Recent Findings on the Static and Dynamic Properties of Municipal Solid Waste


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ABSTRACT: The design of Municipal Solid Waste (MSW) landfills requires the selection of representative MSW material properties. The profession’s understanding of the mechanical response of MSW has evolved significantly in recent years, but many aspects of the response of MSW remain uncertain. A research project involving five organizations was conducted to systematically evaluate the factors that affect the static and dynamic properties of MSW. A summary of major findings from the work performed to date by this team of investigators is briefly described in this paper.

INTRODUCTION

The selection of representative MSW properties is important for the reliable performance of landfill analyses such as the static and seismic slope stability, the seismic response of landfills, the design of the containment system, and the design of facilities for post-closure development. The profession’s understanding of the response of MSW has evolved significantly since the early work performed by Sowers (1973) and Landva and Clark (1986). However, despite many advances in our understanding of MSW properties, many of the factors affecting the response of MSW remain largely uncertain. In 2002, the US National Science Foundation funded a collaborative research project that involved the University of California at Berkeley (UCB), the University of Texas at Austin (UT), and Geosyntec Consultants to evaluate systematically factors that affect the static and dynamic properties of MSW by means of in situ investigations and an extensive large-scale laboratory testing program. Subsequently, Arizona State University (ASU) and the University of Patras, Greece
(UP), joined the project team. The fieldwork and laboratory testing performed by this team of investigators are briefly described in this paper. Relevant findings are presented that provide insight regarding the mechanical response of MSW.

FIELD INVESTIGATION AND WASTE CHARACTERIZATION

Waste sampling was coordinated by Geosyntec Consultants. Two large-diameter (760 mm) borings were augered to depths of 10 m and 32 m using a bucket auger at the Tri-Cities landfill, located in the San Francisco Bay Area. Shallow and deep bulk samples of waste were retrieved and stored separately in 39 sealed 55-gallon drums. Bulk samples of similar visual composition from the same depth interval within a borehole were designated as sample groups. Sample groups included relatively young waste (waste placed within the past 2 years) and relatively old waste (waste placed for approximately 15 years) as well as waste of varying composition. In situ unit weight tests were performed using a gravel replacement procedure developed by Geosyntec Consultants (Matasovic and Kavazanjian, 1998) and described in Zekkos et al. (2006a). The MSW unit weight was found to range from 10 kN/m$^3$ near the surface to 16 kN/m$^3$ at depth. Shear wave velocity soundings were performed by UT at the boring locations using the Spectral Analyses of Surface Waves (SASW) method. The shear wave velocity was found to vary from 75 to 210 m/sec at the surface, reaching 250 m/sec at a depth of 25 m (Lin et al., 2004).

Waste material was characterized using a procedure that was developed to efficiently collect relevant information about the waste material. The procedure is described in Zekkos (2005) and included segregating the waste into material larger and smaller than 20 mm (0.75 in). This segregation is useful because: a) material <20 mm is composed predominantly of equidimensional particles, including soil from daily cover, organic materials, and some fine waste inclusions, whereas material >20 mm consists mostly of fibrous constituents; b) material <20 mm can be characterized using conventional soil mechanics tests and can be tested using conventional size geotechnical testing equipment. Evaluation of the influence of the fibrous >20 mm material on MSW was an important part of this investigation.

About 50-75% by weight of each waste sample was <20 mm material. This material contains a significant amount of soil (and soil-like) particles, but also contains organic material so that it is lighter, and softer than many inorganic soils. The remaining coarser material consisted primarily of paper, plastic, wood, and gravel. Constituents such as metals, glass, stiff plastics, and textiles, comprised a significantly lower percentage of the material by weight and by volume. Laboratory tests were performed on the three sample groups summarized in Table 1. Group A3 is older material sampled from a relatively large depth. Group C6 is younger material sampled from a relatively shallow depth. Group C3 was selected for testing as the most different sample group from the previously tested sample groups A3 and C6. An extensive large-scale and small-scale laboratory testing program on material from these groups was performed at the various institutions through a coordinated testing program. A brief summary of the laboratory testing performed on the waste and some of the primary findings are presented in this paper.
Table 1. MSW sample groups tested

