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SHEAR MODULUS REDUCTION AND MATERIAL DAMPING RELATIONS FOR MUNICIPAL SOLID-WASTE

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ABSTRACT

Results of laboratory tests are presented for the evaluation of dynamic properties of Municipal Solid-Waste (MSW) from the Tri-Cities landfill in the San Francisco Bay Area. Values of small-strain shear modulus, G_{max}, and the normalized shear modulus reduction and material damping ratio curves are measured using large-scale cyclic triaxial tests. The test results, which are considered representative for depths up to 20 m, are used for investigating the dependence of the waste material's dynamic properties on specimen composition, duration of confinement, unit weight of material, and loading frequency.

Introduction

Municipal Solid-Waste (MSW) landfills are engineered systems with strict seismic performance criteria. The reliability of dynamic analyses of landfills depends on proper characterization of critical dynamic properties of the waste materials. Those properties are:

- The MSW unit weight profile.
- The small-strain shear modulus (G_{max}) or shear wave velocity (V_s).
- The strain-dependent normalized shear modulus reduction (G/G_{max}) and material damping relationships.

The selection of the MSW unit weight profile has an important effect on the results of seismic site response analyses and the predicted seismic displacements of cover sliding (Zekkos, 2005). Recently, Zekkos et al. (2005) used information collected from in-situ unit weight data from landfills in the US and other countries as well as large-scale laboratory test data of MSW and presented a framework for the development of a landfill-specific MSW unit weight profile. The authors also recommended generalized MSW unit weight profiles depending on the waste composition and the compaction effort during placement of waste.

The small-strain shear modulus (G_{max}) is related to the shear wave velocity (V_s) and the mass density (ρ) of the material by the following relationship:

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$$G_{max} = \rho * V_s^2 \quad (1)$$

The shear wave velocity of waste materials in a landfill can be measured in situ by various seismic methods. The Spectral Analysis of Surface Waves (SASW) method has become particularly popular in landfills, because it is reliable, non-intrusive, and cost-effective. For preliminary purposes and when landfill-specific data are not available, Kavazanjian et al. (1996) recommended typical shear wave velocity profiles for Southern California MSW landfills.

Normalized shear modulus reduction and material damping relationships for MSW have been recommended by various researchers (e.g. Idriss et al. 1995, Matasovic and Kavazanjian, 1998, Augello et al. 1998, Elgamal et al. 2004). The majority of the currently used recommendations are primarily based on back-analyses of the seismic response of the OII landfill in Southern California. However, the OII landfill is a particular case of landfill, because it includes significant amounts of soil material as well as commercial and industrial waste (Matasovic and Kavazanjian, 1998). In addition, there are important differences among the recommended curves. Limited laboratory investigations have been performed on MSW primarily due to the difficulties in performing such tests. Such difficulties include the health issues associated with testing waste material, sample disturbance, and the large test specimens required to include the larger waste particles. Matasovic and Kavazanjian (1998) performed large-diameter (457 mm) cyclic simple shear tests on waste from the OII landfill. Data were collected for shear strains larger than 10^{-2}%. Limited cyclic triaxial tests at shear strains of approximately 0.3% were performed by Towhata et al. 2004.

Testing Program and Waste Characterization

The purpose of the investigation was to evaluate the effects of various parameters on the dynamic properties of MSW. The effects of specimen composition, confining stress, unit weight, loading frequency, and time under confinement have been studied. The effect of confining stress will not be presented in detail in this paper due to page limitations. Tests presented in this paper were performed under an isotropic confining stress that ranged between 25 kPa and 90 kPa. The test results are considered representative of MSW to a depth of approximately 20 m. More than 80 cyclic triaxial test series have been performed on 26 large-scale specimens of Municipal Solid-Waste from the Tri-Cities landfill. Information regarding the in situ tests, the drilling operations, and the waste characterization of the Tri-Cities landfill is described in Zekkos (2005). A large-scale cyclic triaxial test device (d = 300 mm, h = 600-630 mm) located at the Richmond Field Station of the University of California at Berkeley was used for the performance of the tests. Two LVDTs were placed directly on the top-cap of the specimens in diametrically opposite locations. The configuration allowed accurate measurements of the shear modulus at shear strains as low as $3*10^{-4}$%, which is approximately G_{max} for this material.

