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Large-scale direct shear testing of municipal solid waste

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ABSTRACT

Large direct shear testing (300 mm × 300 mm box) of municipal solid waste (MSW) collected from a landfill located in the San Francisco Bay area was performed to gain insight on the shear response of MSW. The study investigated the effects of waste composition, confining stress, unit weight, and loading rate on the stress–displacement response and shear strength of MSW. The amount and orientation of the fibrous waste materials in the MSW were found to play a critical role. The fibrous material had little effect on the MSW's strength when it was oriented parallel to the shear surface, as is typically the case when waste material is compressed vertically and then tested in a direct shear apparatus. Tests in which the fibrous material was oriented perpendicular to the horizontal shear surface produced significantly stronger MSW specimens. The test results indicate that confining stress and loading rate are also important factors. Based on 109 large-scale direct shear tests, the shear strength of MSW at low moisture contents is best characterized by cohesion = 15 kPa, friction angle = 36° at a normal stress of 1 atmosphere, and a decrease in the friction angle of 5° for every log-cycle increase in normal stress.

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1. Introduction

The response in shear of municipal solid waste (MSW) is an important consideration in landfill design, particularly for the evaluation of a landfill's static and seismic stability. Several MSW landfill instabilities have occurred in recent years, including the Rumpke Landfill in Ohio (Eid et al., 2000), Dona Juanna Landfill in Colombia (Hendron et al., 1999), Payatas Landfill in Philippines (Kavazanjian and Merry, 2005), and Java landfill in Indonesia (Koelsch et al., 2005). These failures had significant economic consequences and in some cases resulted in the loss of human life. An improved understanding of the shear response of MSW is required to support sound stability evaluations of landfills.

With the aim of providing insights regarding the mechanical response of MSW, a collaborative research program that involved the University of California at Berkeley, Arizona State University, Geosyntec Consultants, University of Patras (Greece), and the University of Texas at Austin was undertaken. One of its primary objectives was to evaluate the static and dynamic properties of MSW by systematically characterizing and testing MSW in the field and laboratory. Findings of the collaborative investigation are summarized in Zekkos et al. (2008a). Recommendations for estimating the unit weight of MSW (Zekkos et al., 2006) and the dynamic properties of MSW (Zekkos et al., 2008a) have been presented elsewhere. An overall assessment of the shear strength of MSW using several testing devices has been presented in Bray et al. (2009). The purpose of this paper is to describe in detail the direct shear results performed as part of the large-scale laboratory testing program. In light of the improved understanding of the mechanics of waste response gained through this investigation, the available large-scale direct shear test data are re-evaluated, and the shear strength of MSW in direct shear is characterized.

2. Literature review

The strength envelope recommended by Kavazanjian et al. (1995) is often used in engineering practice to characterize the shear strength of MSW. This bilinear strength envelope consists of a purely cohesive material with cohesion (c) of 24 kPa for normal stresses up to 30 kPa and a purely frictional material with a friction angle (ϕ) of 33° at higher normal stresses. The envelope was intended to be a conservative estimate of the shear strength of MSW; it was based on a limited number of laboratory and field tests and the back-calculation of stable waste slopes. More recently, Eid et al. (2000) relied on a larger database of laboratory data and back-calculations of three unstable slopes in developing a linear shear strength envelope that was characterized on average by $c = 25$ kPa and $\phi = 35°$. Zekkos (2005) performed an extensive review of the literature and identified significant differences in the MSW shear strength parameters proposed by other researchers. Mohr–Coulomb strength parameters with cohesions varying from 0 to 80 kPa and friction angles varying from 0° to 60° have been proposed by several different researchers (Fig. 1). The se-

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lected value of the cohesion and friction angle used in conducting landfill analyses is obviously critical.

3. Characterization of the waste tested in this study

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 in north California. Bulk waste samples from small and large depths, varying in age from 0 to 15 years old, were retrieved and stored separately in 39 sealed 55-gallon drums of bulk waste material. Excessive grinding of the waste particles was not observed, so the collected waste materials are assumed to be unprocessed. Two to four drums of waste were collected at each 3 m sampling interval. The in situ unit weight of waste was measured using the procedures described in Zekkos et al. (2006). Its unit weight increased from 10 kN/m^3 near the surface to 16 kN/m^3 at greater depths. Waste material was transported to the Richmond Field Station of the University of California at Berkeley, where it was characterized. Waste characterization included separating the waste material into material larger and smaller than 20 mm. This segregation is considered useful, because material <20 mm is composed of soil-like material that is derived primarily from daily cover, other soil materials, and some fine waste inclusions, whereas material >20 mm generally consists of bulk and fibrous waste materials. Additionally, material <20 mm can be characterized using conventional soil mechanics index tests, such as sieve analyses and Atterberg limits, and it can be tested using geotechnical testing equipment.

Waste samples that were collected as part of this study form three general classes. Class A is relatively "deep old waste" and included sample groups A1–A4. Class B is "deep old waste with fibrous <20 mm material" and included sample group B1. Class C is "shallow fresh waste" and included sample groups C1–C6. Classes A and B waste were placed in 1987; whereas Class C waste was placed after 1999. The percentage by weight of the <20 mm material and the amount of plastic, paper, wood, gravel and other constituents of the >20 mm material were measured for a total of 6 waste sample groups. The mass of the processed samples varied from 60 to 320 kg. About 50–75% of the total waste sample by weight was <20 mm material, and the >20 mm material consisted primarily of paper, plastic, wood, and gravel. Other constituents such as metals, glass, stiff plastics, and textiles, comprised a significantly lower percentage of the material by weight and by volume. Details of the field investigation and waste characterization are provided in Zekkos (2005).

Based on this characterization of the waste, three sample groups were selected for a comprehensive program of laboratory testing that included compressibility and strength testing using several test devices, such as direct shear, simple shear, and triaxial. Group A3 is material sampled from borehole BH-2 at 26 m depth and was 15 years old at the time of drilling (placed in 1987). Group C6 includes material sampled from borehole BH-1 at a different location of the landfill at 8 m depth and was 2 years old at the time of drilling (placed in 2000). A third sample Group C3 was selected for testing, because it was judged to be composed of material that differed most from the other two tested groups. It originated from borehole BH-2 at a depth of 3.5–4.5 m, was less than 1 year old at the time of drilling (placed in 2002), and was visually identified as having significantly more paper constituents in the <20 mm fraction than sample groups A3 and C6. The organic content of the <20 mm material, as measured by the loss of mass due to heating from a temperature of 105–440 °C was 13–23%, 11–13%, and 17–27% for the A3, C6, and C3 sample groups, respectively.

Triaxial testing was performed on material from all three samples without any systematic differences in the results among sample groups (Bray et al., 2009). The direct shear testing was performed on material from the A3 group, shown in Fig. 2. All specimens were prepared at the in situ moisture content of the material, which was found to be approximately 12% for the <20 mm material and about 20–25% for the >20 mm material. Moisture content is defined as the ratio of weight loss at 55 °C to the weight that remained after the completion of the test. Because these moisture contents are low (i.e., below typical field capacities of waste), the response of the material is essentially fully drained. The effects of the moisture content on the shear response of MSW were not investigated as part of this study.

