RESPONSE OF MUNICIPAL SOLID-WASTE FROM TRI-CITIES LANDFILL IN TRIAXIAL COMPRESSION

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SUMMARY: Twenty-seven large-scale triaxial tests were performed on MSW from the Tri-Cities landfill, located in the San Francisco Bay Area. Factors that influence the stress-strain response of Tri-Cities MSW in triaxial compression were evaluated in the testing program. Emphasis was given to the influence of waste composition, which was found to have a significant impact in stress-strain response. The observed upward curvature of the stress-strain response and the continued increase in mobilized shear tress at very large strains in specimens composed of larger-sized particles is attributed to a fibrous reinforcement effect that is mobilized when the MSW is sheared at an angle to the preferred particle orientation. A limiting strain failure criterion of 5% strain from the K_o field consolidation condition is proposed as representative of the field conditions. Secant friction angles evaluated using this criterion ranged between 36 and 41 degrees for Tri-Cities landfill MSW in triaxial compression for confining pressure (σ_3) values up to 200 kPa but were found to reduce with increasing confining stress.

1. INTRODUCTION

The stress-strain response and shear strength of Municipal Solid Waste (MSW) is an important consideration in landfill design, particularly for the evaluation of the static and seismic stability of the landfill slopes. Large-scale laboratory testing results on in situ and reconstituted MSW are available in the literature and have been used to aid in the development of recommended MSW shear strength envelopes. For example, Kavazanjian et al. (1995) and the Eid et al. (2000) used in situ and laboratory direct shear test results in conjunction with back analyses of stable and failed MSW slopes to develop their recommended MSW shear strength envelopes.

Large-scale Triaxial Compression tests on MSW have been reported in the literature for more than 15 years. However, the use of these triaxial test results for development of MSW shear strength envelopes has been limited due to the relatively unusual characteristics of an upward curvature of the stress-strain response and the failure to reach peak shear stress conditions at large strains observed in many of these tests. The triaxial compression test results of Jessberger

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and Kockel (1993) and Grisolia et al. (1995) are two examples of this unusual stress-strain response. To the authors' knowledge, an adequate explanation for this atypical stress-strain response has not been provided. Due to this unusual response, a limiting strain criterion has traditionally been used to define the shear strength of MSW in triaxial compression. Depending on the strain criterion used, the resulting shear strength could be significantly lower, similar, or higher than the shear strengths recommended by Kavazanjian et al. (1995) and Eid et al. (2000) from direct shear tests and back analyses.

As part of a comprehensive collaborative investigation funded by the US National Science Foundation to study the factors that affect the static and dynamic properties of MSW, 27 large-scale (300 mm diameter) triaxial tests were conducted on reconstituted specimens. The testing program was designed to investigate the effects of waste composition, unit weight, confining stress, time under confinement, and loading strain. This paper summarizes and interprets the results of this testing program. Interpretation of the test results provide an explanation for observed unusual aspects of MSW triaxial compression response and resolves the apparent inconsistency between the MSW shear strength envelopes developed from triaxial compression tests and from direct shear tests and back analysis of field performance of waste slopes.

2. FIELD INVESTIGATION AND WASTE CHARACTERIZATION

Bulk samples of MSW were collected from the Tri-Cities landfill located in the San Francisco Bay Area. Two boreholes extending to a depth of 9 m and 32 m were advanced using a 760 mm bucket auger. The bulk materials were placed in sealed drums and sent to the laboratory. In situ unit weight tests (Zekkos et al. 2006) and shear wave velocity measurements were also conducted as part of the field investigation. Information regarding the field activities at the Tri-Cities landfill is provided in Zekkos (2005).

Waste characterization procedures, presented in detail in Zekkos (2005), were developed to characterize the sampled waste. Based on the results of these procedures, three bulk sample groups were selected for large-scale laboratory testing. The characteristics of the three bulk sample groups are listed in Table 1**.** Group A3 is representative of older waste material retrieved from higher depths, Group C6 is representative of younger waste material from relatively shallow depths, and Group C3 was selected as the sample group most different than the previously tested sample groups based on the waste characterization information.