<table>
<thead>
<tr>
<th>Borehole</th>
<th>A3</th>
<th>C6</th>
<th>C3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth, m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BH-2</td>
<td>25.6-26.2</td>
<td>7.6-9.6</td>
<td>3.5-4.5</td>
</tr>
<tr>
<td>BH-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BH-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% moisture content&lt;sup&gt;1&lt;/sup&gt;</td>
<td>12</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>% organic&lt;sup&gt;1&lt;/sup&gt;</td>
<td>15-30</td>
<td>10-16</td>
<td>20-36</td>
</tr>
<tr>
<td>Age (years)</td>
<td>15</td>
<td>&lt;1</td>
<td>2</td>
</tr>
</tbody>
</table>

<sup>1</sup>As measured on the smaller than 20 mm material at 55°C.

LABORATORY TESTING AT THE UNIVERSITY OF CALIFORNIA AT BERKELEY AND THE UNIVERSITY OF PATRAS

Large-scale cyclic triaxial (CTX) equipment (d=300 mm, h=600-630 mm upon specimen preparation) was used at UCB to perform cyclic triaxial, triaxial compression, extension and lateral-extension tests. Additional conventional-scale cyclic triaxial tests were performed on waste that was processed to make all particles less than 20 mm in size. A direct shear (DS) box, 300 mm by 300 mm by 180 mm, was used at UP to perform shear testing. 1-D compression tests were performed prior to shearing. More information about the devices is presented in Zekkos (2005).

The laboratory testing program evaluated the effects of unit weight, compaction effort, confining stress, waste composition, and loading rate on the monotonic stress-strain response and shear strength, and the dynamic properties, i.e. the small-strain shear modulus, strain-dependent shear modulus and material damping, of MSW. Poisson’s ratio was also measured during some of the triaxial tests.

A total of 23 large-scale direct shear and 27 large-scale monotonic triaxial tests were performed. As shown in Figure 1, direct shear test specimens prepared with the same compaction effort and with 100%, 62% and 12% <20 mm material, were found to have a conventional concave (e.g. hyperbolic) stress-displacement response and similar shear resistances. The similarity in shear resistance is attributed to the fact that shearing occurred parallel to the sub-horizontal orientation of fibrous materials within the waste, and thus, the contribution of the fibrous materials is minimal. The tendency of the fibrous materials to be oriented horizontal was confirmed by sample inspection after testing. This tendency was also observed in triaxial testing of this investigation, and has also been observed in the field by Matasovic and Kavazanjian (1998). Subsequent direct shear tests performed with waste fibers oriented perpendicular to the shear failure surface yielded a convex, upward curvature in the stress-displacement response, which is attributed to the progressive mobilization of the fibrous materials within the waste matrix. Figure 2 illustrates this anisotropic aspect of MSW behavior, comparing two specimens with the same composition, prepared with the same compaction effort, and tested at the same normal stress. The only difference between the two specimens is the orientation of the >20 mm, fibrous materials. The stress-displacement response is different. Details are provided in Zekkos et al. (2007a).

Consistently with the direct shear tests, the stress-strain response in triaxial compression was found to be strongly dependent on fibrous waste content. An upward curvature of the stress-strain curve was observed for all the triaxial compression tests, with the exception being specimens with 100% <20 mm material. This observed behavior may also be attributed to the progressive mobilization of fibrous materials during shearing, as shearing in triaxial compression occurs at an angle from the horizontal orientation of the fibers. This explanation is supported by the observation
that the shear resistance in triaxial compression was higher than that observed in direct shear. The secant friction angle was found to decrease with confining stress both in direct shear and triaxial testing, indicating that a nonlinear strength envelope may be most appropriate for MSW. Shear resistance was found to increase with unit weight, compaction effort, and strain rate (for axial strain rates between 0.5%/min and 50%/min). Test results are presented in Zekkos et al. (2007a, 2007b) in greater detail.

