Effects of Waste Composition and Decomposition on the Shear Strength of Municipal Solid Waste

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Abstract: The objective of this study was to evaluate the effects of waste composition and decomposition on the shear strength of municipal solid waste. Waste was collected from two sources (an operating landfill and a transfer station) and degraded in laboratory anaerobic reactors to prepare wastes with different degrees of decomposition. Shear strength was measured in a 280-mm-diameter direct shear ring on nine wastes with normal stress ranging between 12 and 90 kPa. The Mohr-Coulomb failure criterion was used to determine shear strength parameters (ϕ = friction angle and c = cohesion intercept) of the wastes, and shear strength was selected at a horizontal displacement of 56 mm (i.e., 20% of the specimen diameter). A composite failure envelope regressed through shear strength versus normal stress data from all wastes was statistically significant, with $\phi = 37°$ and $c = 20$ kPa. A comparison between tests conducted in this study and in the literature indicates that larger ϕ are obtained for waste with a greater fraction of soil-like, gravel, and inert constituents, whereas lower ϕ are coincident with higher fractions of paper and cardboard or plastic. This effect of waste composition on ϕ is applicable when fibrous particles are primarily parallel with the shear plane, which is the common particle orientation in direct shear. Tests conducted in this study also indicate ϕ increases with decreasing volatile solids or the ratio of cellulose + hemicellulose to lignin (i.e., increasing decomposition). Contrasting correlations have been reported in the literature, attributed to the initial waste composition, which influences the effect of decomposition on ϕ. No correspondence was found between c and waste composition or the degree of waste decomposition. **DOI:** 10.1061/(ASCE)GT.1943-5606.0000702.

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Introduction

Shear strength of municipal solid waste (MSW) is necessary to assess the stability of a landfill during operation and after closure. Shear strength parameters derived with the Mohr-Coulomb failure criterion (ϕ = friction angle and c = cohesion intercept) are commonly used to quantify MSW shear strength (Landva and Clark 1990; Edincliler et al. 1996; Kavazanjian 2001; Bray et al. 2009). These strength parameters can be measured directly in laboratory (direct shear, direct simple shear, triaxial compression) or field-scale experiments (direct shear), or back-calculated from existing or failed waste slopes.

Shear behavior of MSW typically displays a progressive increase in shear stress with increased shear displacement, which is attributed to the compressible and fibrous nature of MSW (Kavazanjian et al. 1999; Vilar and Carvalho 2004; Harris et al. 2006; Bray et al. 2009). In direct shear, the shear behavior has been reported to be anisotropic with respect to orientation of fibrous (i.e., inclusions with flat morphology and tensile strength, such as plastic, textiles, or wood) particles (Bray et al. 2009; Zekkos et al. 2010). Additionally, friction angles of MSW decrease with increasing normal stress (Pelkey et al. 2001; Bray et al. 2009; Zekkos et al. 2010). Estimating strength parameters for slope stability calculations requires stress conditions that simulate expected field conditions, as well as systematic procedures for data analysis. Additional variables that influence shear strength of MSW can include waste composition, shear rate, and unit weight (Bray et al. 2009; Stark et al. 2009; Zekkos et al. 2010).

MSW contains a heterogeneous assemblage of materials that vary in size (Bareither et al. 2010), strength (Dixon et al. 2008), and biodegradation potential (Eleazer et al. 1997; Staley and Barlaz 2009). Throughout the lifespan of a landfill, waste composition and material properties change as waste moistens (both naturally and via bioreactor operations) and eventually decomposes. The effect of waste decomposition on shear strength of MSW is important for assessing waste stability throughout landfill operations, particularly in bioreactor landfills.

A summary of 12 laboratory studies on MSW shear strength is included in Table 1. These studies include either waste composition or waste decomposition data (presented graphically in Figs. 6, 7, 9, and 10) amenable to analysis and are used for comparison with test methods and shear strength results from this study. Shear strength parameters (ϕ and c) tabulated in Table 1 are in terms of total stress. This notation is used throughout this paper as MSW is generally unsaturated in full-scale landfills, as well as in laboratory experiments.