4. Large-scale direct shear laboratory testing program

The large-scale direct shear test apparatus at the University of Patras was used in this study (Fig. 3). The shear box is 300 mm × 300 mm in plan view and 180 mm high. It has a load capacity of 100 kN in both horizontal and vertical directions. Displacement rate can be controlled up to a maximum value of 5 mm/min. In this study, the displacement rate was selected nominally to be 1 mm/min, but it was varied in a subset of the tests to

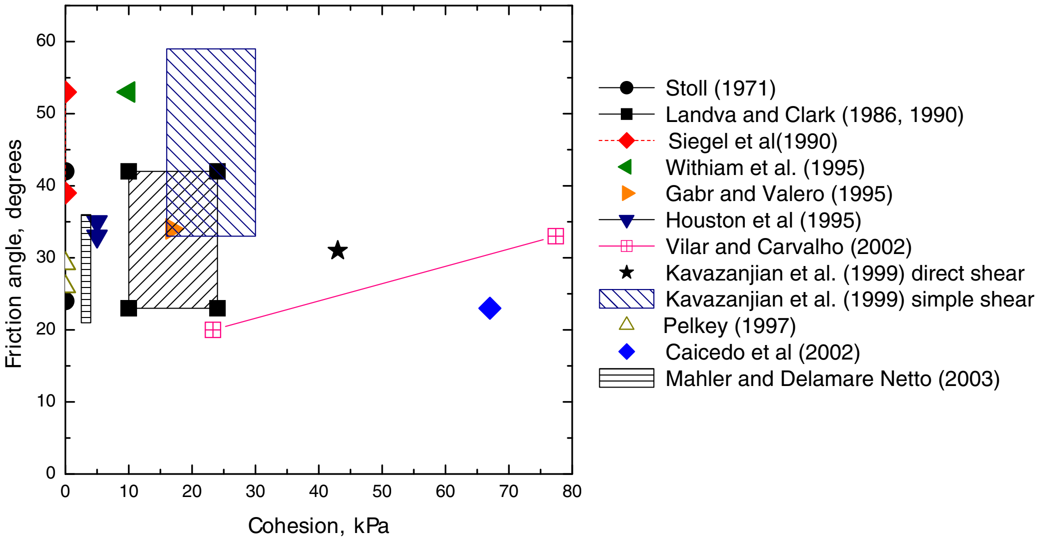

Fig. 1. MSW Mohr–Coulomb shear strength parameters reported in the literature. (see above mentioned reference for further information.)

Fig. 2. Tested sample of municipal solid waste.

explore the effects of loading rate. While maintaining a constant vertical load, the horizontal displacement of shear box, the vertical displacement of specimen top cap, and the horizontal shear force were recorded during testing using a digital data acquisition system. The direct shear tests are presented in detail in Grizi (2006) and Theodoratos (2007). Interpretations of these test results and insights from these interpretations are described in this paper.

A total of 23 large-scale (300 mm × 300 mm × 180 mm in height) specimens were tested in the laboratory at initial normal stresses of 2 kPa, 50 kPa, 150 kPa, 370 kPa, and 700 kPa. Initially, five specimens were prepared consisting entirely of <20 mm material and were tested at various normal stresses. Subsequently, the >20 mm material was added and the specimens were prepared using the same compaction effort, except when necessary to study the effect of compaction effort. The >20 mm material consists of paper, plastic, wood, and gravel. Thus, with the exception of the gravel that represents a relatively small volumetric portion of the >20 mm material, the >20 mm material is fibrous. Two different maximum particle size criteria were established. For stiff, bulky waste particles, such as gravel and wood, a sieve with a 38 mm (1.5″) opening was used. For flexible waste particles, such as paper and soft plastics, the maximum particle size was allowed to be 76 mm (3″), because paper and flexible plastics are soft, elongated, and generally sheet-like materials that can fold during specimen preparation. Hence, larger size materials than those of the bulky wood and gravel were allowed for flexible, fibrous waste materials.

MSW specimens with 100% by weight <20 mm material, 62% <20 mm material, and 12% <20 mm material were tested. The compositions of the waste test specimens are provided in Table 1. Specimens with 62% <20 mm material had compositions that were similar to the field sample composition. The other waste specimen compositions of 100% <20 mm and 12% <20 mm material allowed the study of this important factor.

Specimens were compacted through a standardized, repeatable method developed by Zekkos (2005). The specimens were prepared in the shear box in three layers and were compacted by repeatedly dropping a 100 N weight from a height of 0.8 m above the specimen surface (Fig. 4) to apply a target compaction effort or achieve a target specimen unit weight by controlling the number of drops per layer. The particle unit weight of the coarser fraction, particularly of the fibrous materials such as the paper, soft plastic and wood is significantly lower than the particle unit weight of the <20 mm material. As a result, the proportion of fibrous materials by volume for the specimens that include 62% by weight <20 mm material, for example, is relatively high. Fig. 5 shows the quantities of paper and <20 mm material that were used to prepare a test specimen containing 62% by weight <20 mm material. The relative weight of paper to soil is 4.7:1; however, the apparent volume of paper is significantly greater than that of the soil.

Direct shear stress–displacement test results for the first eleven test specimens described in Table 1 are presented in Fig. 6. These waste specimens contained 100% and 62% <20 mm material. They were compacted to unit weights varying from 8.5 to 14.1 kN/m^3, and tested at vertical stresses as low as 1.8 kPa and as high as 857 kPa. As displayed in Fig. 6, a relatively wide range of shear stress vs. horizontal displacement responses was observed. Using these test results and those from tests on the other 12 test specimens, this study investigated the effects of compaction energy, unit weight, waste composition, confining stress, and loading rate on the stress–displacement response and shear strength of MSW. Shear strength is defined in the direct shear tests of this investigation as the mobilized shear stress at a displacement of 55 mm, which is the maximum displacement of the testing apparatus, unless peak shear stress conditions are reached at smaller horizontal displacements. Except in one case, the mobilized shear stress was continuing to increase up to the maximum displacement of 55 mm. The stress–strain response of waste in these direct shear tests that applied a slightly increasing normal stress was largely strain-hardening as shown in Fig. 6.