**FIG. 1.** Direct shear strength of MSW with horizontal fiber orientation (from Zekkos et al. 2007a).

**FIG. 2.** Direct shear testing for MSW specimens with different fiber orientations (from Zekkos et al. 2007a).

**FIG. 3.** Strain-dependent (a) normalized shear modulus reduction and (b) material damping curves for MSW based on results from all CTX tests at confining stress <125 kPa (from Zekkos et al. 2006b).

More than 90 cyclic triaxial test series were performed at UCB to evaluate the parameters that affect the dynamic properties of MSW. Of the parameters investigated, waste composition and unit weight were found to have the most important effect on the dynamic properties of MSW. As the amount of fibrous >20 mm material increases, the absolute value of $G_{\text{max}}$ decreases, the normalized shear modulus reduction curve shifts to the right (i.e., threshold strain increases), and the material damping at larger strains reduces significantly. $G_{\text{max}}$ is also significantly affected by confining stress, by unit weight, and by time under confinement, and to a lesser degree by loading frequency. The strain-dependent normalized shear modulus reduction and material damping relationships are affected primarily by waste composition (i.e., amount of
fibrous material larger than 20 mm) and confining stress. They are not significantly affected by unit weight, time under confinement, or loading frequency. The normalized shear modulus reduction curves shift to the right as the amount of material larger than 20 mm increases or as confining stress increases. Correspondingly, material damping reduces at larger strains as the amount of material larger than 20 mm increases or as confining stress increases. Figure 3 illustrates the effect of waste composition on the normalized shear modulus reduction and material damping for all three sample groups and for tests performed at confining stresses <125 kPa. No significant differences in the absolute value of the $G_{\text{max}}$, the $G/G_{\text{max}}$ or damping were observed among the three sample groups. The results of the cyclic triaxial investigation are presented in more detail in Zekkos et al. (2006b).

LABORATORY TESTING AT THE UNIVERSITY OF TEXAS AT AUSTIN

The linear and nonlinear dynamic properties of MSW were investigated at UT with torsional resonant column devices. Two devices were employed. One device was a combined resonant column and torsional shear (RCTS) device. In this device, the specimen has a fixed-free configuration, with nominal dimensions of 71 mm in diameter and 142 mm in height. In the second device, called the large-scale resonant column (LSRC), the specimen has a free-free configuration, with nominal dimensions of 152 mm in diameter and 305 mm in height. The devices are described in Lee(2007).

Reconstituted specimens were tested in both resonant column devices. The advantage of the LSRC device is that larger particle sizes can be used in constructing the specimens. Particle sizes as large as 38 mm were used to construct LSRC specimens. The specimens were reconstituted using the same procedure as used to construct the specimens tested by UCB and ASU. MSW specimens of two ages were tested; old MSW (A3 group) that was about 15 years old and fresh MSW (C6 group) that was less than one year old. For each age, three different waste composition groups were tested: (1) 100% of particles smaller than 20 mm, (2) 62% smaller than 20 mm, and (3) 14% smaller than 20 mm. The larger particles in groups #2 and #3 consisted of paper, soft plastic, wood and gravel. The total unit weights for these three specimen groups were, on average, 12 kN/m$^3$, 10 kN/m$^3$, and 8 kN/m$^3$, respectively.