The material was divided into fractions smaller and larger than 20 mm to facilitate the investigation of the influence of waste composition on MSW behavior. In general, 50-75%, by weight, of sampled Tri-Cities landfill MSW material was composed of particles smaller than 20 mm. The material with particle size smaller than 20 mm consists primarily of soil and soil-like material and includes the daily cover and other soil materials, degraded waste, and some undegraded fine waste inclusions. The fraction with particle size greater than 20 mm includes primarily undegraded waste particles, including paper, soft plastics, wood and small amounts of gravel. The larger than 20 mm fraction is primarily fibrous in nature and has a lower particle unit weight than the smaller than 20 mm fraction.

3. LARGE SCALE TRIAXIAL LABORATORY TESTING PROGRAM

Specimens reconstituted from the three sample groups were tested using a large-scale triaxial test device (d = 300 mm, h = 600-630 mm) located at the Richmond Field Station of the University of California at Berkeley. Specimens were reconstituted in layers using a 100 N weight that was dropped repeatedly from a constant height to achieve a target unit weight. Specimens were prepared with 100%, 62-76%, and 8-25% by weight smaller than 20 mm material. The maximum particle size used for the larger than 20 mm material in the triaxial tests was 76 mm. Particles larger than this dimension were discarded. The 27 large-scale monotonic triaxial tests included triaxial compression, triaxial extension, and triaxial compression-unloading tests. Table 2 presents a summary of the specimens tested. The specimen ID includes the sample group. The testing confining stress, the unit weight prior to shearing, the moisture content, the loading strain rate, and the composition of each sample are also provided in the table. This paper focuses on the triaxial compression test results. The results of the triaxial extension and the triaxial compression unloading tests are presented in Zekkos (2005).

Table 1: Characteristics of tested MSW sample groups

	A3	C6	C3
Borehole	BH-2	BH-1	BH-2
Depth, m	25.6-26.2	7.6-9.6	3.5-4.5
% by weight <20mm material	59	72	64
% moisture content[1]	12	13	23
% organic[1]	15-30	10-16	20-36
Age (years)	15	<1	2

[1] Information for the smaller than 20 mm material.

Table 2: Summary of triaxial monotonic tests on MSW specimens.

Test Conditions						% material by weight					
Specimen ID	Test Type	Confining stress (kPa)	Strain rate (%/min)	Unit weight (kN/m^3)[1]	Moisture (%)	<20 mm	Paper	Soft Plastic	Wood	Gravel	Textiles
A3-1L	C	68	0.05, 0.2	13.9	12	100	0	0	0	0	0
A3-2L	C	80	0.47	13.2	9	100	0	0	0	0	0
A3-3L	E	77.5	0.18	12.6	8	100	0	0	0	0	0
A3-4L	C	0	0.47	13.4	11	100	0	0	0	0	0
A3-5L	C	185	0.48	13.4	11	100	0	0	0	0	0
A3-6L	C	75	0.51	10.9	12	76	13	4	7	0	0
A3-7L	C	75	0.56	12.3	12	62	14	3	11	10	0
A3-8L	C	75	0.52	10	10	62	14	3	11	10	0
A3-9L	C	185	0.51	11.5	10	62	14	3	11	10	0
A3-10L	C	75	110	11.2	13	62	14	3	11	10	0
A3-11L	E	77	0.46	11.2	12	62	14	3	11	10	0
A3-12L	C	75	0.5	7.3	25	14	56	5	13	12	0
A3-14L	C-LU	510	SC	14.2	13	62	14	3	11	10	0
A3-15L	C-LU	340	SC	7.5	20	11	56	5	15	13	0
C6-1L	C	75	0.48	14.7	14	100	100	0	0	0	0
C6-2L	C	185	0.5	13.8	13	100	100	0	0	0	0
C6-3L	C	75	0.5	11.1	12	62	18	5	5	10	0
C6-4L	C	75	0.5, 50	11.9	12	62	18	5	5	10	0
C6-5L	C	75	0.5	11.5	12	62	18	5	5	10	0
C6-6L	C	75	0.5	11.5	11	62	18	5	5	10	0
C6-7L	E	84.5	0.5	11.9	11	62	18	5	5	10	0
C6-8L	C	73	0.5	12.5	14	62	18	5	5	10	0
C6-10L	C	510	0.5	14.0	15	62	18	5	5	10	0
C6-11L	C-LU	1150	SC	15.6	15	62	18	5	5	10	0
C3-1L	C	92	0.5, 5, 50	12.8	23	100	100	0	0	0	0
C3-2L	C	75	0.5	10.9	21	72	14	4	6	5	0
C3-3L	C	75	0.5, 50	8.1	23	21	42	18	10	10	0