Contrasting conclusions have been reported on the effect of waste decomposition on MSW shear strength. Landva and Clark (1990) report no direct evidence that waste decomposition influences the shear strength of MSW. Van Impe (1998) concludes from a survey of

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Table 1. Summary of Laboratory Studies on the Shear Strength of Municipal Solid Waste

Reference[a]	Waste description	Test procedure	Specimen dimensions	Shear rate (mm/min)	Normal stress (kPa)	Initial dry unit weight (kN/m^3)	Friction angle (°)	Cohesion intercept (kPa)
Gabr and Valero (1995)	15- to 30-year-old waste retrieved from auger cuttings; Pennsylvania	DS; scalped waste to ≤ 6.3 mm; compacted in shear ring	64 mm diameter × 23 mm thick	0.024	69–207	7.4–8.2	34.0	20.0
Edincliler et al. (1996)	Waste exhumed from working face; Wisconsin	DS; scalped waste to ≤ 50 mm; compacted in shear ring; controlled compaction effort	280 mm diameter	0.4	7–138	5.9–12.7	42.0	27.0
Sadek et al. (1999)	9- to 24-year-old waste retrieved via excavation; Beirut, Lebanon	DS; hydrated waste to different water contents; compacted in shear box	600 mm^2 × 800 mm thick	10	49–196	NR	22.0–28.0	6.0–44.0
Harris et al. (2006)	Waste retrieved from auger cuttings; New York and Kentucky	DSS and DS; shredded waste and scalped to ≤ 12.7 mm for DSS and ≤ 75 mm for DS; compacted waste in test apparatuses	DSS: 152 mm diameter × 50 mm thick; DS: 300 mm^2	DSS: 0.013–0.13; DS: 0.025–0.25	69–690	6.4–12.1	23.5–28.0	9.3–11.6
Gabr et al. (2007)	Waste collected from transfer station; North Carolina	shredded waste to ≤ 20 mm; decomposed in laboratory reactors; compacted in shear ring	100 mm diameter × 50 mm thick	0.03	50–150	NR	24.0–32.0	0.0
Dixon et al. (2008)[b]	Synthetic wastes prepared in the laboratory with different compositions	DS; max particle size ≈ 500 mm; compacted waste in layers in shear box and statically loaded each layer with 75 kPa normal stress	1,000 mm^2 × 800 mm thick	6	25–100	1.0–14.1	28.7–43.3	0.0–30.8
Zhan et al. (2008)[c]	Intact waste samples retrieved from boreholes; Suzhou, China	TC; intact samples used directly as triaxial specimens with negligible trimming to preserve waste structure	82 or 96 mm diameter × 200 mm tall	0.3	50–400	4.4–7.8	27.0–39.0	0.0–33.0
Hossain and Haque (2009)[d]	Waste collected from transfer station; Texas	TC; cut waste to ≈ 50 mm pieces; decomposed in laboratory reactors; remolded specimens with modified compaction effort	71 mm diameter × 145 mm tall	0.7	69–207	5.5–6.9	19.0–29.0	2.4–30.7
Reddy et al. (2009a)	Waste exhumed from working face; Illinois	DS; shredded to ≤ 40 mm; compacted in shear ring at different water contents	63 mm diameter × 49 mm thick	NR	176–774	3.7	26.0–30.0	31.0–64.0
Reddy et al. (2009b)	Waste retrieved via auger cuttings from active bioreactor landfill; Illinois	DS; shredded to ≤ 40 mm; compacted in shear ring at different water contents	63 mm diameter × 49 mm thick	NR	176–774	4.4	31.0–35.0	12.0–63.0
Reddy et al. (2009c)	Synthetic waste prepared to average U.S. composition	DS; max particle size ≈ 15–20 mm; compacted in shear ring	63 mm diameter × 34 mm thick	0.035	89–253	5.4	28.0	18.0

Table 1. (*Continued.*)

Reference[a]	Waste description	Test procedure	Specimen dimensions	Shear rate (mm/min)	Normal stress (kPa)	Initial dry unit weight (kN/m^3)	Friction angle (°)	Cohesion intercept (kPa)
Singh et al. (2009)	Waste excavated from closed landfill; Ontario, Canada	DS; large material removed; waste lifts statically compacted in shear box under desired normal stress	1,000 mm^2 × 1,000 mm thick	5	60–150	8.4	36.0	14.0
Zekkos et al. (2010)	0- to 15-year-old MSW retrieved via bucket auger; California	DS; max particle size ≤ 38 mm for stiff bulky materials and ≤ 76 mm for flexible sheet-like materials; controlled compaction effort	300 mm^2 × 180 mm thick	1	2–700	5.1–11.9	32.3–33.0	21.0–23.4

