Determination of shear strength of MSW. Field tests vs. laboratory tests.

Détermination de la résistance au cisaillement des déchets urbains (MSW). Essais in situ *vs* essais de laboratoire.

Cañizal J., Lapeña P., Castro J., Costa da A., Sagaseta C.
University of Cantabria. Santander, Spain

ABSTRACT: The knowledge of the mechanical properties of MSW has many implications on landfill design. The shear strength of the wastes determines the inclination to be given to the landfill slopes, which in turn governs the landfill capacity.
The measurement of these properties is not an easy task. Different approaches are possible. Conventional geotechnical laboratory tests face two main problems: the lack of representativeness of the samples, and the environmental difficulties associated to testing these materials in laboratories usually placed in general use buildings (odour problems). Due to these limitations, the number of published results is relatively short. The use of in situ tests has become an attractive alternative, because it eliminates the above two problems. However, the interpretation of these tests is based on the experience with conventional geotechnical materials (soils, rocks, compacted fills), but MSW have a different behaviour, with a seemingly unlimited strain, and no definite "failure" in most cases. A third approach is the back-analysis of the monitored behaviour of actual landfills. Some of these cases have been published, and even some compilations are available.

RÉSUMÉ : La connaissance des propriétés mécaniques des déchets urbains (MSW) a de nombreuses implications quant à la conception d'une décharge. La résistance au cisaillement des déchets détermine l'inclination des talus, qui se répercute sur la capacité de la décharge.
La détermination de ces propriétés n'est pas facile, différentes approches sont possibles. Les essais conventionnels de laboratoire présentent deux problèmes : le manque de représentativité des échantillons et les difficultés associées aux aspects environnementaux du fait que les laboratoires sont généralement situés dans des bâtiments à usage général (problèmes olfactifs). À cause de ces limitations, le nombre de résultats publiés dans la littérature est relativement faible. La pratique d'essais in situ est devenue une alternative intéressante, car elle élimine les deux problèmes ci-dessus. Cependant, l'interprétation de ces essais est basée sur l'expérience tirée des matériaux géotechniques conventionnels (sols, roches, remblais compactés), mais les déchets ont un comportement bien différent, avec une déformation apparemment illimitée et sans indice précis de "rupture". Une troisième possibilité repose sur l'analyse inverse du suivi de cas réels instrumentés. Quelques cas ont été publiés, et certaines compilations sont disponibles.

KEYWORDS: MSW, municipal solid wastes, landfill, site exploration, mechanical properties, shear strength.

1 INTRODUCTION

The stability of a landfill relies on the shear strength of its elements. It depends on the characteristics of the waste materials disposed in it, as well as in the characteristics of the materials that form the protection, isolation and sealing layers. As far as the waste material is concerned there are several factors influencing the strength characteristics such as composition, age, confining pressure, details of landfill operation, existence of soil layers as waste cell coverage, etc. In any case the shear strength of the wastes determines the inclination to be given to the landfill slopes, which in turn governs the landfill capacity. The necessity of establishing berms at mid-height of the slopes has also an important role in the capacity.

Municipal Solid Wastes (MSW) have some special characteristics making a clear distinction with soils in terms of behaviour. However, in landfill stability analyses the behaviour of MSW is usually based on models derived from soils, mainly the Mohr-Coulomb failure criterion, defined by two parameters: cohesion (c) and friction angle (ϕ).

Strength parameters of MSW can be obtained testing samples in the laboratory or conducting in-situ tests. In addition to these methods there is also a third way to obtain parameters using back-analysis of real scenarios, most of the times from landfill failure cases.

Both laboratory and in-situ tests, in their different variations, have several advantages and disadvantages, due to that, a pros-and-cons analysis of the different methods using the existing bibliography was conducted, considering their methodology, operative issues, reliability and repeatability of the results to determine the test procedure that fits best to our purposes.