SC: Stress Controlled test

C: Compression; E: Extension; C-LU: Axial Compression – Lateral Stress Unloading

[1] Total unit weight prior to shearing

4. TESTING RESULTS

4.1 Effect of composition

Figure 1 illustrates the stress-strain response of three specimens compacted with the same compaction effort and sheared at a confining stress of 75 kPa with a strain rate of 0.5%/min. The total unit weights of the specimens are different as a result of their different composition. Specimen A3-2L includes 100% <20 mm material, specimen A3-7L includes 62% <20 mm material and specimen A3-12L includes only 14% <20 mm material by weight. Specimen A3-2L exhibited relatively conventional stress-strain behavior, reaching a peak shear stress (at an axial strain of about 22%) and then exhibiting a post-peak shear stress reduction. Specimen A3-7L (62% <20 mm) exhibits initially a softer response than A3-2L, an upward curvature at larger strains, and does not reach a peak shear stress condition. Specimen A3-12L (14% <20 mm) exhibits a more pronounced upward curvature than A3-7L. The upward curvature of the stress-strain response observed in specimens A3-7L and A3-12L is similar to the triaxial compression response reported by Jessberger and Kockel (1993) and Grisolia et al. (1995).

The data in Figure 1 indicate that the upward curvature observed in triaxial compression for MSW specimens can be attributed to waste composition, i.e. the presence of large fribrous particles. This observed response is consistent with direct shear tests performed as part of this investigation (Zekkos et al., 2007) wherein upward curvature of the stress-displacement response was observed when the relative orientation of the long axis of the larger particles with respect to the horizontal shear plane allowed the mobilization of a “fibrous reinforcement effect”, i.e. when the specimens were prepared with the long axis of the large particles oriented at an angle to the horizontal failure surface. In triaxial testing, the failure plane would be expected to be oriented at approximately an angle of $45^o+\phi/2$ from the horizontal, while the preferred orientation of the waste particles during specimen compaction was horizontal (Zekkos, 2005). As a result, in the triaxial testing reported herein, the failure surface was at an angle to the preferred fiber orientation. It is worth noting that for a friction angle of 30 degrees the angle between the failure plane and preferred fiber orientation is 60 degrees and that studies of reinforced soils (e.g., Jewel and Wroth, 1987) suggest that when the failure surface is oriented at about 60 degrees to the fiber orientation, the reinforced material exhibits the highest shear strength.

With one exception, peak stress conditions were observed in this study only for specimens that included 100% <20 mm particles and no peak shear stress condition in triaxial compression were observed for the specimens that included particles >20 mm. The one exception was specimen C6-8L, which included 62% <20 mm material. This specimen was compacted with significant energy input during specimen preparation and had a unit weight upon compaction and prior to shearing, greater than that of other specimens with the same composition. The stress-strain response in monotonic compression of specimen C6-8L is shown in Figure 2. Specimen C6-8L exhibited the upward curvature response characteristic of the other specimens prepared with >20 mm particles but at axial strains of about 40% reached peak shear stress conditions. To the authors’ knowledge, this is the first MSW specimen reported in the literature that exhibits upward curvature and reaches peak shear stress conditions in triaxial compression. However, the peak shear resistance occurred at very large strains and thus may not be relevant to field behavior for some practical problems, as discussed subsequently.