Tests were performed on three sample groups from the Tri-Cities landfill. The characteristics of the sample groups are provided in Table 1. Group A3 is material sampled from a relatively large depth and was 15 years old at the time of drilling. Group C6 includes material sampled from a different location of the landfill at relatively shallow depths and was 2 years old at the time of drilling. Finally, Group C3 was selected based on the waste characterization information, as the most different sample group than the previously tested sample groups A3 and C6. As shown in the following sections, the dynamic properties of the three sample groups were found to be similar.

Specimens were reconstituted in a specimen preparation mold in 8-9 layers using a 100 kN weight that was dropped repeatedly from a constant height to achieve a target unit weight. From the estimated small-strain shear modulus and the unit weight of the specimen, the shear wave velocity of the specimen was calculated, and it was found to be just slightly lower than or similar to the shear wave velocity of the material in situ, which was evaluated using the SASW method. From each sample group, several specimens of varying composition were prepared.

Specimens were prepared with 100%, 62-76%, and 8-25% smaller than 20 mm material. The material was divided in the smaller and larger than 20 mm fraction based on the methodology of waste characterization, which is presented in detail by Zekkos (2005). Briefly, the material with particle size smaller than 20 mm consists primarily of soil-like material and includes the daily soil cover and some fine waste inclusions. The fraction with particle size greater than 20 mm includes the waste fraction, which based on the waste characterization consists primarily of 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. Additional advantages of this discretization is that the finer fraction can be characterized according to geotechnical engineering practices and can also be tested in typical geotechnical laboratory testing devices. The waste characterization of the Tri-Cities landfill suggested that 50-75% by weight is material with particle sizes smaller than 20 mm material.

Table 1: Characteristics of tested MSW sample groups

	A3	C6	C3
Borehole	BH-1	BH-2	BH-2
Depth, m	25.6-26.2	7.6-9.6	3.5-4.5
% 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.

Small-Strain Shear Modulus G_{max}

The effects of waste composition on the small-strain shear modulus is important. Fig. 1 presents testing results from specimens from all three sample groups. The tests presented in Fig. 1 were performed at a sinusoidal loading frequency of 1 Hz for specimens that remained under constant mean confining stress for 24 hrs. Specimens with 100%<20 mm (indicated with full symbols) at a mean confining stress of about 25 kPa have a small-strain shear modulus of about 12.5 MPa whereas at a mean confining stress of about 75 kPa, the small-strain shear modulus is about 25 MPa. As the fraction of larger than 20 mm fibrous material increases, the specimen unit weight and the small-strain shear modulus decrease. For a mean confining stress of 75 kPa, the small-strain shear modulus decreases from 25 MPa for specimens with 100% smaller than 20 mm material to 14 and 5 MPa for specimens with 62-76% and 8-25% smaller than 20 mm material, respectively. The decrease in the value of the small-strain shear modulus as the larger than 20 mm material increases is a result of the reduction in specimen unit weight and the reduction of shear wave velocity of the specimen.