2 OVERALL STRENGTH CHARACTERISTICS OF MSW

MSW show some overall strength characteristics that are reflected in almost all the existing bibliography. They can be summarized as follows (Bray et al., 2009; Stark et al., 2009):

- As a general trend, MSW shear strength increases with the average confining pressure in a nonlinear way, and the slope of the shear strength envelope decreases with the level of normal stress. For very low confining pressure, there is some strength provided by the fibrous material contained in the waste, giving rise to an equivalent cohesion.
- Fitting this non-linear strength envelope with a linear Mohr-Coulomb criterion line must be done for the range of interest of normal stress, and the values of frictional angle and cohesion have to be defined accordingly.
- Test results are influenced by test conditions and sample preparation.
- Within the usual ranges, variations in density do not produce large changes in MSW strength.
- Degradation and aging seem to have an important effect on the shear strength, decreasing the cohesive term and increasing the friction.

- The shear stress-strain curve of the MSW shows a noticeable hardening (Grisola et al., 1996; Jessberger et al., 1993; Eid, 2000; Zhan et al., 2008), and a horizontal asymptotic level is not reached even with large deformations. So it is necessary to define a certain level of deformation in which it is assumed that the failure situation is being reached.

3 METHODS FOR OBTAINING MSW STRENGTH

The methods for obtaining cohesion and frictional angle parameters can be grouped in three kinds: laboratory test, in-situ test and back-analysis of actual failures.

3.1 Laboratory tests

3.1.1 Sample conditions

Although laboratory tests are the most direct method for obtaining the strength parameters of a material, they show several problems that make difficult both their usage and the subsequent interpretation when working with MSW.

The first problem is to find representative samples. Samples obtained in the same landfill show a large dispersion in composition due to the heterogeneity of the waste mass. Some research has been done on “synthetic” samples, reconstituted with the average composition of the MSW mass in the landfill region or country (Sivakumar Babu et al., 2010).

On the other hand, among the MSW there are elements with a medium to large size. So it is necessary to take large samples, this is quite easy for MSW that have just arrived to the landfill, or for recently disposed and superficial waste, but makes it necessary to bore large diameter bore-holes (over 760 mm in diameter) (Bray et al., 2009) for deep waste.

It is very hard to take undisturbed samples from MSW, particularly at great depth. Densification is produced during the sampling process due to the large deformability of MSW. Because of the low cohesion, the loose nature of the material and the differences in size and stiffness among the different constitutive elements, alterations and collapses are produced during the sampling and trimming operations.

For these reasons, tests are made using samples prepared and compacted to in-situ density and moisture content, and with the prevailing composition. The uncertainties associated to these conditions make that this procedure can be only considered as an approximation of actual landfill conditions. Besides, the elements with a size over 1/5-1/10 of the minimum size of the specimen to test, usually fibrous materials such as paper, plastic, wood or metallic pieces, have to be removed or cut to fit this size in order to not interfering with the movement of the test equipment invalidating the results obtained. Furthermore, the tensile strength of fibrous elements introduces an anisotropic behaviour, making the strength obtained in the test depend on the preferred direction of the fibres (Bray et al., 2009).

3.1.2 Test types

The tests used to obtain strength parameters are direct shear, triaxial and simple shear tests.

From 23 research works revised by Stark et al. (2009), dated from 1990 to 2005, 48% used laboratory direct shear tests, 22% triaxial tests, and just one simple shear tests. The rest of them are in-situ direct shear tests. Recently, Bray et al. (2009) have presented the results of simple shear tests on 400x300 mm rectangular samples.

In general test specimens have a relative large size. It is frequent for the direct shear test probes to have a length of 300 millimetres or more and using triaxial specimens with over 200mm in diameter. Besides, the test equipment has to be prepared to provide large deformations. This circumstance is stated on plenty of the revised researches, and makes it necessary to modify the original design of the equipment.

3.1.3 Other aspects

In tests on MSW samples, the applied shear stress increases monotonically with deformation, and in most cases a maximum or asymptotical value is not reached even with the application of large displacements. The plots shown in Figures 1 and 2 belong to a compilation of results from several authors made by Stark et al. (2009). It is shown that shear stress does not grow only with the applied normal stress, but it also increases with the deformation or the displacement reached. Those authors attribute this behaviour to the reinforcement action of the wastes’ fibrous elements when deformation increases.