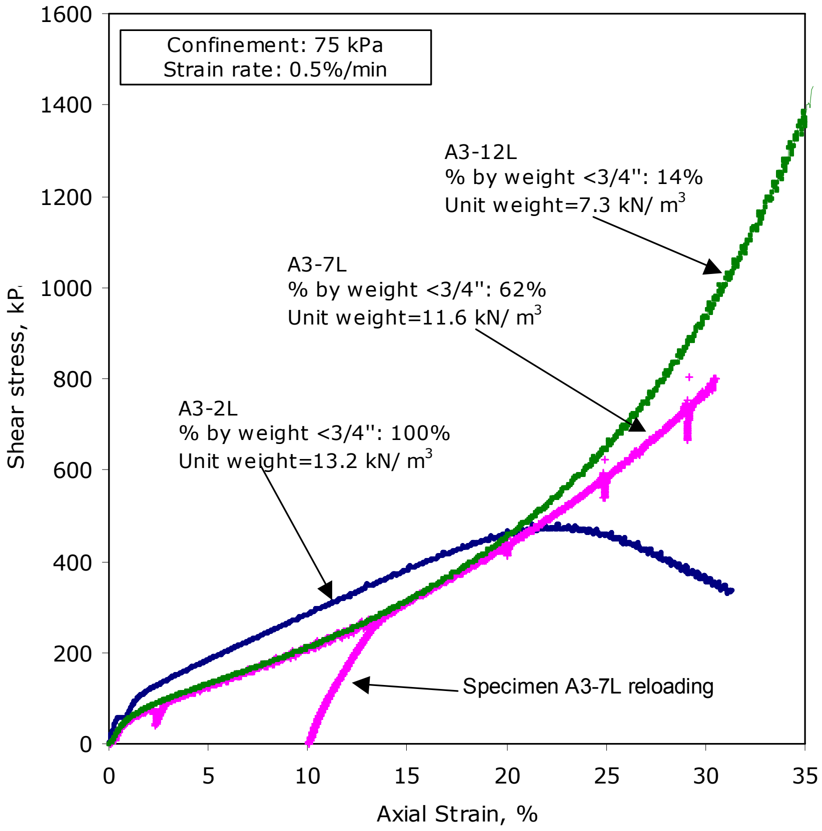


Figure 1. Responses of MSW in monotonic triaxial compression testing for specimens with varying waste composition.

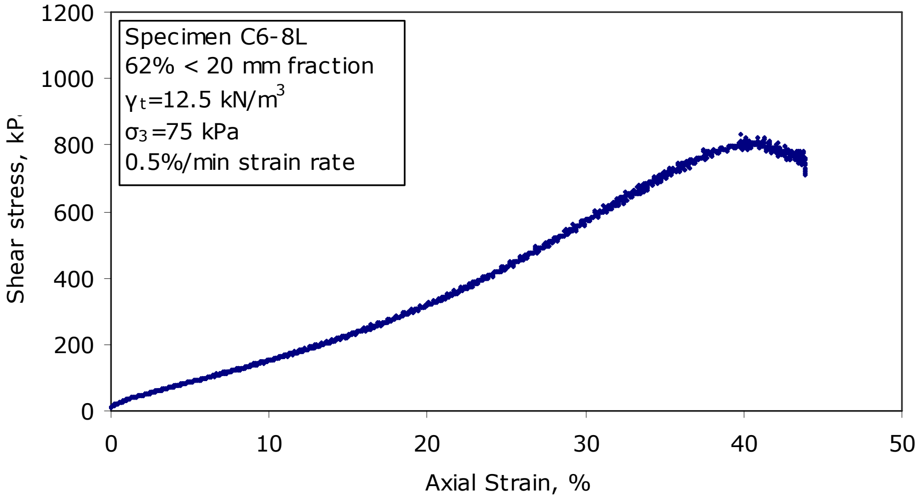


Figure 2. Upward curvature and mobilization of peak shear stress conditions for a MSW specimen.

4.2 Strain-dependent failure criterion

The observed trend of an increasing mobilized shear stress with increasing strain until relatively large strains for MSW in triaxial compression suggests that a potentially unstable slope in MSW may undergo significant deformation prior to failure and that this deformation will occur over a wide band within the waste (as opposed to being localized along a well-defined shear failure surface). Furthermore, because landfill foundation materials, e.g. native ground and geosynthetic liner systems, may reach peak shear stress conditions at smaller strains or displacements than those required to fully mobilize the strength of MSW, the use of the shear strength mobilized at large strains in MSW may not be prudent. To accommodate this "strain incompatibility" between waste and foundation materials, the concept of a shear strength envelope based upon the "mobilized shear stress" at a specified level of strain has been sometimes employed to characterize the shear strength of MSW in triaxial compression (Manassero et al. 1997). Most commonly 5% or 10% axial strains from the isotropic stress condition have been used to develop MSW failure criteria from triaxial test results, but axial strains of 15% or 20% have also been used. As the initial condition for waste in the field is the K_o condition, the use of the isotropic stress state in a triaxial compression test as the starting point from which the limiting strain is measured is only representative of field conditions if the coefficient of lateral earth pressure at rest, K_o, for MSW is close to 1.