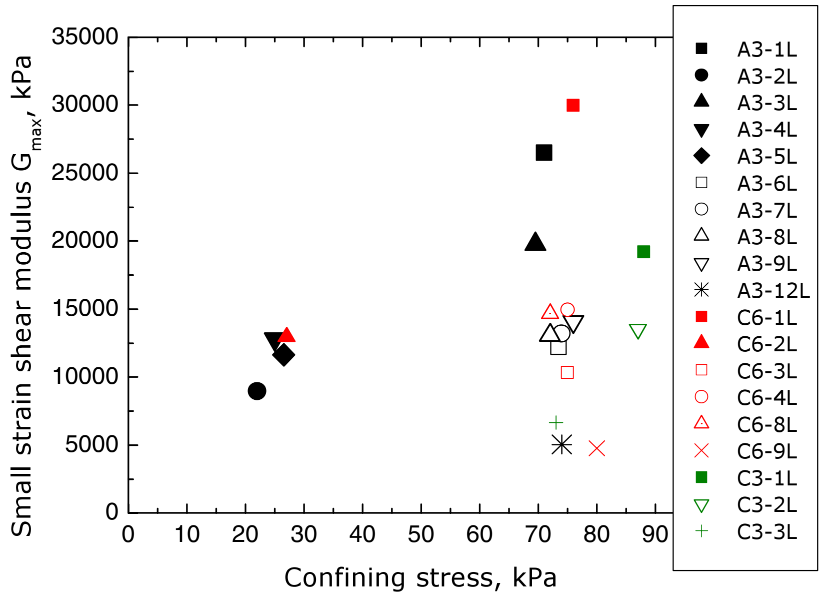

Figure 1. G_{max} vs. confining stress for MSW specimens

The scatter in the data observed in Fig. 1 for a confining stress of approximately 75 kPa is primarily attributed to the influence of the unit weight. Fig. 2 presents the small-strain shear modulus as a function of the specimen unit weight for a mean confining stress of approximately 75 kPa. As the specimen unit weight reduces, the small-strain shear modulus reduces. Specimens with increasing amounts of the larger than 20 mm material exhibit further reduction in the unit weight and the small-strain shear modulus. Interestingly, the data for all three sample groups appear to follow the same relationship of unit weight vs. small-strain shear modulus.

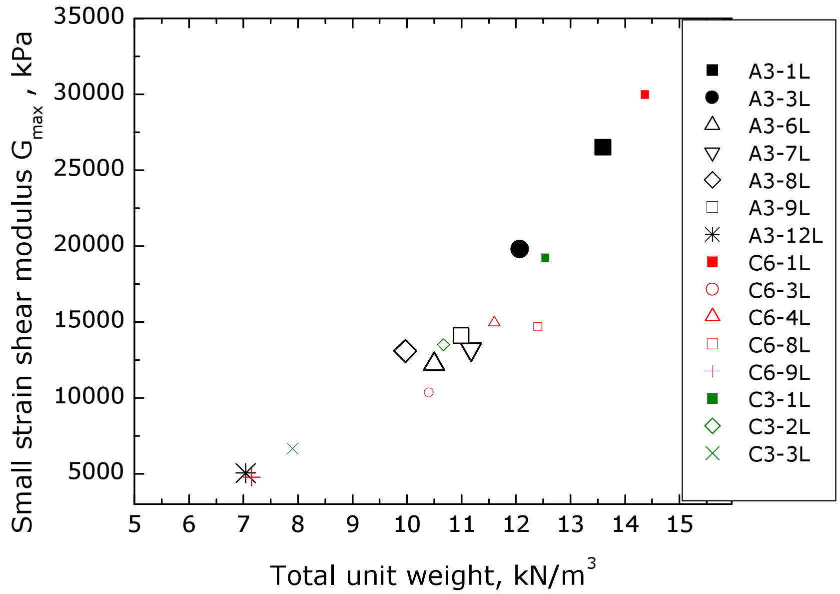

Figure 2. Small-strain shear modulus vs. total unit weight for a confining stress of 75 kPa.

The small-strain shear modulus increases significantly with time under confinement. Cyclic triaxial tests have been performed for time under confinement equal to more than a month. The small-strain shear modulus was also evaluated from shear wave velocity measurements using accelerometers mounted on the specimen. The results regarding the effect of time under confinement from the two methods were in good agreement. Fig. 3 presents the ratio of the small-strain shear modulus at any given time divided by the small-strain shear modulus at 24 hrs under confinement as a function of the time under constant confinement. The test results are for specimens from all three sample groups and varying waste composition. The relationship presented in Fig. 3 can be expressed by the following equation:

$$\frac{G_{\max}(t)}{G_{\max}(t=24hrs)} = 0.32 \cdot \log(t) + 0.63 \tag{2}$$

where $G_{max}(t)$ is the small-strain shear modulus at time under confinement t, and $G_{max}(t=24hrs)$ is the small-strain shear modulus at time under confinement equal to 24 hrs.

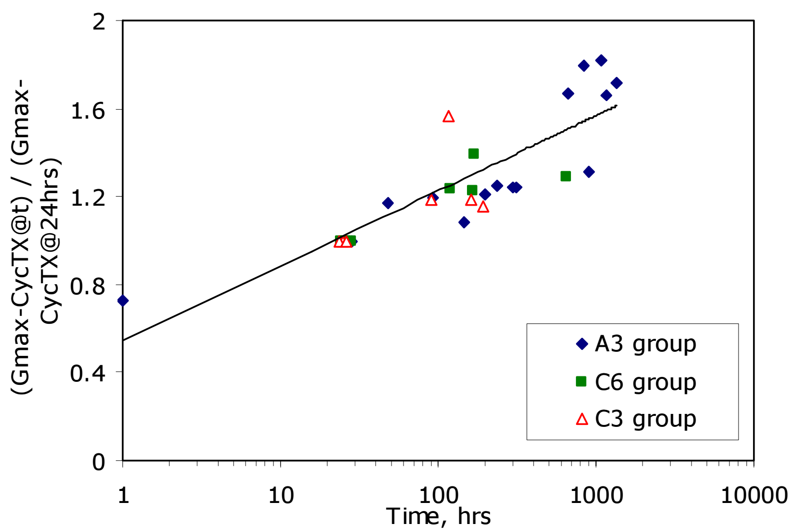

Figure 3. Change of small-strain shear modulus as a function of time under confinement.