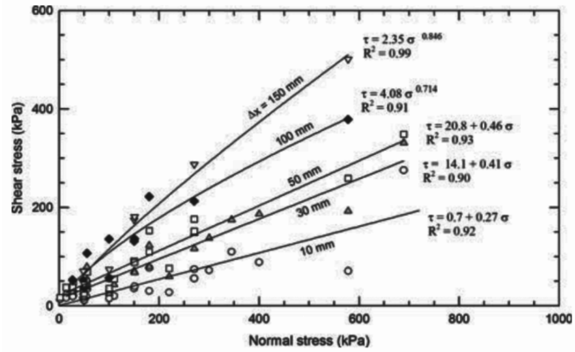

Figure 1. Summary of direct shear lab tests (Stark et al., 2009)

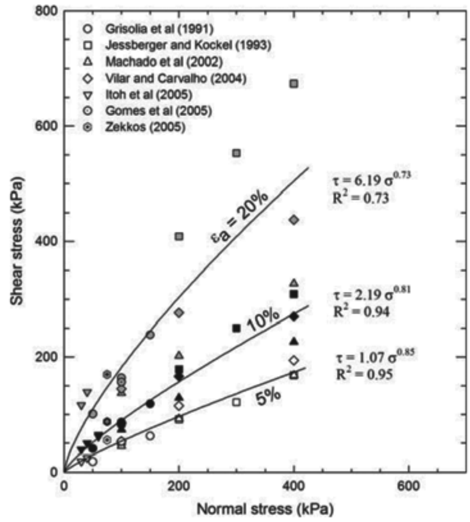

Figure 2. Summary of triaxial lab tests (Stark et al., 2009)

It has to be taken into consideration that in regular landfill operation the possible deformation is much smaller than during a test. Movement compatibility between MSW and the more rigid sealing layers, and also with the deformation limit of draining elements, gas evacuation elements, etc., limits waste deformation to acceptable levels, forcing the definition of strength parameters to an imposed deformation value (Machado et al., 2002).

The environmental conditions where the laboratory tests are conducted are problematic because of the odour and the hazardous sample management, making necessary to fit out a specific area, isolated from the rest of the laboratory. In some research it is necessary to carry out most of the tests in facilities belonging to the landfill grounds.

The difficulty in obtaining truly representative samples and test environmental conditions affects negatively to the possibility to undertake systematic shear strength laboratory test campaigns. The revised bibliography shows that there are a scarce number of tests executed for the amount of means mobilized (Bray et al., 2009, Sivakumar Babu et al., 2010).

3.2 In situ tests

3.2.1 Comparison with laboratory tests

In-situ tests are an alternative to the execution of laboratory tests on landfill samples. With in-situ tests there is no need to take and manipulate samples, with the subsequent alteration, very high when dealing with MSW. In-situ tests are made over the material in real conditions, not in a simulated laboratory scenario.

Besides, scale is larger in field tests, affecting more material. This bigger scale reduces the influence of MSW heterogeneity, making possible to take into consideration medium to large fibrous elements. However, these advantages over laboratory tests bring some additional problems:

- Although the alteration produced by taking the sample is removed, effects produced by the installation of the testing elements appear.
- Field tests control (stress state, displacements, drainage) is lesser than in laboratory tests.
- Even though the area affected by field tests is larger than the regular specimen size, scale problems are still present.
- Results obtained from some in-situ tests cannot be analysed using theoretical models to obtain strength parameters, the only way to obtain them are using empirical correlations.
- Interpretation complexity is higher for in-situ tests in comparison with those conducted in a laboratory. If the theoretical model depends on two or more parameters, like Mohr-Coulomb failure criterion, it is only possible to obtain the relationship between them. This implies that only a curve for different possible values for cohesion and frictional angle can be obtained.