5. Effects of waste composition

A series of tests were performed to investigate the importance of the amount and orientation of fibrous materials to the shear stress–displacement response of MSW. Fig. 7 presents the results

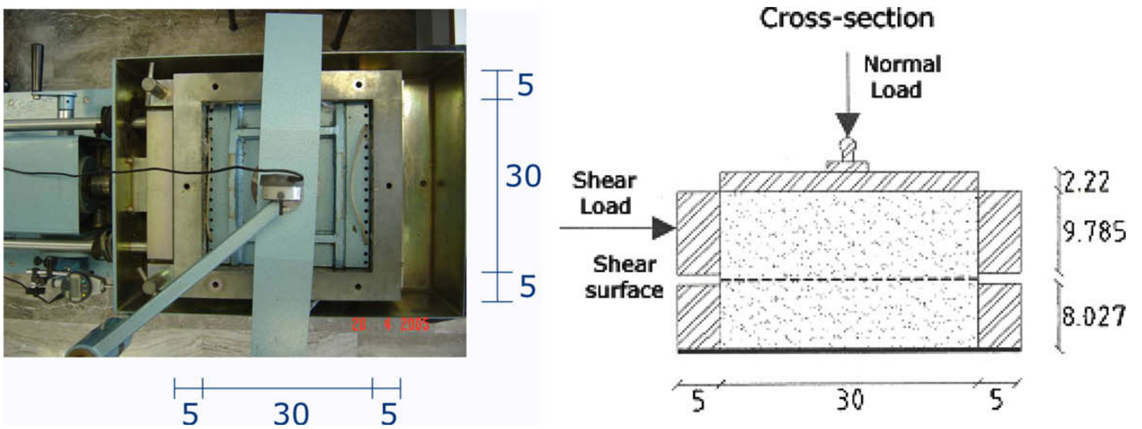

Fig. 3. Plan view and cross-section of large direct shear box (dimensions in cm).

Table 1

Summary of large direct shear specimens and tests performed as part of this research project.

Specimen ID	Normal stress (kPa)[d]	Unit weight upon preparation (kN/m^3)	Unit weight immediately prior to shearing (kN/m^3)	<20 mm material	Paper	Wood	Soft plastics	Gravel	Shear stress at 55 mm (kPa)	Fiber orientation (degrees)	Shearing rate (mm/min)
UP-1[a]	150 (178.8)	13.1	14.5	100	0	0	0	0	153.0	0	1
UP-2	50 (61.3)	14.0	15.1	100	0	0	0	0	78.1	0	1
UP-3	370 (453)	14.07	17.5	100	0	0	0	0	316.9	0	1
UP-4[b]	1.8 (1.9)	14.1	14.1	100	0	0	0	0	12.8	0	1
UP-5	150 (183.6)	11.4	13.9	100	0	0	0	0	127.4	0	1
UP-6	50 (61.23)	10.2	11.5	62.1	17.9	4.7	4.7	10.6	83.0	0	1
UP-7	150 (183.6)	10.1	12.2	62.1	17.9	4.7	4.7	10.6	150.7	0	1
UP-8	370 (453)	10.1	13.6	62.1	17.9	4.7	4.7	10.6	311.3	0	1
UP-9	700 (857.2)	10.5	15.5	62.1	17.9	4.7	4.7	10.6	502.6	0	1
UP-10	1.8 (2.27)	10.4	10.4	62.1	17.9	4.7	4.7	10.6	17.4	0	1
UP-11	150 (183.6)	8.5	10.2	62.1	17.9	4.7	4.7	10.6	122	0	1
UP-12	1.8 (2.27)	10.4	10.4	62.1	17.9	4.7	4.7	10.6	17.4	0	1
	50 (61.25)	N/A	12.0						89.0		1
	150(183.6)	N/A	13.9						186.7		1
	370 (453)	N/A	15.6						337.0		1
UP-13[c]	150 (183.6)	10.2	13.6	62.1	17.9	4.7	4.7	10.6	186.6	90	1
UP-14[c]	370 (453.2)	10.5	14.7	62.1	17.9	4.7	4.7	10.6	325.3	90	1
UP-15[c]	1.8 (2.27)	10.3	10.3	62.1	17.9	4.7	4.7	10.6	36.8	90	1
	50 (61.2)	N/A	12.1						99.6		1
	150 (183.6)	N/A	13.7						201.2		1
	370 (451.2)	N/A	16.5						334.0		1
UP-16[c]	150 (183.7)	9.9	11.8	62.1	17.9	4.7	4.7	10.6	173.0	0	0.1/5
UP-17[b]	2 (2.3)	5.9	5.9	12	52.8	17.6	17.6	0	11.4	0	1
UP-18[b]	50 (61.2)	5.9	7.2	12	52.8	17.6	17.6	0	62.4	0	1
UP-19[b]	50 (61.2)	6.0	6.8	12	52.8	17.6	17.6	0	73.7	90	1
UP-20[c]	50 (61.2)	6.4	7.7	12	52.8	17.6	17.6	0	71.0	0	0.1/5
UP-21[c]	50 (61.3)	6.6	6.7	12	52.8	17.6	17.6	0	86.3	90	0.1/5
UP-22[b]	150 (183.8)	6.4	8.4	12	52.8	17.6	17.6	0	135.1	0	1
UP-23[b]	370 (453.3)	6.2	10.1	12	52.8	17.6	17.6	0	306.0	0	1

[a] Specimen sheared to a displacement of 48.2 mm and the shear stress at this displacement is reported.

[b] Specimen reached peak shear stress conditions at 9.2 mm displacement and the shear stress at this displacement is reported.

[c] Specimens with particle orientation perpendicular to the horizontal failure surface.

[d] The applied vertical stress at the beginning of the test and at a displacement of 55 mm (in parenthesis).

Fig. 4. Drop weight used for the MSW specimen preparation.

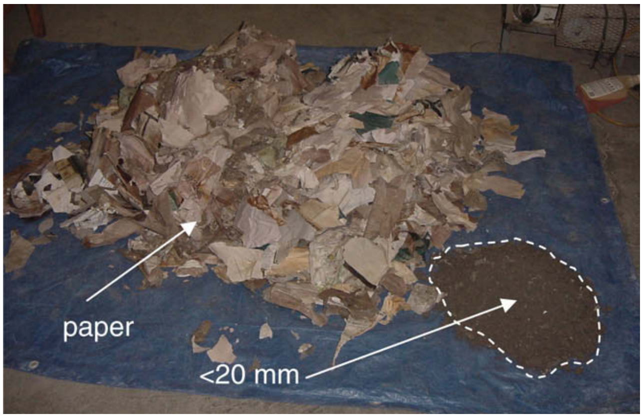

Fig. 5. Comparison of volumes of paper and material <20 mm, used for preparing a test specimen.

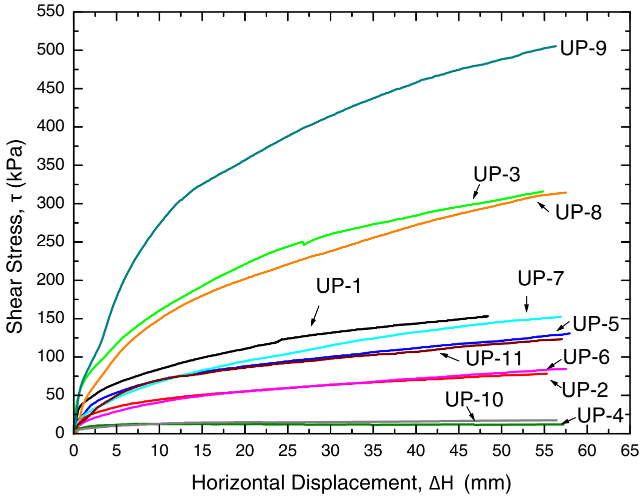

Fig. 6. Representative direct shear stress–displacement data on MSW.