Note: DS = direct shear; DSS = direct simple shear; TC = triaxial compression; NR = not reported.
[a]Ranges of dry unit weight and shear strength parameters are tabulated. Waste composition and decomposition, water content, and dry unit weight data for individual waste specimens are presented graphically in Figs. 6–10.
[b]Additional information extracted from Langer (2005).
[c]Confining stress and approximate dry unit weights listed.
[d]Additional information extracted from Haque (2007). Confining stress listed.

literature that shear strength is higher for older MSW compared with fresher MSW. Harris et al. (2006) also report larger mobilized shear strength for more decomposed waste relative to fresh waste. This difference was attributed to an increasing fibrous content for decomposed waste that increased reinforcement during shear. In contrast, Gabr et al. (2007) and Hossain and Haque (2009) report a decrease in shear strength with increasing waste decomposition. Kavazanjian (2001) recommended the use of the same shear strength parameters for conventional and degraded MSW.

The contrasting reports of the effect of waste decomposition on shear strength may in part be attributed to differences in waste composition. Hossain and Haque (2009) report that ϕ of MSW at four different states of decomposition increased with the addition of soil (20–30% by mass) to replicate the presence of daily cover. However, Zekkos et al. (2010) report negligible effect of the passing 20-mm fraction of MSW (i.e., soil-like material) on ϕ and c measured in direct shear. An increasing plastic content in MSW has been reported to decrease MSW shear strength (Thomas et al. 1999), which agrees with lower ϕ reported for plastic compared with MSW (Landva and Clark 1990; Gabr et al. 2007).

The objective of this study was to investigate the effects of waste composition and decomposition on the shear strength of MSW. Waste samples were collected from two waste streams containing different initial compositions. Subsamples from both wastes were decomposed in laboratory anaerobic reactors to prepare wastes with different degrees of decomposition. Shear strength was assessed for one waste at four stages of decomposition and on the other waste sample for undecomposed and well-decomposed states, as well as undecomposed at field capacity water content. Decomposition was quantified via chemical characteristics of the MSW. Shear strength was evaluated on all wastes in a 280-mm-diameter direct shear ring. Kavazanjian et al. (1995) and Eid et al. (2000) report that direct shear tests on MSW provide similar shear strength to that estimated from stable and failed landfill slopes.

Materials and Methods

Municipal Solid Waste

MSW Sources

Municipal solid waste for the direct shear tests was collected from two sources: (1) Deer Track Park Landfill in Watertown, Wisconsin; and (2) a transfer station in Wake County, North Carolina. Waste from Wisconsin was collected during construction and decommission of the Deer Track Bioreactor Experiment (DTBE), a lysimeter experiment to assess the influence of leachate addition on physical, chemical, and biological behavior of MSW (Bareither et al. 2012c). Waste from North Carolina was collected as part of a laboratory evaluation on abiotic and biotic contributions of MSW compression (Bareither et al. 2012a).

A single bulk waste sample (~100 kg) was collected from North Carolina and hand-sorted to assess composition. Twelve waste samples ranging between 35 and 76 kg (dry mass) were collected during construction of the DTBE and analyzed for composition (Bareither et al. 2010). MSW exhumed for filling the DTBE had only been in place for approximately 3–4 months prior to sampling. Waste from both sources is considered as fresh (F) MSW in this study and distinguished by state origin (i.e., F-WI and F-NC).

F-WI samples were initially screened on a 25-mm screen to separate small unidentifiable waste constituents and soil or soil-like materials from larger identifiable waste constituents. Particles retained on the 25-mm screen were separated by hand into material-related categories (e.g., paper, wood, metal). Material passing the 25-mm screen (F-P25) was aggregated to a single waste fraction. The composite F-WI waste contained approximately equal mass fractions (dry mass basis) of material passing (46.6%) and retained (53.4%) on a 25-mm screen.

A summary of the waste composition for F-WI, F-P25 (subfraction of F-WI), and F-NC is in Table 2. The F-P25 composition was assessed on select subsamples from the larger F-P25 fraction as described in Bareither et al. (2010). The average F-WI composition (Table 2) is similar to that reported by Hull et al. (2005) for 1- to 3-year-old MSW. The negligible yard waste component for all fresh wastes is a result of a yard waste ban in Wisconsin and North Carolina landfills. The negligible food waste fraction for F-WI and F-P25 (Table 2) is attributed to decomposition before waste was exhumed for use in the DTBE. The F-P25 composition consisted predominantly of inert material, with approximately 85% characterized as soil-like, gravel, and glass (Table 2). F-NC contained primarily (~85%) paper/cardboard, plastic, and food waste.