Figure 3 illustrates the effective stress path for a typical triaxial compression test initiating from isotropic stress conditions. Figure 3 also shows the consolidation line for a K_o value unequal to (less than) 1. During triaxial compression loading, the effective stress path crosses the field K_o line and continues at a 45-degree angle until it reaches the failure surface. A potentially significant amount of strain occurs while the specimen deforms from the isotropic "laboratory" conditions to the "field" K_o conditions. The amount of deformation that occurs as a specimen is loaded to a specific K_o condition depends on a number of factors including compaction effort during preparation, unit weight, composition, and strain rate.

There is considerable uncertainty in estimating representative K_o values for MSW. An extensive discussion of published data for K_o in MSW is included in Zekkos (2005). Limited field measurements by Dixon and Jones (2005) yielded values mostly from 0.2 to 0.8. K_o values measured in large scale laboratory tests on MSW (e.g. Landva et al. 2000, Towhata et al. 2004, Kavazanjian, 2007) range from 0.2 to 0.3. Based upon laboratory measurements of Poisson's ratio made on the MSW specimens from the Tri-Cities landfill testing program, elasticity theory yields K_o values from 0.1 to 0.7, with lower values being representative of the specimens with higher composition of >20 mm material, i.e. larger particle sizes.

To examine the effect of K_o on the "mobilized" strength of MSW in the field, mobilized strength envelopes were generated from the triaxial data developed in this investigation for the cases of K_o=1 (isotropic), K_o= 0.6, and K_o= 0.3 at "incremental" strains of 5% or 10%. For each case, a secant friction angle was calculated assuming no cohesion. The results are shown in Figure 4 and suggest that:

- As the K_o value decreases, the mobilized strength increases.
- The scatter in the data (as indicated by the R^2 values) reduces significantly as the selected K_o value decreases and as the selected level of limiting strain increases.
- The results in terms of mobilized strength appear to be very similar for the A3, C6 and C3 waste group.
- At low levels of strains (e.g., Figure 4(a) for 5% strain starting from K_o =1) the specimens with 100% < 20 mm (hollow symbols) are stiffer and the mobilized strengths are higher than the specimens which include the > 20 mm material (solid symbols).
- At large strains (e.g., Figure 4(f), for 10% strain starting from K_o =0.3) the specimens with >20 mm material exhibit larger mobilized stresses than the specimens with 100% < 20 mm.
- At intermediate levels of strains, there is not a clear difference between the specimens that include >20 mm material and those that do not. This is because the concave upwards curvature of the specimens with >20 mm material counteracts the initially stiffer response of the specimens with 100% <20 mm.

Considering the issues discussed previously, the mobilized shear stress in triaxial compression at a limiting strain of 5% beyond an in-situ stress state of K_o= 0.3 is considered by the authors to be a reasonable limiting strain failure criterion for defining MSW shear strength from triaxial compression tests. For the K_o = 0.3+5% failure criterion, the secant friction angle of Tri-Cities MSW is on average approximately 42° in triaxial compression. For K_o = 0.6+5%, the friction angle of Tri-Cities MSW in triaxial compression for confining pressures of up to about 200 kPa is about 35°. We note that for the specimens that included >20 mm material, the secant friction angle at the maximum axial strains (generally between 27% and 33% depending on the specimen) was 65°, significantly higher than the friction angle estimated using either of the two K_o failure criterion. Thus, a friction angle on the order of 36 to 41 degrees appears to be reasonable as a lower bound for characterization of the strength of the Tri-Cities landfill MSW in the field for confining pressure (σ_3) values of up to 200 kPa (2 atm).