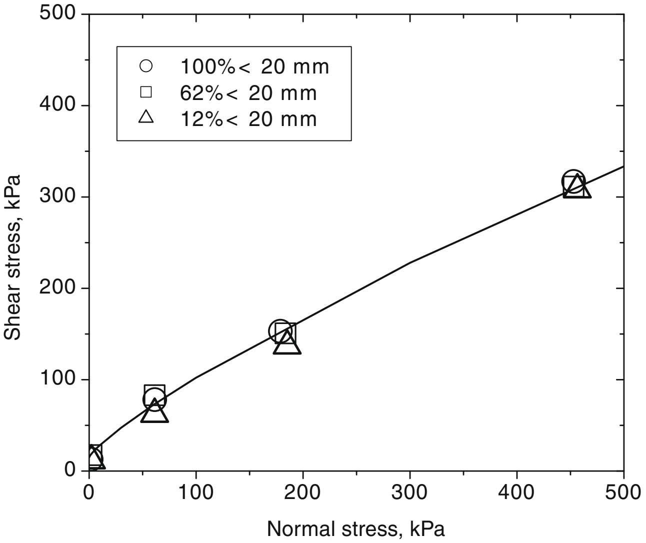

Fig. 7. Shear vs. normal stresses for MSW specimens from Tri-Cities landfill.

for waste specimens that were prepared with approximately the same compaction effort, but varying waste composition. Specimens that consisted entirely of <20 mm material exhibited essentially the same shear strength with specimens that included 62% and 12% <20 mm material, indicating that the fibrous materials within the MSW did not participate significantly in the shear response of the specimen. It is surmised that this occurred, because the fibrous materials tend to become oriented nearly parallel to the horizontal shear surface, even though they were randomly placed in the specimen preparation mold when originally preparing the specimen. During compaction of the waste within the direct shear box, the elongated, planar, fibrous waste particles were observed to become horizontally oriented. This type of waste particle structure was also observed in field surveys of waste materials in operating landfills. Although the waste material was not oriented preferentially when placed initially, the fibrous constituents of the waste tend to become aligned sub-horizontally as a result of compaction and the increasing vertical stress from placing additional waste on top of previously placed waste (Matasovic and Kavazanjian, 1998). The horizontal layering of the fibrous waste constituents likely occurred also in the MSW direct shear specimens tested by others (e.g., Landva and Clark, 1990; Edincliler et al., 1996; Kavazanjian, 1999).

Therefore, it is reasonable to expect that the MSW specimen shear response is anisotropic. When shearing in direct shear occurs parallel to the long axis of the fibrous waste particles, the fibrous constituents are not engaged and their reinforcing effect is minimal, resulting in a relatively weaker waste specimen. The waste material is expected to be significantly stronger when shearing is forced to cut across the fibrous material so that it reinforces the waste material.

Several direct shear tests were performed with the fibrous materials oriented perpendicular to the horizontal shear surface (i.e., in the vertical direction) to evaluate the validity of this hypothesis. A custom-made specimen preparation split-mold was used with plan dimensions of 300 mm × 180 mm and a height of 300 mm (Fig. 8a). The waste specimen was compacted in the specimen preparation mold using the same compaction device and procedure described previously. The mold walls were subsequently removed, and the specimen stood unsupported (Fig. 8b). The specimen was then wrapped with a thin film and carefully placed in the direct shear box after being rotated 90°.

Three specimens that included 62% <20 mm material and two specimens that included 12% <20 mm material were prepared as described above and were tested at normal stresses of 2 kPa, 50 kPa, and 150 kPa. Fig. 9 illustrates the shear stress–displacement response of two pairs of specimens sheared at normal stresses of 2 kPa (UP-10 and UP-15) and 50 kPa (UP-18 and UP-19), respectively. The two specimens tested at 2 kPa normal stress have identical specimen compositions and the same unit weight prior to shearing. Specimen UP-10 has fibrous waste oriented approximately parallel to the horizontal shear plane (*i* = 0°), whereas specimen UP-15 has fibrous waste oriented perpendicular to the horizontal shear plane (*i* = 90°). The two responses are significantly different. Specimen UP-15 has lower shear resistance at smaller displacements, but the shear resistance increases significantly at larger displacements and the stress–displacement response exhibits a pronounced upward curvature instead of approaching peak shear stress conditions. The lower shear resistance of specimen UP-15 compared to UP-10 at smaller displacements may be attributed to the displacement that is required before the fibers are "engaged" so that they can contribute to the shear resistance. Specimen UP-15 has a shear resistance that is over twice that of UP-10 at horizontal displacement of 55 mm. Hence, the shear resistance of MSW is anisotropic and is significantly affected by the relative orientation of the fibers to the horizontal shear surface. The important effect of the relative orientation of the fibers to the horizontal shear surface has also been confirmed on synthetic waste from Greece (Athanasopoulos et al., 2008).

Similar results are observed for the pair of waste specimens tested at a normal stress of 50 kPa, however, the difference is less pronounced, and the ratio of the shear resistances of the two specimens at 55 mm is only 1.2. The upward curvature observed for the specimens with the fiber orientation at an angle of 90° to the horizontal shear plane is becoming progressively less pronounced at higher normal stresses. Fig. 10 illustrates the shear resistance for specimens with 62% <20 mm material and fiber orientation of 90° to the horizontal at different normal stresses. The stress–displacement response of each test is normalized by the corresponding shear resistance at 55 mm displacement. The stress–displacement response of specimen UP-13 at a normal stress of 150 kPa still exhibits a slightly upward curvature, but it is much less pronounced than the response of specimen UP-15 at a normal stress of 2 kPa. The response of specimen UP-14 at a normal stress of 370 kPa exhibits essentially no upward curvature for displacements up to 55 mm. It does exhibit a slightly higher shear resistance compared to its counterpart specimen that was tested at a fiber orientation of 0° to the horizontal, but the difference between

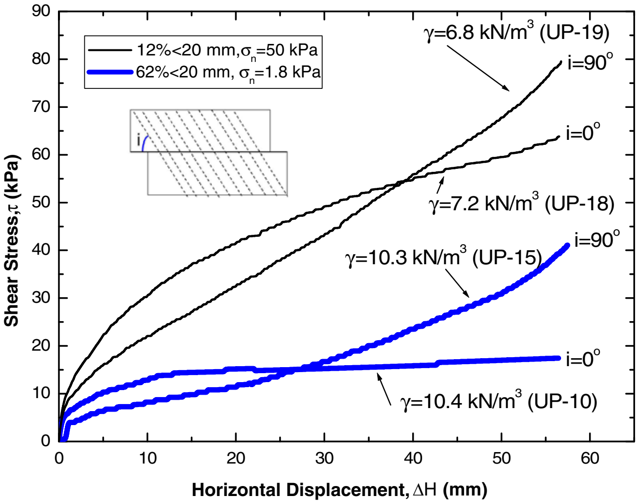

Fig. 9. Effects of the amount of fibrous material and its orientation with respect to the shear surface.

