1.96
	5	4.26	3.54	2.97	2.71	2.52	2.38	2.27
6.25	1	1.84	1.42	1.20	1.06	0.96	0.89	0.83
	2	2.49	1.99	1.72	1.56	1.44	1.36	1.29
	3	3.09	2.52	2.21	2.02	1.89	1.79	1.72
	4	3.58	2.97	2.69	2.48	2.34	2.23	2.15
	5	4.01	3.40	3.07	2.85	2.71	2.60	2.52
12.5	1	3.08	2.26	1.85	1.60	1.38	1.26	1.17
	2	3.83	2.92	2.45	2.16	1.96	1.81	1.70
	3	4.47	3.84	2.97	2.66	2.44	2.28	2.16
	4	5.05	4.03	3.49	3.16	2.93	2.75	2.62
	5	5.58	4.53	3.97	3.62	3.36	3.19	3.04
25	1	5.53	3.92	3.12	2.63	2.31	2.08	1.90
	2	6.56	4.53	3.92	3.62	3.01	2.76	2.53
	3	7.14	5.50	4.72	3.99	3.60	3.26	3.09
	4	8.05	6.13	5.38	4.72	4.49	3.84	3.61
	5	8.51	6.82	5.80	5.15	4.70	4.38	4.11

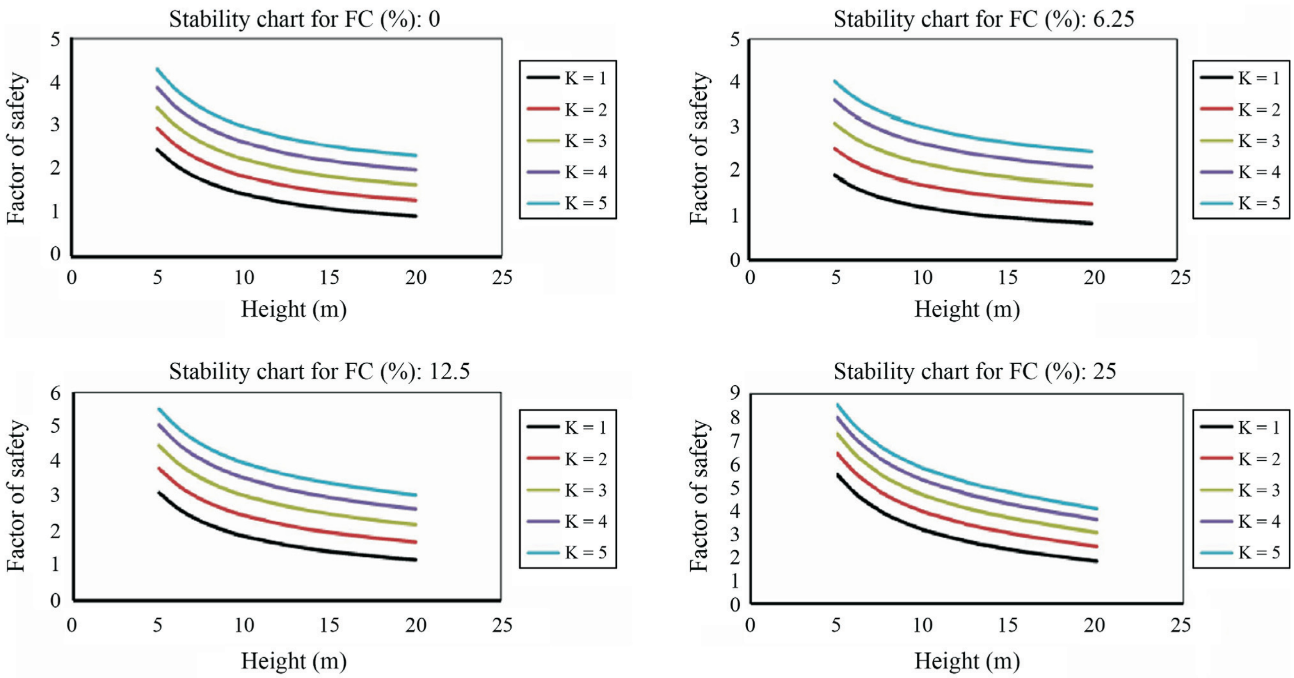

Figure 15 - Stability chart of slopes with varying geometries and fiber contents.

sults of the constitutive model presented for MSW materials by Machado *et al.* (2008) and Machado *et al.* (2002) and many other authors in the technical literature (Zekkos 2005, Georgiopoulos 2005, Athanasopoulos *et al.* 2008).

The error analysis performed using the results of effective stress from CU tests and assuming the results of CD tests as a reference showed that ignoring particle compressibility could cause an overestimation of up to 50% in the shear strength of MSW. Using Eqs. (2) and (3) this error was reduced to less than 15%.

The results of waste fill stability analysis have shown that decreasing the MSW fiber content the Factor of Safety also decreases. For a height of 20 m, reducing the fiber content from 25% to 0% results in a decrease in the Factor of Safety from 2.53 to 1.28, considering a slope of 1:2. For a slope of 1:3, these values change from 3.09 to 1.62.

Finally, there is a a new trend to recycle plastic material for energy recovery purposes instead of landfilling. The staff responsible for landfill management must be aware that this practice will imply a reduction in the storage capacity of the landfill in order to preserve adequate levels of security.

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List of Symbols

A – Pore water pressure reduction factor
B – Skempton pore water pressure parameter.
c' - MSW effective cohesion
c^* - MSW reduced or mobilized cohesion
C_s - Compressibility of the MSW the waste particles
C - Compressibility of the waste as a whole
CD – Consolidated Drained
CU – Consolidated Undrained
E – Modulus of elasticity
F.C.- Fiber Content
FS – Factor of Safety
H - Slope heigh
k - Slope inclination
MSW – Municipal Solid Waste
p - Mean normal stress
SSR – Shear strength reduction technique
TX – Triaxial Test
β - Shear strength ratio
μ - Mean of the natural logarithm values of β
σ_β - Standard deviation of the natural logarithm values of β
γ_0 - Initial density of the samples
ε_a - axial strain
ε_r - radial strain
σ_v - volumetric strains
σ_3 - Consolidation pressure
υ - Poisson coefficient
ϕ'- MSW effective friction angle
ϕ^* - MSW reduced or mobilized friction angle
τ - Shear strength, shear stress.
τ_r - Shear strength based on stress analysis of CD test results
τ_p - Shear strength based on effective stress analysis of CU tests
σ' - Effective normal stresses
σ - Total normal stresses