Waste was exhumed from the DTBE after 2.9 years of experiment operation. Seven final waste samples ranging between 54 and 90 kg (dry mass) were collected from auger cuttings and waste composition was determined in a similar manner to F-WI. The average waste composition of the degraded waste from the DTBE (D-WI) is in Table 2. The paper/cardboard fraction decreased from 16.1 to 1.2% because of waste decomposition (Bareither et al. 2012c). D-WI material passing a 25-mm screen was not sorted, but aggregated to a single soil-like fraction (Table 2).

MSW Processing

Processing MSW samples collected from the field via shredding or scalping is common practice for laboratory evaluation of MSW shear strength (Table 1). Waste materials constituting F-WI and D-WI that were larger than 25 mm were shredded in a low-speed high-torque shredder and passed through a 25-mm screen. Shredded fibrous materials (e.g., paper, plastic, textiles, and wood) were generally elongated relative to the dimension passing through the 25-mm screen; however, the elongated dimension of the fibrous materials was not measured. F-NC waste was also shredded, but only to a maximum particle size ≤ 100 mm. Different maximum particle sizes were selected to accommodate separate testing protocols as part of another study conducted prior to direct shear testing (Bareither et al. 2012a, b). All material groups were shredded individually and then recombined to the average waste composition of F-WI, D-WI, and F-NC (Table 2) as needed for experimentation. Waste materials from F-WI, D-WI, and F-NC were not mixed.

Table 2. Percent Material Composition (Based on Dry Mass) for F-WI, F-P25, D-WI, and F-NC Wastes Used in This Study

Material	F-WI	F-P25	D-WI	F-NC
Paper/cardboard	19.0	6.1	1.2	56.8
Flexible plastic	5.2	0.6	5.1	16.1
Rigid plastic	5.6	2.1	4.9	
Textile	2.9	0.4	6.1	2.3
Wood	7.8	1.6	4.0	0
Gravel and inerts	17.0	18.2	5.4	0
Yard waste	0.3	0.4	0	0.2
Food waste	1.1	1.9	0	11.8
Metal	5.6	0.7	2.7	3.5
Glass	2.9	5.2	0.2	3.4
Miscellaneous	2.8	1.1	1.2	0.5
Soil-like[a]	29.8	61.8	69.3	5.4

Note: F-WI = initial waste composition of the Deer Track Bioreactor Experiment (DTBE); F-P25 = initial waste from the DTBE passing a 25-mm screen; D-WI = waste exhumed from the DTBE at the end of operation (2.9 years); F-NC = waste from a transfer station in Wake County, North Carolina.

[a]Material passing a No. 4 sieve (4.75-mm) for F-WI, F-P25, and F-NC; material passing a 25-mm screen for D-WI.

MSW Decomposition

Approximately 450 kg of shredded and recombined F-WI waste was divided between three 0.27-m^3 (0.61 m diameter by 0.91 m tall) laboratory reactors for anaerobic decomposition (Bareither 2010). Waste specimens were prepared to an initial dry unit weight (γ_d) of 6.0 kN/m^3 and dry weight water content (w_d) of 28%, which were similar to the average initial conditions of the DTBE (6.3 kN/m^3, 33%). A 2-kPa gravel surcharge was placed on the surface of each waste specimen that was representative of interim landfill cover. Waste temperature was maintained between 30 and 40°C using electric heaters affixed to the sides of the reactors. Two 10-L doses of leachate, sampled from Deer Track Park Landfill in Wisconsin, were added to each reactor to inoculate the waste with an active anaerobic microbial community. Effluent leachate from the reactors was recirculated at a rate of 1 L every 2–3 days to enhance waste decomposition. Methane production was monitored to assess decomposition progression. Bulk samples were exhumed from the reactors at three progressively higher cumulative methane yields corresponding to three levels of decomposition: low degraded (LD), medium degraded, (MD) and high degraded (HD).

Approximately 98 kg of shredded and recombined F-NC waste was divided between three 0.27-m^3 (0.61 m diameter by 0.91 m tall) laboratory reactors (Bareither et al. 2012a). These reactors were operated for 1,150 days under the following conditions: dry—no liquid addition; biotic—leachate recirculation to promote biological decomposition; and abiotic—liquid addition spiked with a biocide to wet the MSW while inhibiting biological activity. Liquid addition/recirculation in the abiotic and biotic reactors was conducted at 2 L/day between 22 and 120 days, followed by 2 L/week for the duration of the experiment. Waste decomposition only occurred in the biotic reactor (Bareither et al. 2012a).