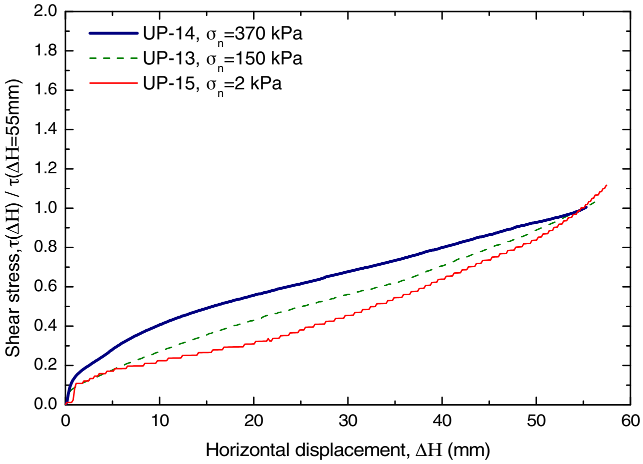

Fig. 10. Normalized shear stress plots for specimens with particle orientation perpendicular to the shear failure surface at different normal stresses.

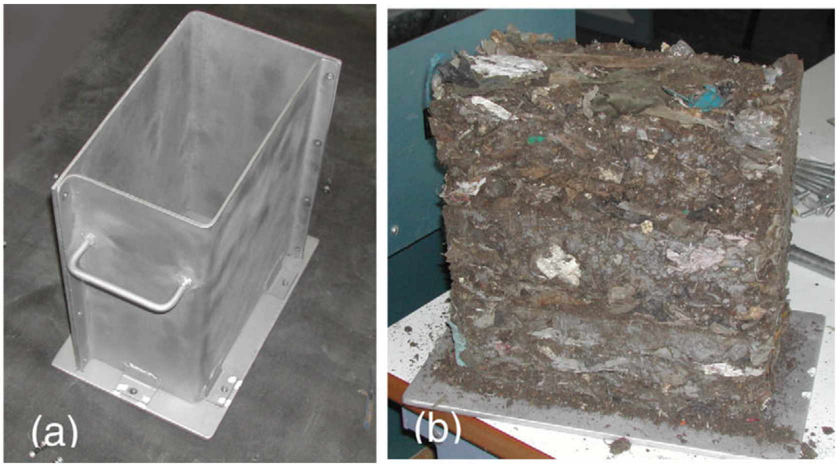

Fig. 8. (a) The split-mold used for compacting specimens outside of the direct shear box, (b) view of specimen prepared outside the direct shear box.

the responses of the waste specimen with fibrous particles oriented perpendicular and parallel to the shear plane is less.

The reasons for the reduction in the upward curvature with increasing normal stress are not entirely clear, but at least four possible mechanisms may be postulated: (i) the mobilization of the fibers at larger confining stresses may actually occur at larger displacements than those reached in the test; (ii) when large normal stresses are applied to specimens that initially included particles oriented in the vertical direction, the fibrous materials are initially under compression and more deformation is required for the fibers to become stretched; (iii) under large normal stresses, the particles that were originally oriented in the vertical direction, are re-oriented in less than vertical orientations to accommodate the increased anisotropic stress conditions; or (iv) the waste response is more dilative at lower normal stresses, and as is the case for reinforced earth materials, this dilative response is more effective in mobilizing the fibrous materials during the shear response. Further research is warranted to resolve this issue.

6. Effects of compaction energy and unit weight

The compaction energy during specimen preparation affects the unit weight of the material and its shear resistance. Fig. 11 presents the shear stress–displacement response for two pairs of waste specimens sheared under an applied vertical stress of 150 kPa. Each pair of waste specimens has the same composition (i.e., either 100% <20 mm material or 62% <20 mm material), but the specimens were prepared with different compaction efforts to achieved different unit weights. The pair of test specimens with 62% <20 mm has unit weight of 10.2 kN/m^3 or 12.2 kN/m^3. The denser specimen exhibits higher shear resistance. This is also observed for the pair of test specimens that had 100% <20 mm material. These test results emphasize the importance of the unit weight of MSW in characterizing its shear stress–displacement response.

For the same compaction energy during specimen preparation, waste specimens that include larger amounts of the >20 mm material have systematically lower unit weights. This is caused by the lower particle unit weight of the >20 mm material compared to the <20 mm material. Fig. 12 presents the shear stress–displacement response of two test specimens with different waste compositions, but with the same compaction energy during specimen preparation. Specimen UP-2 has 100% <20 mm material with a unit weight of 15.1 kN/m^3 prior to shearing. Specimen UP-6 has 62% <20 mm material with a unit weight of 11.5 kN/m^3 prior to shearing. The two specimens have different unit weights (as a result of their different composition), but have similar shear stress–displacement responses and both curves approach but do not reach peak shear stress conditions. This similarity in their responses is attributed to the fact that the two specimens have essentially the same compaction effort and similar soil matrices. The fibrous waste, while present in specimen UP-6 does not participate in shearing and thus does not affect the MSW's shear resistance. These test results emphasize the importance of waste composition in characterizing the strength of MSW. Therefore, both waste composition and unit weight affect the shear stress–displacement response of MSW, and neither one of them can be used independently of the other to describe waste.

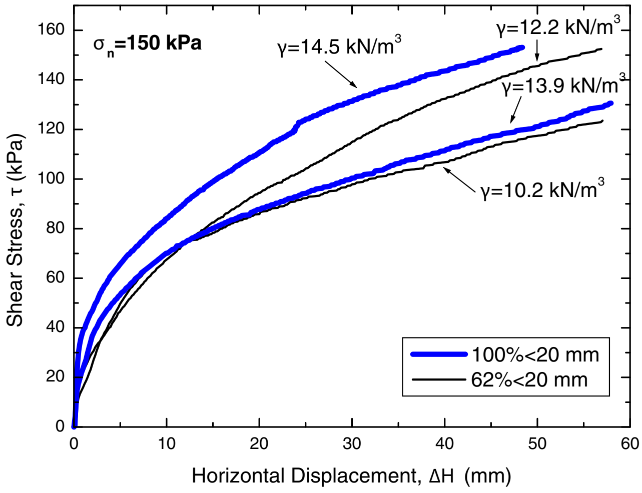

Fig. 11. Effects of unit weight on the direct shear stress–displacement response of solid waste.

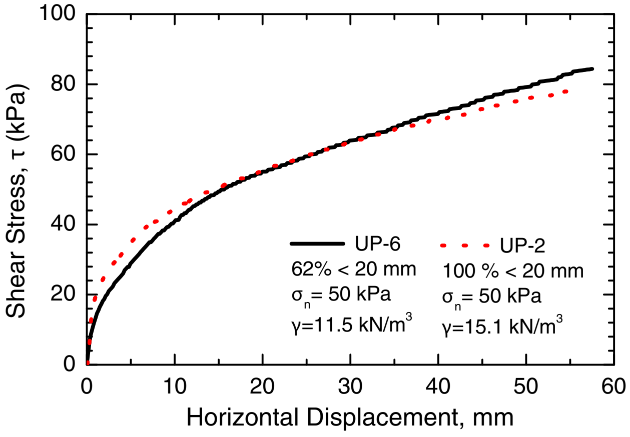

Fig. 12. Shear stress vs. horizontal displacement from direct shear tests of specimens with same compaction effort and different content of <20 mm material.