Tests have also been performed on specimens of varying composition for loading frequencies of 0.01, 0.1, 1, and 10 Hz, and the results are presented in Fig. 4. Regardless of the specimen composition, the absolute value of the small-strain shear modulus increases roughly linearly with the logarithm of the loading frequency for loading frequencies ranging between 0.01 and 10 Hz according to the following equation:

$$\frac{G(f)}{G(@1Hz)} = 0.092 \cdot \log(f) + 1.0 \tag{3}$$

where G(f) is the value of the shear modulus at relatively small-strains (~10^{-3}%) for a loading frequency f, and G(f@1Hz) is the value of the shear modulus at the same strain level for a loading frequency of 1 Hz.

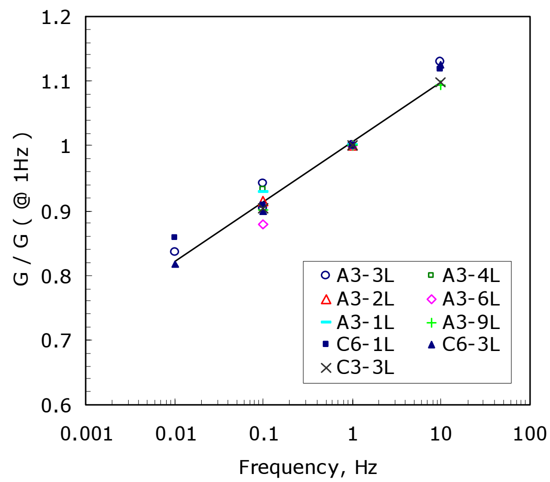

Figure 4. Effect of loading frequency on the shear modulus.

Shear Modulus Reduction and Material Damping Curves

The laboratory test results allowed the investigation of the effects of various parameters on the strain-dependent normalized shear modulus reduction and material damping ratio curves. Specimen composition was found to have the most important effect on the dynamic curves. Confining stress also had an effect, whereas time under confinement, unit weight, and loading frequency (for frequencies between 0.1 and 1 Hz) did not have a significant influence on the normalized dynamic curves.

Tests were performed on all three sample groups with 100%, 62-76% and 8-25% by weight smaller than 20 mm material. The laboratory results are presented in Fig. 5 as a function of the amount that is smaller than 20 mm. As the amount of larger than 20 mm increases, the shear modulus reduction curves shift significantly to the right, the threshold strain increases, and the material response becomes more linear at intermediate strains (Fig. 5a). The observed shift of the curve to the right is attributed to the fibrous nature of the larger than 20 mm fraction and the size of the fibers. The shear modulus reduction curves were similar for all three sample groups tested even though the waste was sampled from different locations and depths of the landfill and had different ages. The laboratory results were fitted to a hyperbolic model which is expressed by the following equation:

$$\frac{G}{G_{\max}} = \frac{1}{1+\left(\frac{\gamma}{a}\right)^{\beta}} \tag{4}$$

where G_{max} is the small strain shear modulus, G is the reduced shear modulus for a shear strain γ and α and β are two hyperbolic parameters, the value of which depends on the specimen composition and confining stress. Table 2 provides the values of the two hyperbolic parameters α and β based on the amount of particles smaller than 20 mm in size. The R^2 values of the fitted curves are also provided.

The material damping ratio curve is also affected by the specimen composition (Fig. 5b). The most important effect is observed for large strains (>10^{-2}%). As the amount of material larger than 20 mm increases, the damping ratio decreases, i.e. the response becomes more linear again at intermediate strain levels. The observed reduction in material damping for specimens with more material larger than 20 mm is consistent with the observed, more linear response in the shear modulus reduction curves. For smaller strains (<5*10^{-3}%) the laboratory results suggest that the material damping ratio is not significantly reduced with strain, but remains roughly constant at values of about 3-4%. This observation is also supported by unpublished resonant column test results generated as part of the present research project at the University of Texas at Austin (Stokoe and Rathje, pers. com). Additionally, for relatively small shear strains (<10^{-3}%) as the content in larger than 20 mm material increases, the material damping ratio increases slightly. The recommended values of material damping ratio as a function of shear strain and waste composition for depths up to 20 m are presented in Table 3.