MSW Characteristics

Cumulative methane yield from each reactor; cellulose (C), hemicellulose (H), and lignin (L) contents; $[C + H]/L$ ratio; volatile solids (VS); and biochemical methane potential (BMP) for the nine wastes used in this study are tabulated in Table 3. A description of the methods used to determine these chemical characteristics of the wastes is in Bareither et al. (2010). Bulk waste samples ranging between 500 and 2,500 g (dry mass) were milled and passed through a 1-mm screen prior to testing. Duplicate C, H, L, and VS measurements and triplicate BMP measurements were completed on each waste. The C and H contents, $[C + H]/L$, and BMP of the D-WI, LD, MD, HD, and biotic wastes decreased relative to the fresh wastes, indicating that these wastes decomposed in the reactors. The C and H contents and $[C + H]/L$ of D-WI are comparable to the MD and HD wastes prepared in the laboratory (Table 3).

The BMP and BMP/VS for LD, MD, and HD both decrease with increasing reactor methane yield (Table 3). This indicates that the level of waste decomposition increases from LD to MD and from MD to HD. The lack of trends in C, H, $[C + H]/L$, and VS between the three levels of decomposed waste are likely because of inherent heterogeneity in chemical properties of components contained in each biodegradable material group (Bareither et al. 2010). For example, the paper/cardboard fraction is the primary biodegradable fraction of F-WI, but components comprising the paper/cardboard fraction (e.g., office paper, newsprint, corrugated cardboard) have

Table 3. Cellulose (C), Hemicellulose (H), and Lignin (L) Contents; $[C + H]/L$; Volatile Solids (VS); and Biochemical Methane Potential (BMP) for All Fresh Wastes Used in This Study; Cumulative Methane Yield from Laboratory Anaerobic Reactors Is Listed for Decomposed Wastes

Material	F-WI	F-P25	D-WI	LD	MD	HD	F-NC	Abiotic	Biotic
C (%)	19.6	4.8	10.1	4.4	10.1	12.5	42.7	43.8	14.0
H (%)	5.4	1.5	4.0	1.6	4.0	4.3	9.4	10.1	5.5
L (%)	28.8	6.6	29.0	43.5	30.6	33.1	20.4	18.7	39.3
(C+H)/L	0.87	0.95	0.49	0.14	0.46	0.51	2.55	2.88	0.50
VS (%)	52.9	16.5	34.6	25.6	56.7	53.8	88.4	88.3	68.4
BMP (mL-CH_4/g-dry)	51.4	12.0	3.4	12.4	12.0	9.3	159.8	6.4	12.8
BMP/VS (mL-CH_4/g-VS)	97.3	72.7	10.1	48.3	21.2	17.3	180.8	7.2	18.7
Reactor methane yield (L-CH_4/kg-dry)	NA	NA	NA	5.3	14.3	18.7	NA	NA	68.7[a]

Note: NA = not applicable.

[a]Methane yield between 255 and 1,150 days of reactor operation.

varying rates of decomposition and cumulative methane yield (Owens and Chynoweth 1993; Eleazer et al. 1997; Staley and Barlaz 2009). Thus, while the initial waste composition (F-WI in Table 2) was consistent between the three laboratory reactors, the chemical signature of the F-WI constituents may have varied between reactors.

The VS, C, and H contents; $[C + H]/L$; and BMP for the biotic waste are all lower than those for the F-NC and abiotic wastes from decomposition. Biotic waste became enriched in L, which is recalcitrant in anaerobic environments (Colberg 1988). In contrast, the F-NC and abiotic wastes have similar C, H, and L contents, indicating solids decomposition was inhibited in the abiotic cell. The $[C + H]/L$ ratios for F-NC (2.55) and abiotic (2.88) are typical of fresh MSW (Barlaz 1997). The low BMP for the abiotic waste (Table 3) is caused by saturation with biocide, which inhibited biological activity during the BMP assay.

Direct Shear

Apparatus

A schematic of the direct shear apparatus is shown in Fig. 1. The steel direct shear ring has an internal diameter of 280 mm and wall thickness of 12.7 mm. The upper and lower shear rings are both 157 mm tall and separated by grooved flanges attached to the sides of the rings that run parallel to the direction of the shear plane (detail not shown in Fig. 1). Ball bearings are placed between these flanges to maintain separation between the upper and lower shear rings (~1 mm) and allow free displacement in the direction of the shear plane.