In any case, most of the in-situ test procedures are quite fast and economical, making possible to execute multiple tests in a reasonable period of time and covering a large volume of material, which is a clear advantage over laboratory tests.

3.2.2 Test types

The in-situ tests commonly used in MSW are: penetration test, plate loading tests, pressuremeter tests and in-situ shear tests.

Penetration tests, both dynamic (DPSH, DPH, SPT) and static (CPT, CPTU) provide an index value for MSW strength, and from these indexes it is possible to empirically obtain strength parameters and other characteristics. Their main advantages are their easy usage and their low time and means consumption, as well as the possibility to check different penetrations in time and space to establish tendencies for the variation of the resistance to penetration.

Use of penetration test for landfill characterization is frequent, being one of the pioneers Sowers (1968) who used dynamic tests. The University of Cantabria (UC) Geotechnical Group has researched about the strength characteristics of landfills using dynamic and static penetration tests (Palma, 1995; Sánchez et al., 1993). In a recent research, Zhan et al. (2008) used, among others, static penetrometers.

Furthermore, the interpretation of plate loading tests is not as straightforward as in soils, due to the heterogeneity of the landfill. It is advisable to use large diameter plates (>600 mm), which is feasible because there is no need to apply large loads in order to produce the needed deformations or even to reach failure due to the soft nature of the MSW.

Several researchers have used this method for deformability and strength characterization of MSW. The UC Geotechnical Group (Palma, 1995; Sánchez et al, 1993) used load plates, interpreting the results using a multi-layer model for MSW and covering layers. In some occasions the rigid plate has been replaced by a container full of material, achieving larger size but lower pressure.

Pressuremeter tests, both with previous borehole execution and using self-boring systems have been recently used in landfills (Dixon et al., 2006).

There are several experiences with in-situ shear tests using parallelepipedic and cylindrical samples with sizes of 500 mm and even 1m in landfills (Withiam et al., 1995; Caicedo et al., 2002).

3.3 Back-analysis of real failures

Failure back-analysis is a widely used method in geotechnical activity and can be easily extrapolated to the study of MSW shear strength (Huvaj-Sarihan and Stark, 2008).

However, this method faces also some uncertainties. First, generalized failure cases are not frequent, and in the few cases occurred it is difficult to detect the failure surface. Besides, failure generally affects to the bottom sealing layers and the foundation ground as well as to the waste mass itself. In other cases the situation analysed is far from failure so a safety factor greater than the unit has to be assumed with no precise justification. Furthermore, the values for material density and phreatic level position are not known exactly and must be estimated. In any case, if the Mohr-Coulomb failure criterion is used, the result of the analysis is only a relationship between cohesion and frictional angle as in some in-situ tests. Only in very few cases, the precise knowledge of the sliding surface position can provide some guidance about the relative ranges for the two parameters. Otherwise, the result is a line plotted in a c-ϕ diagram. This diagram must be used with care, because it does not mean that all the points on the line are valid, but instead, only one point is the correct result, but it is not possible to identify it within the whole line (Figures 3 and 4).

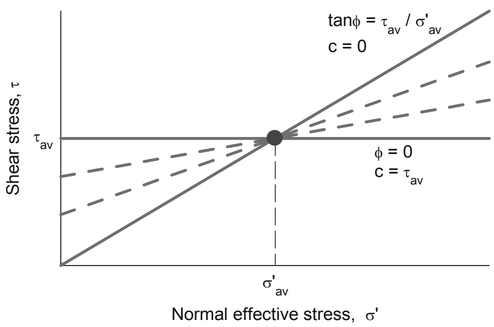

Figure 3. Mohr's plane of the results of a back-analysis

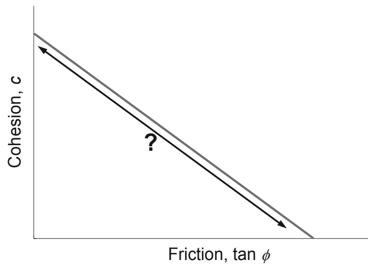

Figure 4. c-ϕ diagram of the results of a back-analysis

4 MOHR-COULOMB STRENGTH PARAMETERS PROPOSAL

Although the research in strength parameters dates back more than two decades, the special characteristics of MSW limit the obtained results. In several publications a compilation of parameter values is shown, but they do not only refer to test results, it also does to representative values deduced by the authors of other previous compilations and to values successfully used in particular cases of landfill design. Besides, the available results belong to different test type and methodology, carried out on MSW of different composition, age, density, etc. Furthermore, due to strain hardening behaviour, different values can be established for the same test according to the deformation level considered as critical.