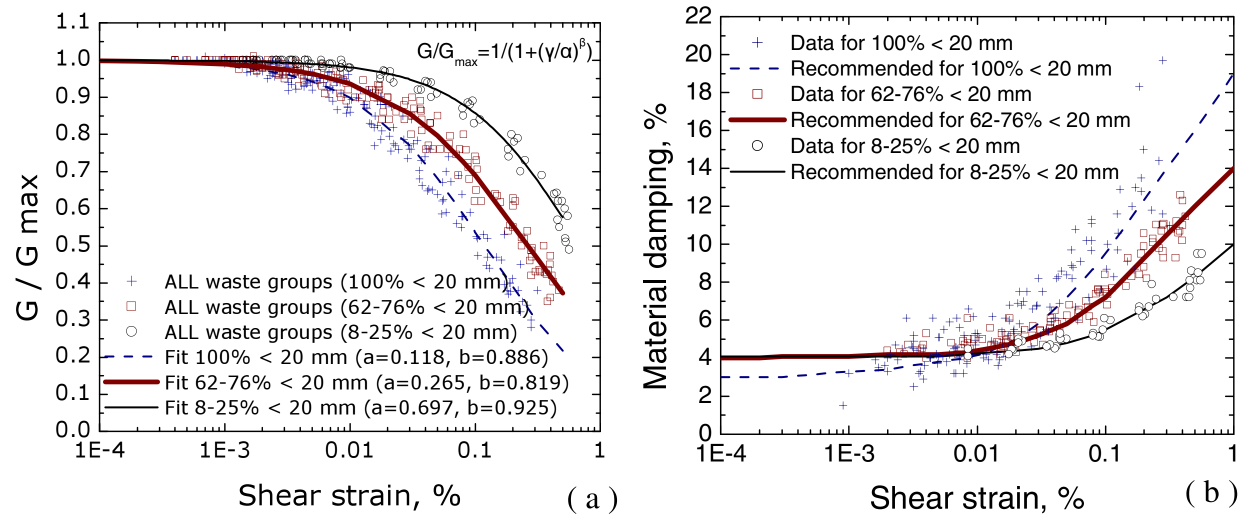

Figure 5. Results of cyclic triaxial tests from all sample groups: a) normalized shear modulus reduction curve, and b) material damping curve as a function of shear strain.

Table 2. Hyperbolic parameters of the regressed cyclic triaxial data as a function of the percentage of material less than 20 mm material (for depths up to 20 m).

	% of material less than 20 mm		
	100	62-76	8-25
α	0.118	0.265	0.697
β	0.886	0.819	0.925
R^2	0.972	0.978	0.981

The laboratory results of Fig. 5 are compared with previously recommended strain-dependent shear modulus reduction and material damping relationships in Fig. 6. As shown in Fig. 6a the shear modulus reduction data for the specimens with 100% smaller than 20 mm fall to the left of the recommended curve by Augello et al. (1998). As the amount of fibrous, larger than 20 mm material increases, the data shifts to the right with the data from specimens with greater amounts of waste materials (i.e. larger than 20 mm material) being similar to the curve of

Table 3. Recommended material damping ratio values as a function of the % of material less than 20 mm (for depths up to 20 m).

	% of material less than 20 mm		
γ (%)	100	62-76	8-25
0.0001	3	4	4.1
0.0002	3	4	4.1
0.0003	3	4.1	4.1
0.001	3.3	4.1	4.1
0.002	3.4	4.2	4.1
0.003	3.6	4.2	4.1
0.005	3.8	4.2	4.1
0.008	4	4.3	4.2
0.012	4.3	4.5	4.3
0.02	5	4.8	4.4
0.03	5.8	5.2	4.5
0.05	7.2	5.8	4.8
0.08	8.7	6.8	5.2
0.1	9.5	7.2	5.5
0.3	14	10.5	7.2
0.5	16	12	8.3
1.0	19	14	10

Matasovic and Kavazanjian (1998). The laboratory results of the material damping ratio as a function of shear strain are shown in Fig. 6b along with previously recommended curves. For large strains, the data fall generally between the Augello et al. (1998) and the Matasovic and Kavazanjian (1998) curves, except for the specimens with high amounts of particles larger than 20 mm which exhibit lower material damping ratio values at large strains than these curves.