Staged testing on a loading pressure sequence was performed at five confining pressures. Typical results from testing old MSW with the LSRC are shown in Figures 4 through 7. Variations in the small-strain dynamic properties with total isotropic confining pressure, $\sigma_o$, are shown in Figures 4 and 5, in terms of shear wave velocity, $V_s$, and material damping ratio, $D_{\text{min}}$, respectively. As seen in Figure 4, the $\log V_s - \log \sigma_o$ relationships for each MSW group are composed of two straight lines. The first straight line represents the waste in the overconsolidated state (induced by compacting the specimen) and the second straight line represents the waste in the normally consolidated state. The maximum preconsolidation pressure, $\sigma_p$, as interpreted based upon the intersection of the two straight lines, is about 48 kPa. At each test pressure, the values of $V_s$ decrease as the percentage of particles <20 mm decreases. As a point of reference, the $V_s$ values for specimens with 100% < 20 mm are about 50-75% of the $V_s$ values of reconstituted loose sand at the same pressures.
The variation of $D_{\text{min}}$ with $\sigma_0$ is shown in Figure 5. The value of $D_{\text{min}}$ increases significantly with excitation frequency. A frequency correction was applied to $D$ using a second order polynomial relating $D/D(1\text{Hz})$ to $\log(f)$, developed based upon tests conducted on MSW over a range of frequencies from 0.03 Hz to approximately 200 Hz. Details are provided in Lee (2007). When corrected to an excitation frequency of 1 Hz, $D_{\text{min}}$ varies only slightly with percentage of particles < 20 mm and decreases slightly with increasing $\sigma_0$. For these tests, the average value of $D_{\text{min}}$ at $f = 1$ Hz is about 3%. This value is on the order of three times that of most granular soils, and is more similar to values for clay or organic soils.
Examples of the nonlinear response of old MSW are shown in Figure 6 for the variation of normalized shear modulus, $G/G_{\text{max}}$, with shearing strain amplitude, $\gamma$, and in Figure 7 for the variation in material damping ratio, $D$, with $\gamma$. All results shown in Figures 6 and 7 were determined at a confining pressure of 76 kPa. The linearity in normalized shear modulus and material damping ratio increases as the percentage of particles < 20 mm decreases; that is, the $G/G_{\text{max}} - \log \gamma$ and $D - \log \gamma$ relationships shift to larger values of $\gamma$ as the percentage of larger particles increases in the waste. As a point of reference, all waste groups exhibit more linear $G/G_{\text{max}} - \log \gamma$ curves than sand. However, they exhibit higher damping than sand at shear strains below 0.02 % and lower values at strains above 0.05 %.

The fresh MSW was tested over the same test and material parameters as discussed above. In comparison with the old waste, the fresh waste generally has: (1) nearly the same values of $V_s$, (2) slightly higher values of $D_{\text{min}}$, (3) very similar nonlinear behavior in terms of $G/G_{\text{max}}$, and (5) slightly higher values of $D$.

**LABORATORY TESTING AT ARIZONA STATE UNIVERSITY**

Large-scale simple shear tests are being conducted at ASU using a stacked-plate direct shear apparatus. Teflon-coated steel plates 12 mm-thick with a rectangular opening approximately 550 mm-long (in the direction of the applied shear stress) and 350-mm wide are used to impose a zero lateral strain condition on the compacted specimen. Specimens approximately 150 mm-tall from A3 group are being tested under monotonic and cyclic loads. Most tests are being conducted at a normal stress of 150 kPa in order to achieve a mean normal stress of 76 kPa, based upon a $K_0$ value of between 0.25 and 0.3, as measured by tactile pressure sensors placed against the side walls of the stacked frames in the simple shear device prior to compaction of the specimen. Uniform cyclic testing was conducted at shear strain amplitudes from 0.03% to 3%. Laboratory tests at ASU are still in progress and will be reported on subsequently. Initial test results, however, show a conventional concave stress-strain curve similar to that observed in triaxial and direct shear tests in shear across the waste fibers and similar modulus reduction characteristics as measured in the UCB tests.

**CONCLUSIONS**

As part of a collaborative research project, an extensive laboratory testing program of representative MSW samples recovered from a landfill in the San Francisco Bay Area using 7 testing devices has been performed. Key factors that affect the static and dynamic properties of MSW were studied. The results from the comprehensive testing program were consistent and indicated, among others, that the influence of waste composition and confining stress on the static and dynamic properties of MSW is critical. In particular, the influence of fibrous materials on the stress-strain and shear strength of MSW is highlighted.
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