7. Effects of loading rate

A series of direct shear tests were performed to evaluate loading rate effects on the strength of MSW. The shearing rate was modified during tests on the same waste specimen to eliminate scatter due to specimen variability. Tests were performed at displacement rates of 0.1 mm/min and 5 mm/min on a waste specimen with 62% <20 mm material and two waste specimens with 12% <20 mm material. One of the 12% <20 mm material waste specimen had horizontally oriented fibrous materials, and the other had vertically oriented fibrous materials. Test results are presented in detail

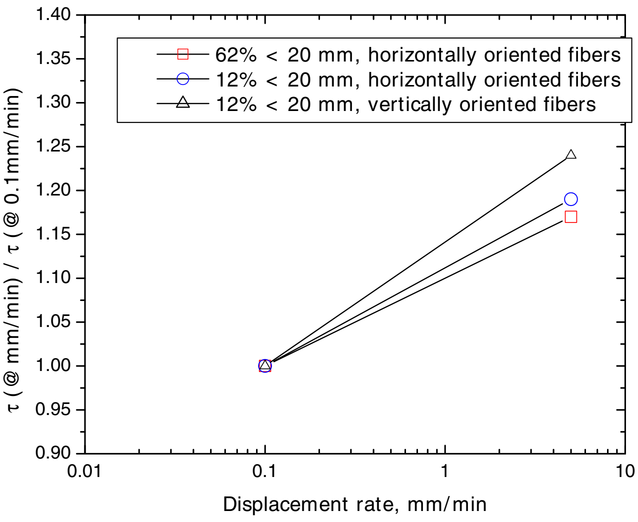

Fig. 13. Summary of direct shear tests sheared at two displacement-rates.

in Zekkos et al. (2007) and are summarized in Fig. 13. The shear strength of MSW increases significantly as the applied displacement rate increases. For these tests, the shear strength increases about 10% for a tenfold increase in the displacement rate. The strength increase is greater when the shearing process fully engages the fibrous materials (i.e., for the test with vertical fibers that are oriented perpendicular to the imposed horizontal shearing surface). When the fibrous materials are oriented parallel to the shearing surface, the rate of strength increase appears to be relatively insensitive to the amount of fibrous materials within the waste specimen. These findings are consistent with previous findings regarding the interaction of fibrous materials within waste when sheared along or across fibers within the waste.

8. Effects of normal stress

Normal stress has an important effect on the shear strength of MSW. As normal stress increases, the shear strength of the waste increases. However, as shown previously in Fig. 7, the increase in shear strength with increasing normal stress is not a linear relationship. Instead, the slope of the Mohr–Coulomb failure envelope decreases slightly as normal stress increases, which indicates a reduction in the friction angle with increasing normal stress. This important effect, discussed in more detail subsequently, is also observed in triaxial testing (Bray et al., 2009).

9. Effects of staged testing

A series of direct shear tests at several levels of increasing normal stress is sometimes performed on the same waste specimen (e.g., Houston et al., 1995; Withiam et al., 1995) to minimize specimen variability effects and to improve testing efficiency. This practice is generally considered to provide conservative estimates of strength, as it is postulated that shearing in stages at higher normal stresses yields lower shear strengths due to the effects of pre-shearing in the previous loading stages. This practice was investigated in this study by preparing and testing two specimens in stages and comparing their shear resistance to nearly identical specimens with similar unit weights, compositions, and fiber orientations. The two specimens (UP-12 for horizontal fibers and UP-15 for vertical fibers) were tested in stages at normal stresses of 2 kPa, 50 kPa, 150 kPa, and 370 kPa. The specimens were sheared at each normal stress level until a horizontal displacement of at least 55 mm was reached, the vertical load was then removed, and the device was returned to its original position (i.e., at zero horizontal displacement). A larger vertical load was applied, and the specimens was allowed to compress for about 2–3 h, after which there was no significant additional vertical deformation occurring. Then, the next direct shear load test stage commenced. The test specimens subjected to the staged tests did not appear to be weaker than their counterpart specimens which were loaded directly to the specified normal stress and were sheared only once. Thus, the staged loading technique did not produce significant bias in these measurements of the stress-dependent strength of MSW.

There are two likely explanations for the observed response in these staged loading tests. First, the tests examined as part of this test did not reach peak shear stress conditions during each load stage because the peak stress was not reached at the maximum displacement of the testing apparatus. It is unlikely that a significant shear band developed in the waste specimen at the end of each load stage. Thus, the waste was not significantly pre-sheared before the next load stage. A second reason may be that during recompression of the specimen under the higher normal stress, the shear surface that may have partially developed previously is compressed downwards so that it is now below the level of shearing imposed in the next stage of the test. Thus, a shear surface that is different than that previously formed is sheared during the next stage of the test. Pre-shearing effects would not be expected in this case.

10. Shear strength for MSW in direct shear

10.1. Tri-Cities landfill large-scale direct shear data

The direct shear test results developed as part of this study indicate that the Mohr–Coulomb shear strength envelope is not linear as has been suggested by previous investigators. Instead, its strength envelope is noticeably concave downward (Fig. 7). Thus, the friction angle reduces with increasing confining stress. Similar to soils (e.g., Duncan and Wright, 2005), it can be hypothesized that the friction angle of MSW decreases linearly with the logarithm of normal stress (Zekkos et al., 2007; Bray et al., 2009). Using this approach, a unique nonlinear stress-dependent shear strength envelope can be defined for all specimens compacted in the conventional manner (i.e., for compaction with a drop weight that produces essentially horizontally oriented fibers) regardless of the amount of fibrous material present in the MSW.

The direct shear strength for MSW can be described by:

$$\tau = c + \sigma_n \cdot \tan(\phi) \tag{1}$$

where τ is the shear strength of MSW in direct shear; σ_n is the normal stress; c is the cohesion intercept; and ϕ is the friction angle defined as:

$$\phi = \phi_o - \Delta\phi \cdot \log\left(\frac{\sigma_n}{p_a}\right) \tag{2}$$

where ϕ_o is the friction angle at a normal stress of one atmosphere (P_a, i.e., P_a = 101.3 kPa); and $\Delta\phi$ is the change in friction angle over a log-cycle change in normal stress. For the large-scale direct shear tests performed on the Tri-Cities landfill waste test specimens as part of this study, a best fit of the data results in c = 15 kPa, ϕ_o = 41°, and $\Delta\phi$ = 12° (Zekkos, 2005).

10.2. Other large-scale direct shear test data

Several studies report in situ or laboratory large-scale (300 mm × 300 mm or greater) direct shear testing of MSW (Zekkos, 2005). These large-scale tests required less processing of MSW and are expected to be more representative of the response of MSW in the field. These large-scale direct shear test data are used to develop generalized shear strength parameters for MSW.