The upper shear ring is bolted to a rigid frame to restrict movement. Shear is induced within the MSW specimen by displacement of the lower shear ring (Fig. 1). A stainless steel plate was welded to the lower shear ring that included flanges attached along the base in the direction of shear movement. Ball bearings placed between these flanges and a slide track attached to the test frame allows the lower shear box to be pulled with minimal frictional resistance. A plastic displacement platform was fixed to the lower shear ring, flush with the shear plane, to prevent loss of material during shear displacement. A perforated plastic plate was placed at the base of the lower shear ring to allow free drainage of pore fluid during testing.

A 173-mm-diameter Bellofram (Burlington, Massachusetts) applied normal force that was distributed on a test specimen via a load distribution plate (Fig. 1). Normal force was measured with a 22.3 kN–capacity load cell with accuracy of ± 0.007 kN (model 9363; Revere Transducer, Tustin, California) and controlled with a 14- to 690-kPa pressure regulator (Fairchild, Winston-Salem, North Carolina). A 152-mm-diameter Bellofram applied shear force that was measured with an 8.92 kN–capacity load cell with accuracy of $\pm$ 0.003 kN (model 1210-AJ; Interface, Inc., Scottsdale, Arizona). Shear displacement rate was controlled by transferring pressurized oil contained in a hydraulic fluid reservoir through a flow regulator to the 152-mm-diameter Bellofram. The flow regulator allows displacement control down to 0.18 mm/min. Horizontal displacement of the lower shear ring and vertical displacement of the test specimen were measured with position transducers with 286-mm displacement capacity and accuracy of ± 0.01 mm (Model 160–0963-S555; First Mark Controls, Inc., Creedmoor, North Carolina). Measurements of load and displacement were recorded during testing with a Campbell Scientific CR23X Micrologger (Campbell Scientific, Inc., Logan, Utah).

Specimens

A summary of the γ_d and w_d of the wastes tested in direct shear is in Table 4. The γ_d and w_d are properties after initial specimen preparation. All waste specimens were compacted in three layers of equal thickness within the direct shear ring. Liquid drainage from the MSW specimens was monitored during compaction procedures, and no drainage occurred.

The target γ_d and w_d for F-WI and D-WI correspond, respectively, to initial and final conditions in the DTBE, which contained waste with the same composition (Bareither et al. 2012c). Initial conditions in the DTBE (6.3 kN/m^3, 33%) were determined via monitoring the mass and thickness of the waste placed in the lysimeter; final conditions (8.1 kN/m^3, 44%) were computed accounting for waste settlement and solids loss attributable to decomposition. Physical water content measurements were conducted on initial and final waste samples (Bareither et al. 2012c). The γ_d for F-P25 was selected to represent the approximate γ_d of the F-P25 fraction in the DTBE (Bareither 2010). The γ_d and w_d of LD, MD, and HD were the γ_d and w_d at the end of reactor operation and waste decomposition. Similarly, the γ_d and w_d for the abiotic and biotic wastes were properties following reactor operation (Bareither et al. 2012a). The γ_d for F-NC was the lowest because of the difficulty in compacting this material, which was from a transfer station and therefore contained no daily cover soil. The higher γ_d for F-WI, F-P25, and degraded states of F-WI (D-WI, LD, MD, and HD) are attributable to their larger fraction of soil and inert waste material compared with F-NC (Table 2) and wastes derived from F-NC (abiotic and biotic). The initial γ_d for all wastes tested in this study (2.1–8.5 kN/m^3) are comparable to the range compiled from literature (Table 1).

The differences in γ_d between the wastes tested in this study are a function of waste composition and w_d, which influence the compaction characteristics of MSW (Hanson et al. 2010). Hanson et al. (2010) conducted laboratory and field compaction tests on MSW with waste composition representative of the U.S. average (i.e., USEPA 2008). They report maximum dry unit weights ($\gamma_{d\max}$)