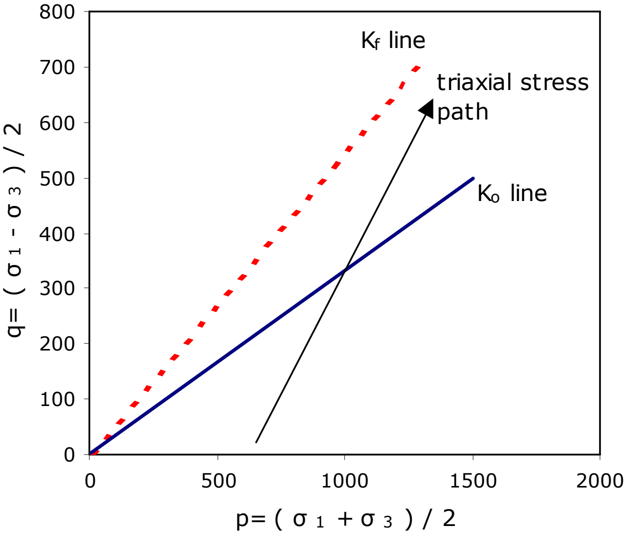


Figure 3. Stress paths during a triaxial compression test.

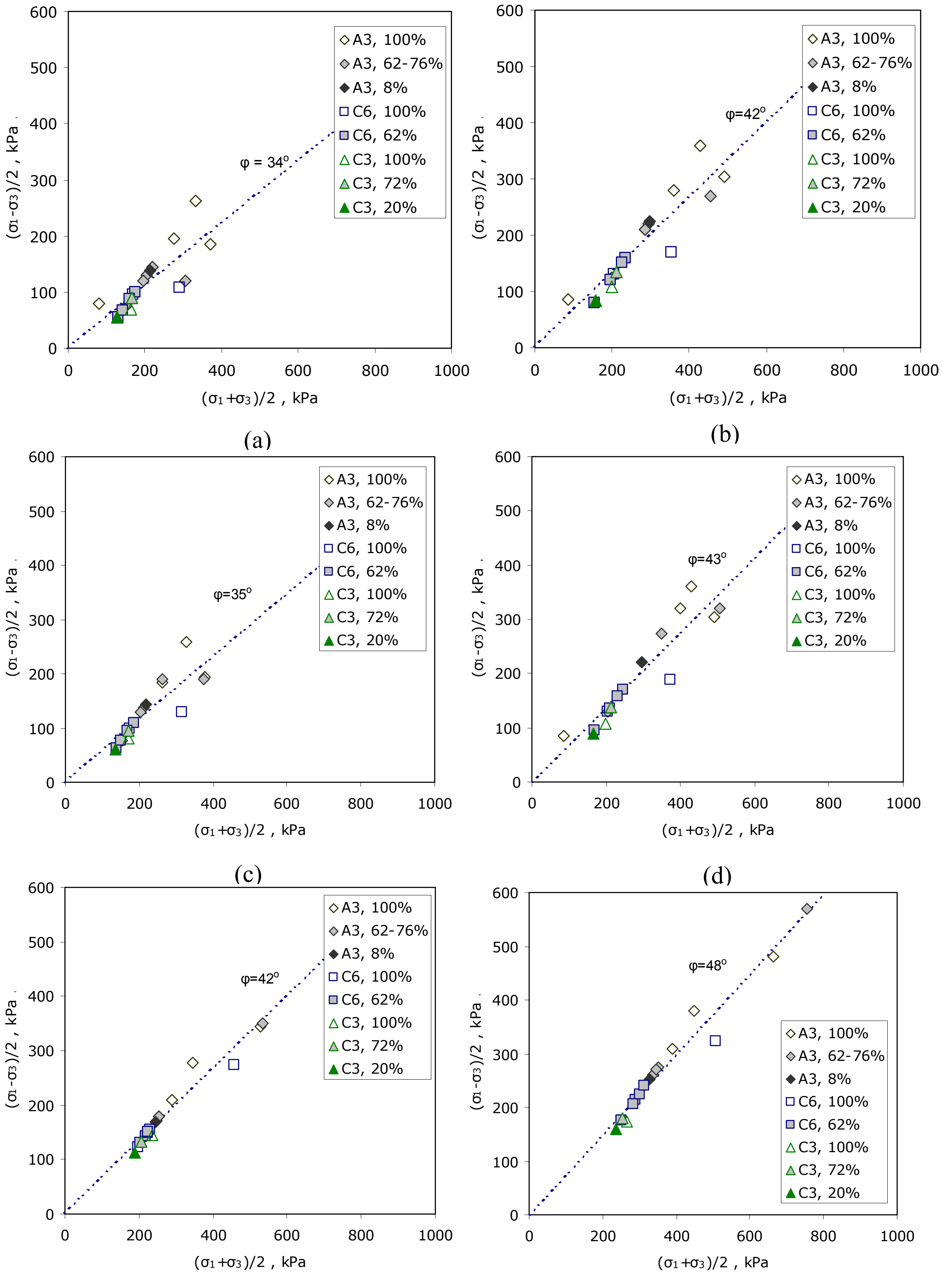
4.3 Effect of confining stress

The effect of confining stress on MSW triaxial compression behavior was studied by testing specimens from the A3 and C6 group with varying compositions. The results are presented in Zekkos (2005). For specimens prepared with the same composition and compaction effort, it was found that as confining stress increased, the secant friction angle reduced. Also, the strain at failure increased for specimens that include only <20 mm material for both sample groups. The effect of confining stress is not easily discerned when all the data are considered, because of the influence of other factors that affect the stress-strain response.

In Figure 5, the mobilized secant friction angle defined by the K_o =0.3+5% criterion is shown for pairs of specimens with identical composition and prepared with similar compaction effort, subjected to different confining stresses. The data indicate a reduction in the friction angle with increasing confining stress, with the decrease in secant friction angle varying from approximately 4° to 8° as the confining pressure increased from approximately 1 atm to 2 atm (100 kPa to 200 kPa).