Landva and Clark (1986, 1990) performed a series of large-scale direct shear tests on waste specimens from various Canadian landfills. The authors used a direct shear device with plan dimensions of 434 mm × 287 mm and the specimens were sheared at a rate of about 1.5 mm/min, unless pore pressure development required the reduction of the shear rate. The measured friction angle varied between 24° and 42° with cohesion ranging between 10 and 23 kPa. Landva and Clark (1986) initially observed a reduction in shear strength for specimens that were stored in plastic containers for a year, but subsequently, Landva and Clark (1990) attributed the difference in waste variability as opposed to decomposition. Tests on waste from Edmonton, which included large amounts of plastic sheets, indicated that the lowest values were observed for specimens when fibrous and elongated particles were sliding against each other. Additional tests on plastic bags stacked horizontally and allowed to slide along the horizontal shear plane yielded a friction angle of only 9°.

Richardson and Reynolds (1991) performed in situ large direct shear tests on MSW from a landfill in Central Maine. The device had a square area of 1.5 m^2. Houston et al. (1995) report two staged direct shear tests using a large square direct shear box with a side of 1.22 m. The tests were performed at the Northwest Regional Landfill Facility located in rural northwestern Maricopa County, Arizona. When the shear stress leveled off during shearing, the vertical load was increased and testing continued, so that tests at three different loads could be performed. Both tests suggested a friction angle of 33–35° and cohesion of about 5 kPa.

Edincliler et al. (1996) performed direct shear tests on waste specimens with a diameter of 30 cm. Two different refuse samples and one sample of cover material were collected at different times from different locations of a landfill in Northeastern Wisconsin. Constituents found in refuse that were larger than 5 cm and were likely to act as reinforcing elements were removed. Both of the refuse samples yielded similar shear strengths. Soaking of the specimens did not appear to have a significant effect in the shear strength of MSW. The resulting Mohr–Coulomb strength envelope suggested $c = 27$ kPa and $\phi = 42°$. Based on the results of the testing program, the authors made the hypothesis that the material being tested in this study was primarily daily cover and for that reason a sample of daily cover was collected. The strength of the daily cover in direct shear yielded comparable strengths with $c = 0$ kPa and $\phi = 42°$. The authors stated that the material they tested should be weaker than the waste material in the field due to the removal of reinforcement constituents during specimen preparation.

Mazzucato et al. (1999) performed large direct shear tests in a landfill in Verona, Italy. The apparatus consisted of two steel rings each having a diameter of 800 mm and a height of 220 mm. The device was used to test both reconstituted waste specimens and "undisturbed" MSW by pushing the rings into the waste in situ. The unit weights of the specimens were estimated to be about 7 kN/m^3. The authors did not observe a significant difference in the peak shear resistance between the reconstituted and in situ specimens. The reconstituted specimens yielded $c = 22$ kPa and $\phi = 17°$, and the "undisturbed" specimens yielded $c = 24$ kPa and $\phi = 18°$. However, the in situ tests exhibited a post-peak shear resistance reduction, which was not observed in the reconstituted specimens.

Kavazanjian (1999) presented results of direct shear tests and direct simple shear tests (DSS) performed on samples collected from the OII landfill in California. The specimen diameter was 460 mm. The best fit direct shear failure envelope was characterized by $c = 43$ kPa and $\phi = 31°$. Only specimens having less than 16% refuse were weaker than the best fit strength line. The stress–strain response of the DSS specimens exhibited the same hyperbolic shape as the direct shear specimens. The shear stress at a shear strain of 10% was selected as the criterion to evaluate the monotonic DSS strength. The strength envelope obtained by assuming a horizontal failure plane is characterized by $c = 0$ and $\phi = 30°$, which was just slightly lower than the results from the direct shear tests. The authors commented that the shear strength on non-horizontal planes may be significantly higher than the shear strength on the horizontal plane.

Caicedo et al. (2002) performed large-scale in situ (cross-sectional area of 0.63 m^2) and laboratory (cross-sectional area of 0.09 m^2) direct shear tests as part of the geotechnical investigation program to evaluate the causes of a waste slide at the Dona Juana landfill in Colombia. One year old waste specimens tested in situ having a diameter of 900 mm were carved and were placed in the direct shear device which was specifically designed for that purpose. Mahler and De Lamare Netto (2003) performed tests on waste from Rio de Janeiro in Brazil. Tests were performed on the fraction that is <20 mm only, and a direct shear device having dimensions 400 × 250 × 100 mm was used. Tests were performed at normal stresses of 25 kPa, 50 kPa, 75 kPa and 100 kPa, and the strength parameters were estimated at different amounts of horizontal displacement.

The test results from these studies are summarized in Table 2. The entire dataset, including the results of the present investigation, form a database of 109 tests on MSW from Canada, Maine, Arizona, Wisconsin, California, Italy, Colombia, and Brazil. Table 2 lists the number of tests considered from each study, as well as other relevant information such as the dimensions of the shear box, type of direct shear testing, and information about the waste. The definition of "failure" used in each study is also provided. In some cases, failure is defined as the peak shear stress condition regardless of the required displacement. In other cases, it is the shear stress at a prescribed displacement. Unfortunately, in some cases, failure is not defined.

10.3. MSW direct shear strength properties

The results of the tests performed directly or collected as part of this study are plotted in Fig. 14. Despite the large number of tests on MSW from different countries and the expected variability in waste, there is surprisingly relatively little scatter in the data. The dataset includes specimens ranging in size from 300 mm to 1220 mm with no systematic differences in the results due to

Table 2
Large-scale in situ and laboratory direct shear tests.

Reference	Waste origin	Laboratory (L) or in situ (I)	Shear box dimensions	Maximum particle size (cm)	Shear rate (mm/min)	Definition of failure	Number of tests
Landva and Clark (1990)	Various Canadian landfills	L	43 cm × 29 cm	NR	1.5	PS	24
Richardson and Reynolds (1991)	Central Maine	I	122 cm × 122 cm	U	NR	NR	17
Houston et al. (1995)	NWRLF, Arizona	I	122 cm × 122 cm	U	NR	PS	6
Edincliler et al. (1996)	Wisconsin	L	30 cm diameter	5	0.4	PS or PD	20
Kavazanjian (1999)	OII landfill, S. California	L	46 cm diameter, 46 cm height	10	NR	NR	9
Mazzucato et al. (1999)	Verona, N. Italy	L & I	80 cm diameter, 44 cm height	U & NR	NR	PS	6
Caicedo et al. (2002)	Dona Juana, Colombia	I	90 cm diameter	U	NR	PS or PD	6
Mahler and De Lamare Netto (2003)	Brazil	L	40 cm × 25 cm × 10 cm (height)	2	NR	PS	4
This study[a]	Tri-Cities, N. California	L	30 cm × 30 cm × 18 cm (height)	7.6	0.5	PS or $D = 55$ mm	17

U: undisturbed.
NR: not reported.
PS: peak stress.
PD: peak displacement.
[a] Only tests prepared with the conventional way are included in this database.