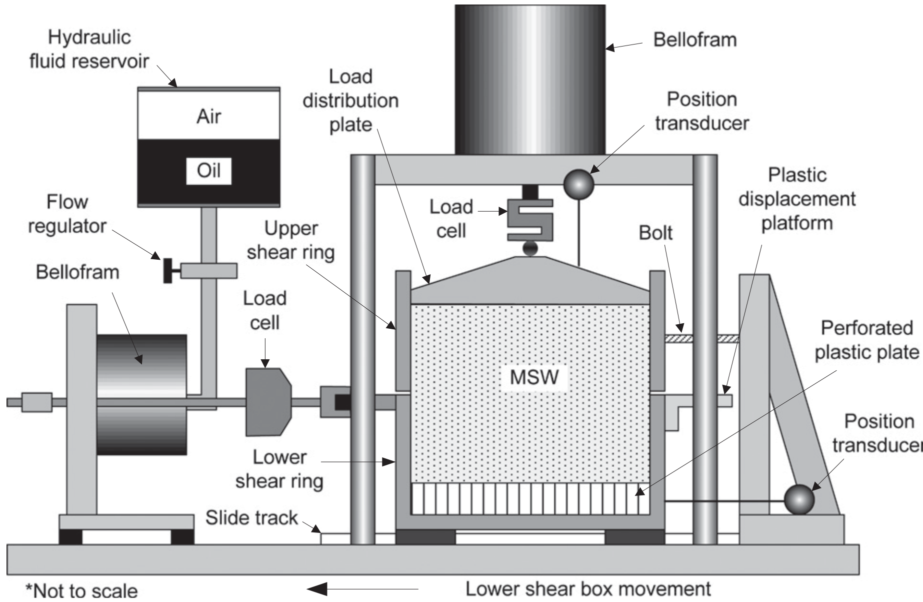

Fig. 1. Schematic of the direct shear apparatus

for laboratory compaction of 5.2 kN/m^3 with modified effort (ASTM 2007) and 6.0 kN/m^3 with 4× modified effort. They also report $\gamma_{d\max}$ for field compaction of 5.7 kN/m^3 with low effort and 8.2 kN/m^3 with high effort. The initial γ_d for F-WI (5.7 kN/m^3) is comparable to the $\gamma_{d\max}$ determined in both laboratory- and field-scale experiments by Hanson et al. (2010). However, the initial γ_d for F-NC (2.1 kN/m^3) is lower because of a paper/cardboard fraction (56.8%) that is more than double that used in Hanson et al. (2010). Although a higher initial γ_d has been reported to increase shear strength when waste properties and testing conditions are constant (Bray et al. 2009), maintaining a consistent γ_d among wastes with different compositions was not feasible in this study.

Specimen compaction within the shear ring produced waste matrices with the long axis of elongated fiber particles (e.g., paper/cardboard, plastic, textiles, and wood) oriented in the horizontal plane. This effect has been observed by Zekkos et al. (2010) for laboratory direct shear tests and is typical of waste compacted in full-scale landfills (Matasovic and Kavazanjian 1998). As the orientation of the elongated fiber particles changes relative to the shear plane in a direct shear box, the shear stress increases with horizontal displacement because of additional fiber reinforcement (Bray et al. 2009; Zekkos et al. 2010). However, Bray et al. (2009) report that when reinforcing particles are oriented parallel to the horizontal shear surface (i.e., similar to this study), shear stress did not continuously increase with additional horizontal displacement. Thus, direct shear tests conducted for this study represent a conservative estimate of shear strength in regard to reinforcing particle orientation, which has been reported to be appropriate for assessing landfill design (Zekkos et al. 2010).

Testing

Direct shear tests were conducted in two phases: compression and shear. Compression strain versus time relationships for F-WI are shown in Fig. 2. Data in Fig. 2 are representative of compression data for all direct shear specimens. A rapid accumulation of strain occurs with load application followed by a diminishing rate of strain, which is characteristic of MSW immediate compression (e.g., Bareither et al. 2012b). As shown in Fig. 2, the accumulation of strain slows considerably following the first few minutes after normal stress (σ_n) application, and 60 min was assumed sufficient for the majority of immediate compression to accumulate prior to shearing.

The range of γ_d for each waste following the compression phase is summarized in Table 4. For all wastes, γ_d increased during compression. The amount γ_d increased ranged from as low as 4% for HD at low σ_n to nearly twice the initial γ_d for F-NC at high σ_n. The shear phase was initiated in all direct shear tests after allowing specimens to compress for 60 min. All direct shear tests were sheared at horizontal displacement rates between 0.35 and 0.55 mm/min to a maximum horizontal displacement of 62 mm (i.e., maximum possible displacement of the direct shear box). The σ_n ranged between 12 and 90 kPa, and four to five tests with different σ_n were conducted on each waste. The range of σ_n used in this study is at the lower end of the σ_n range compiled from literature (Table 1). A σ_n of 90 kPa is equivalent to a vertical waste depth of approximately 7–13 m, dependent on waste unit weight (Zekkos et al. 2006).