Regarding the back-analysis of failures, the uncertainties commented above limit their use.

One of the first proposals was due to Singh and Murphy (1990), but with no attempt to reduce the wide ranges of cohesion and friction resulting from real failures.

Based on the limited data available at the time, Sánchez et al. (1993) proposed a joint consideration of the results of laboratory and in situ tests and back-analysis of failures. The first ones gave a set of pairs of values of cohesion and friction, increasing with the strain. The real failure cases help to identify the relevant strain level, and reciprocally, the lab tests help to identify the real c/ϕ ratio. In situ tests can also give information on that respect. The result is shown in Figure 5.

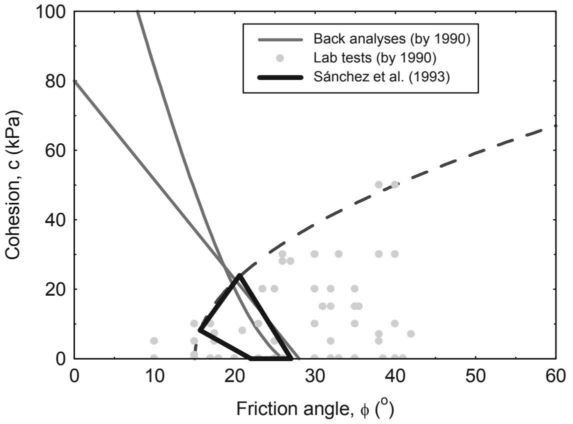

Figure 5. Strength parameters. Early design recommendations (Sánchez el al., 1993)

In the last two decades, some additional results have been published, from laboratory and in situ tests and from real failures (see, for instance, the compilation by Stark et al. (2009), among others). Considering these data, the recommended values in Figure 5 can be increased. Figure 6 includes the results of failures compiled by Stark et al. (2009), and their recommended values, based on the proposal by Eid et al. (2000).

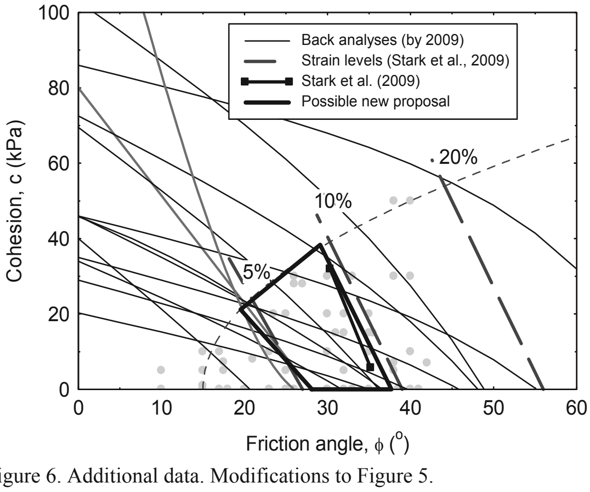

Figure 6. Additional data. Modifications to Figure 5.

5 CONCLUSIONS

Prior work has shown that it is no easy to obtain the mechanical properties of the waste mass.

After merging the data from the revision of existing bibliography and the experience of the U.C. Geotechnical Group, new research is being undertaken in order to establish a method to perform that task during the next three years. The study will be based on the use of field tests, complemented with medium to large scale laboratory direct shear tests. It will cover several landfills, with conventional MSW, together with wastes subjected to mechanical and biological pre-treatment (MBT), introduced in Spain in the last years (projects GEORES-03.2843.64001 and PROMERSU-BIA2012-34956).