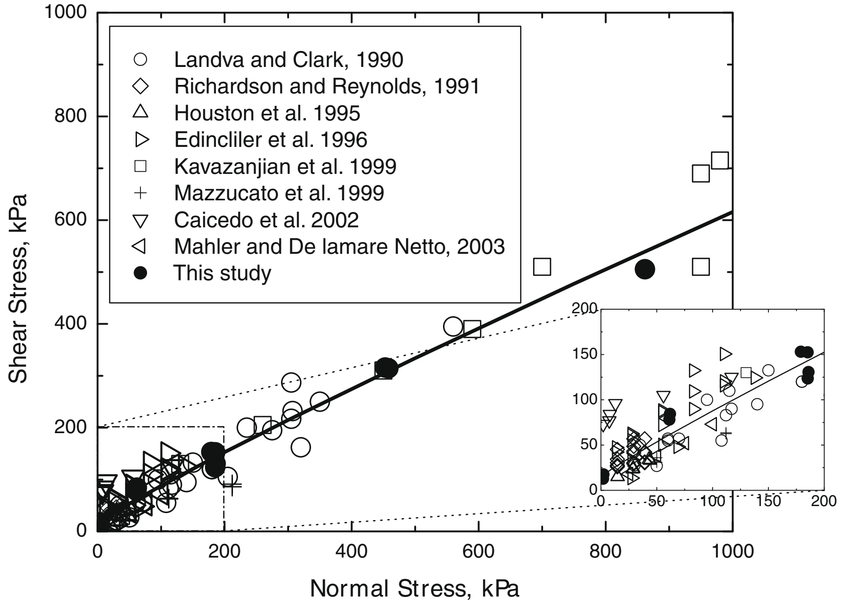

Fig. 14. Large direct shear test results on MSW and recommended strength envelope.

specimen size. However, significant differences in results have been observed between 300 mm in diameter triaxial specimens and 68 mm in diameter triaxial specimens (Zekkos et al., 2008b), indicating the importance of large-scale testing of MSW. Also, whereas the moisture content in the majority of the tests is not known, it is expected to be relatively low. Thus, the database may not capture the effect of increased moisture content on the MSW shear resistance.

The entire dataset, similarly to the Tri-Cities landfill waste test results, indicate a reduction in the secant friction angle with normal stress (Fig. 15). Regression of the data at different normal stresses suggests a nonlinear strength envelope as captured by Eqs. (1) and (2). The best fit shear strength parameters for this comprehensive direct shear MSW testing data set are $c = 15$ kPa, $\phi_o = 36°$, and $\Delta\phi = 5°$.

The majority of the data points are close to the recommended shear strength envelope; whereas the data points from Caicedo et al. (2002) and Edincliler et al. (1996) are slightly above the recommended envelope and the data points from Mazzucato et al. (1999) are slightly below the recommended envelope. Thus, although the recommended shear strength envelope captures the expected response of MSW in general, site-specific testing of waste can provide refined strength estimates. Considering the wide range of test materials and investigators involved in the data in Fig. 14, the regressed shear strength properties developed considering these data is recommended for use in landfill design practice when more reliable site-specific test data are not available. This strength characterization has the following advantages compared to previous recommendations (e.g., Kavazanjian et al., 1995; Eid et al., 2000):

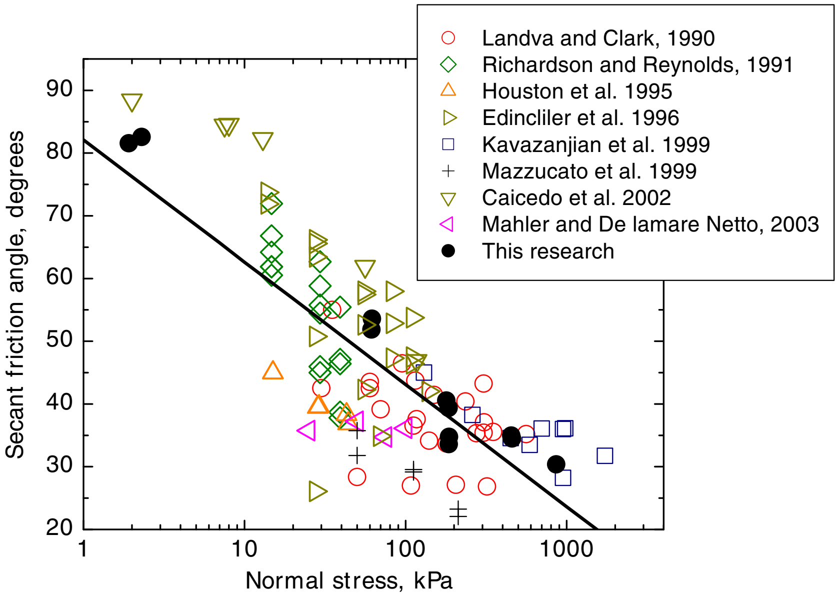

Fig. 15. Relationship of the secant value of friction angle with confining stress for all test data in the database ($R^2 = 0.57$).

(i) it is based on a significantly larger number of large-scale tests (i.e., 109 tests);
(ii) it includes tests at significantly higher normal stresses (and equivalent landfill depths);
(iii) and it considers the important effect that confining stress has on the friction angle of MSW.

11. Conclusions

Large-scale direct shear tests have been performed on MSW from the Tri-Cities landfill. It was found that the horizontal shear plane is generally parallel to the orientation of the fibrous materials. As a result, the fibers do not contribute significantly to the shear stress–displacement response of the waste during a conventionally performed direct shear test on vertically compacted or compressed waste specimens. Subsequent tests on MSW with the same composition and compaction effort, but with fibers oriented perpendicular to the horizontal shear surface, indicate that the shear stress–displacement response is significantly different due to the mobilization of the fibers. For these tests, the mobilized shear resistance at large displacements is significantly higher, indicating that the shear resistance of MSW is highly anisotropic and depends on the relative orientation between the failure surface and the fibers. The shear resistance also increases with unit weight, compaction effort, and rate of shearing.

The results of this testing program of MSW from northern California were integrated with available large-scale direct shear test results from tests on waste from Canada, Italy, Colombia, Brazil, Maine, Arizona, Wisconsin, and southern California. The estimated shear strength from these 109 large-scale tests most likely corresponds to the weakest orientation of the shearing plane. Thus, the strength envelope based on these test results is a conservative estimate of the shear strength of MSW, which is judged to be appropriate for evaluating typical landfill designs. The recommended strength envelope is characterized by cohesion = 15 kPa, friction angle = 36° at a normal stress of 1 atmosphere, and a decrease in the friction angle of 5° for every log-cycle increase of normal stress.

The strength envelope for MSW developed as part of this study is considered to be an improved estimate of the shear strength of MSW along its weakest orientation in a direct shear mode. It is based on a significant number of large-scale direct shear tests, many of which were performed at higher normal stresses that are representative of greater depths in the landfill, and it captures the reduction of the friction angle with increasing confining stress. The recommended strength envelope is expected to be representative of MSW under relatively low moisture conditions. Such conditions are likely representative of modern landfills (such as Subtitle D regulated landfills in the US). The tested waste may not be representative of waste with high moisture contents that would be encountered in leachate recirculation landfills, bioreactor landfills or in some cases old waste dumps without a leachate collection system.

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