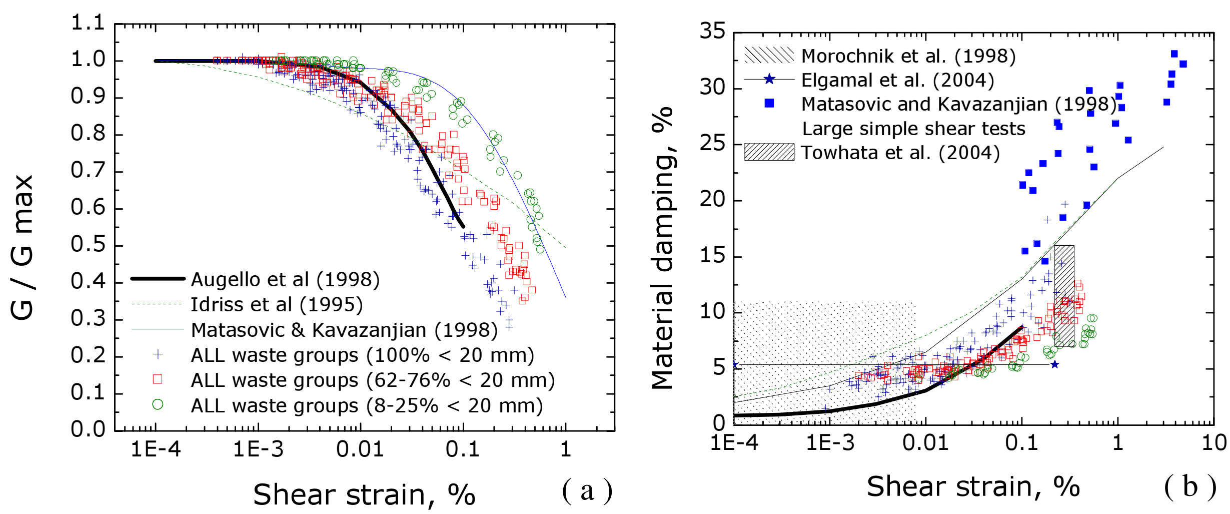

Figure 6. Cyclic triaxial test results and comparison with the literature: a) Normalized shear modulus reduction curve, b) Material damping curve, as a function of shear strain.

The results of this investigation are also consistent with the limited laboratory results of previous investigations. The large-scale simple shear test results on waste from the OII landfill (Matasovic and Kavazanjian, 1998) that had more than 80% by weight soil-like material exhibit similar and slightly higher material damping ratio values than those measured for the specimens with 100% smaller than 20 mm material from Tri-Cities landfill. Also, Fig. 6b presents the triaxial test results by Towhata et al. (2004) on solid-waste from Germany. From the tests that were performed at shear strains of about 0.3%, the higher values of material damping ratio represent tests on specimens that included only the finer soil-like material, whereas the lower material damping ratio values were measured for the specimens that included plastic fibers. The results of Towhata et al. (2004) are in good agreement with the results of the present study, with the higher values of damping ratio being in agreement with the results of this study for specimens with 100% smaller than 20 mm material, and the lower values of damping ratio being in agreement with the results for specimens with 62-76% smaller than 20 mm material.

The presented family of curves can be used in conjunction with landfill-specific waste characterization information to select representative shear modulus reduction and material damping ratio curves for use in dynamic analyses. For example, as previously mentioned, the waste characterization procedure in the Tri-Cities landfill suggested that the placed waste material consists on average of 50-75% of smaller than 20 mm material. Thus, for the performance of dynamic analyses of this landfill, the best-estimate curves would be those recommended for 62-76% smaller than 20 mm material for depths less than 20 m.

Conclusions

More than 80 cyclic triaxial tests at varying strain levels have been performed on large-scale specimens from three sample groups of solid-waste from the Tri-Cities landfill, and the effects of different parameters on the dynamic properties of MSW were studied. Of the parameters studied, waste composition was found to have the most important effect on the dynamic properties of MSW. The small-strain shear modulus is significantly affected by composition and confining stress, but also is affected by the unit weight, the time under confinement, and the loading frequency. The normalized shear modulus reduction and material damping curves are affected primarily by the specimen composition and confining stress. Strain-dependent shear modulus reduction and material damping ratio curves as a function of waste composition are recommended for the performance of dynamic analyses of landfills; they are considered to be representative of MSW in the upper 20 m of a solid-waste landfill.

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