4.4. Unit weight and strain rate effects

The initial (as compacted) MSW unit weight and the associated compaction effort also affect the stress-strain response of MSW. Briefly, specimens with lower initial unit weight have a softer initial response and lower mobilized shear strengths (at a given strain), as described in Zekkos (2005). A number of tests were also performed to evaluate the effect of loading strain rate. These tests are summarized by Zekkos et al. (2007) and indicate that MSW is significantly affected by the loading rate with strength increasing as loading rate increases by approximately 11-16% per log cycle of strain rate, similar to the observed behavior of clayey soils.



(a) (b)

(c) (d)

(e) (f)

Figure 4: Mobilized stresses and envelope friction angles for: a) K_o=1 and 5% axial strain (R^2=0.66) b) K_o=1 and 10% axial strain (R^2=0.85); c) K_o=0.6 and 5% axial strain (R^2=0.75); d) K_o=0.6 and 10% axial strain (R^2=0.87); e) K_o=0.3 and 5% axial strain (R^2=0.95); f) K_o=0.3 and 10% axial strain (R^2=0.96).

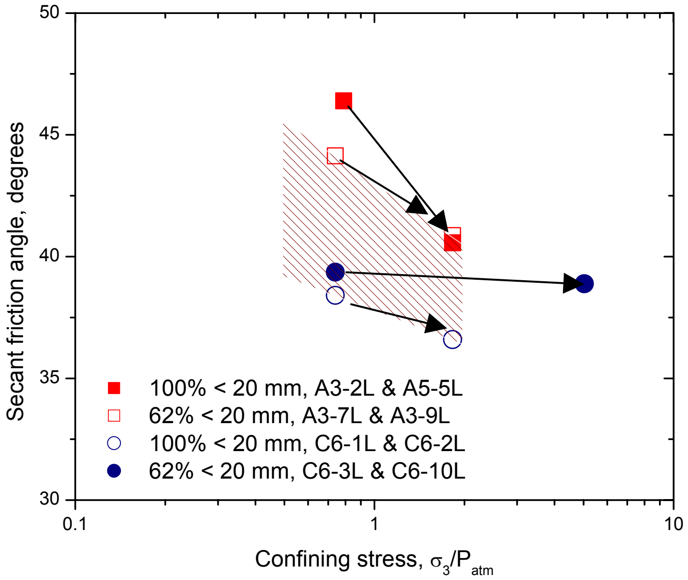


Figure 5. Reduction in secant friction angle with confining stress at K_o=0.3+5% axial strain for the specimens that the effect of confining stress has been investigated.