The study will be performed in several landfills. In parallel with the test campaign, numerical modelling of the landfills under study will be undertaken to obtain feedback and refine the data acquisition process.

After all the data are gathered and the process is considered optimum, a method to obtain the mechanical properties of a landfill using field tests and a new proposal for the design strength parameters will be obtained as a result of the research.

6 REFERENCES

Bray, J.D., Zekkos, D., Kavazanjian, E., Athanasopoulos, G.A. and Riemer, M. F. 2009. Shear strength of municipal solid waste. *Journal of Geot. and Geoenv. Eng.*. ASCE 135(6),709-722.

Caicedo, B., Yamin, L., Giraldo, E. and Coronado, O. 2002. Geomechanical properties of municipal solid waste in Doña Juana sanitary landfill. *Proc. 4th Env. Geotechnics – 4th ICEG*, Rio de Janeiro 1,177-182.

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

Dixon, N., Whittle, R.W., Jones, D.R. V. and Ng'ambi, S. 2006. Pressuremeter tests in municipal solid waste: measurement of shear stiffness. *Géotechnique* 56(3),211–222.

Eid H, Stark T.D., Evans W.D. and Sherry P. 2000. Municipal solid waste slope failure I: Waste and foundation properties. *Journal of Geot. and Geoenv. Eng.*. ASCE 126(5),397-407.

Grisolia, M. and Napoleoni, X. 1996. Geotechnical characterization of municipal solid waste: choice of design parameters. *Proc. 2nd Int. Cong. on Env. Geotechnics*, Osaka, Japan 2,641–646.

Huvaj-Sarihan, N. and Stark, T.D. 2008. Back analyses of landfill slope failures. *VIth Int. Conf. on Case Histories in Geot. Eng. and Symp. in Honor of Prof. James K. Mitchell*. Paper 2.34.

Jessberger, H.L. and Kockel, R. 1993. Determination and assessment of the mechanical properties of waste materials. *Proc. Sardinia 93, 4th Int. landfill Symp.*, Cagliari, Italy,1383–1392.

Kavazanjian, E. 2003. Evaluation of MSW properties using field measurements". *Proc.17th GSI/GRI Conf.* Las Vegas, USA.74-113.

Machado, S. L., Carvalho, M.F. and Vilar, O.M. 2002. Constitutive Model for Municipal Solid Waste. *Journal of Geot. and Geoenv. Eng*. ASCE. 128(11),940-951.

Palma, J. 1995. *Comportamiento geotécnico de vertederos controlados de residuos sólidos urbanos*. PhD Thesis. Univ. of Cantabria.

Sánchez, J.M., Palma, J., Sagaseta, C. and Cañizal, J. 1993. Mechanical properties of wastes in a sanitary landfill. *Waste Disposal by Landfill. (R.W. Sarsby, ed.)*. Bolton, U.K. 357-364.

Singh, S., and Murphy, B. 1990. Evaluation of the stability of sanitary landfills. *Geotechnics of Waste Fills — Theory and Practice*, ASTM STP1070,240–258.

Sivakumar Babu, G.L., Reddy, K.R. and Chouksey, S.K. 2010. Constitutive model for municipal solid waste incorporating mechanical creep and biodegradation-induced compression". *Waste Management* 30,11–22.

Sowers, G.F. 1968. Foundation problems in sanitary landfills. *Journal of the Sanitary Div.*, ASCE 94(SA1),103-116.

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

Withiam, J.L., Tarvin, P.A., Bushell, T.D., Snow, R.E. and Germann, H.W. 1995. Prediction and performance of municipal landfill slope. *Proc. Int. Conf. Geoenv. 2000*, GSP46, ASCE, New Orleans, Lousiana, 2,1005-1019.

Zekkos, D., Athanasopoulos, G. A., Bray, J. D., Grizi, A. and Theodoratos, A. 2010. Large-scale direct shear testing of municipal solid waste. *Waste Management* 30(8-9),1544-1555.

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