5. CONCLUSIONS

A comprehensive investigation of the response of MSW in triaxial compression has been performed using a large-scale triaxial device. It was found that the stress-strain response in triaxial compression is significantly affected by waste composition. The presence of sub-horizontally oriented larger particles results in an upward curvature of the stress-strain response and a continued increase in the mobilized shear stress, with a lack of a peak stress condition, even at very large strains. Interpretation of the results suggests that this somewhat unusual stress-strain response is attributable to the reinforcement effects of MSW particles >20 mm in dimension. Rather than defining shear strength based upon a limiting strain measured from isotropic consolidation conditions, a failure criterion based upon a K_o value of 0.3, assumed representative of field conditions and an incremental axial strain (beyond the K_o condition) of 5% was used to evaluate MSW shear strength. This criterion yielded secant friction angles ranging between 36 and 41 degrees for MSW from the Tri-Cities landfill in triaxial compression for confining pressure (σ_3) values of up to approximately 200 kPa. However, the secant friction angle was found to decrease with increasing confining stress. Due to the reinforcing effects of the larger particles, the friction angles measured in this testing program may only be representative of failure surfaces that are oriented at an angle to the preferred orientation of the long axis of larger waste particles.

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REFERENCES

Dixon, N., Jones, D. R. (2005) Engineering properties of municipal solid waste, Geotextiles and Geomembranes, 23 (2005), pp. 205-233.

Eid, H.T., Stark, T.D., Douglas, W.D. & Sherry, P.E. (2000) Municipal Solid waste slope failure 1. Waste and foundation properties, Journal of Geotecnical and Geoenvironmental Engineering, ASCE, Vol.126, No.5, pp.397-407.

Grisolia, M., Napoleoni, Q., & Tangredi, G., (1995) The use of triaxial tests for the mechanical characterization of municipal solid waste, Proc. of the 5th International Landfill Symposium - Sardinia '95, 2: 761-767. Cagliari (I): CISA.

Jessberger, H.L. & Kockel, R. (1993) Determination and assessment of the mechanical properties of waste. Waste disposal by landfill - Green '93. R.W. Sarsby (edit). pp. 313-322. Rotterdam- Balkema.

Jewell, R. A. & Wroth, C. P.(1987) Direct shear tests on reinforced sand, Geotechnique, 37, No. 1, pp. 53-68

Kavazanjian, E. Jr. & Matasovic, N, (1995) Seismic analysis of solid waste landfills, Proceedings of Geoenvironment 2000, ASCE Geotechnical Special Publication No. 46, New York, NY, pp. 1066-1080.

Kavazanjian, E., Jr. (2007) Waste mechanics: Recent findings and unaswered questions, *Advances in Unsaturated Soil, Seepage, and Environmental Geotechnics*, ASCE Geotechnical Special Publication 148, Proceedings of GeoShanghai, Shanghai, China, pp. 34-54

Landva, A. O., Valsangkar, A. J., & Pelkey, S. G. (2000) Lateral earth pressure at rest and compressibility of municipal solid waste, Canadian Geotechnical Journal, 37, pp. 1157-1165.

Manassero, M., Van Impe, W. F., Bouazza, A. (1997) Waste disposal and containment, Proceedings of the Second International Congress on Environmental Geotechnics, Osaka, Japan, 5-8 November 1996, pp. 1425-1474.

Towhata, I., Kawano, Y., Yonai, Y., Koelsh, F. (2004) Laboratory tests on dynamic properties of Municipal Wastes, 11th Conference in Soil Dynamics and Earthquake Engineering and 3rd International Conference on Earthquake Geotechnical Engineering, Vol.1, pp.688-693.

Zekkos (Zeccos) D. P. (2005) Evaluation of static and dynamic properties of Municipal Solid-Waste". Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Department of Civil and Environmental Engineering, University of California, Berkeley, Fall. 2005 (Also available at http://waste.geoengineer.org).

Zekkos D, Bray J. D. , Riemer M., Kavazanjian E., Matasovic N., Rathje E. & Stokoe K. H. (2006) Unit Weight of Municipal Solid-Waste". ASCE Journal of Geotechnical and Geoenvironmental Engineering, 132 (10), pp.1250 -1261 2006.

Zekkos, D., Bray J. D., Athanasopoulos, G.A., Riemer, M. F., Kavazanjian, E., Founta, X., Grizi, A. (2007) Compositional and loading rate effects on the shear strength of Municipal Solid Waste, 4th International Conference on Earthquake Geotechnical Engineering, Thessaloniki, June 25-28, 2007, paper no. 1525.