Liquid contained in the waste specimens was allowed to drain from an outlet port at the base of the lower shear ring during compression and shear. The perforated plate at the base of the lower shear ring (Fig. 1) allowed drainage of pore water during testing.

Results

Shear Behavior

Shear stress and vertical strain versus horizontal displacement for all wastes tested in this study at low (12–20 kPa) and high (87–90 kPa) normal stress are shown in Fig. 3. Shear stress versus displacement response for all wastes exhibit a hyperbolic-shaped curve that either reaches (e.g., F-P25) or approaches (e.g., F-WI) an ultimate stress toward the end of the direct shear test. This shear stress versus displacement behavior is comparable to that reported by Bray et al. (2009) for direct shear tests on MSW with the long-axis of fibrous particles oriented in the direction of shear. Similar shear-stress versus displacement behavior was recorded for all other direct shear tests conducted as part of this study, and a compilation of these data are included in Figs. S1–S3.

Table 4. Summary of the Dry Weight Water Content and Dry Unit Weight for MSW Direct Shear Tests Conducted in This Study, and Friction Angle, Cohesion Intercept, and Coefficient of Determination for the Coulomb Failure Envelopes

Material	Dry weight water content (%)	Initial dry unit weight (kN/m^3)	Dry unit weight after compression (kN/m^3)	Friction angle (°)	Cohesion intercept (kPa)	Coefficient of determination (R^2)
F-WI	31.3	5.7	6.0–7.0	40.0	22.3	0.982
F-P25	28.1	8.5	8.9–11.7	39.9	18.3	0.991
D-WI	44.2	7.9	8.5–9.9	42.6	21.7	0.994
LD	46.4	6.7	7.0–8.8	43.9	15.6	0.964
MD	55.5	6.5	6.8–8.9	41.6	24.0	0.972
HD	62.9	6.4	6.7–8.3	37.2	25.7	0.912
F-NC	64.2	2.1	2.7–4.1	31.5	8.9	0.883
Abiotic	140.3	2.9	3.3–4.5	35.4	13.3	0.964
Biotic	158.9	3.3	3.9–5.7	38.1	6.8	0.988

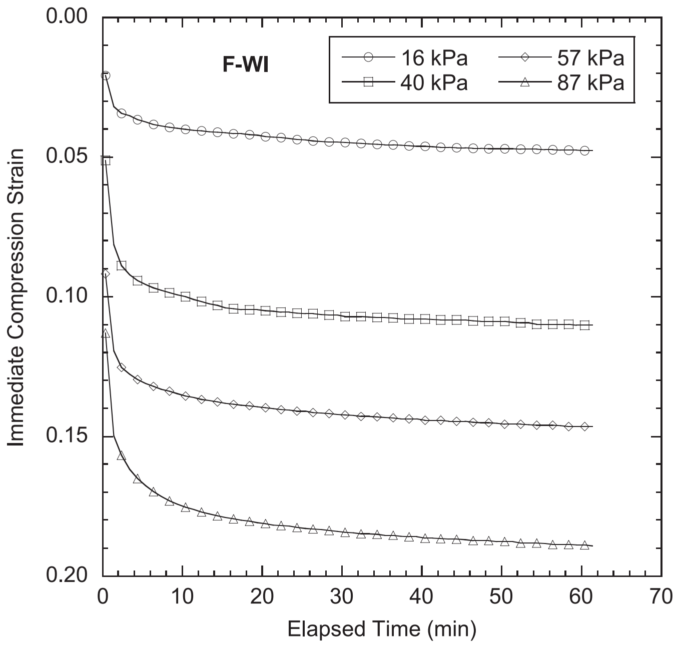

Fig. 2. Temporal trends of immediate compression strain for F-WI during the compression phase of the direct shear tests; 10% of data points shown

The largest shear stresses for direct shear tests conducted at high σ_n were measured for D-WI, HD, MD, and LD (in decreasing order), which are all decomposed wastes derived from F-WI. Shear stress for LD, MD, and HD at low σ_n [Fig. 3(a)] also increased with increasing waste decomposition (i.e., LD < MD < HD for $\sigma_n = 12$ kPa). Similarly, a higher shear stress was measured for biotic waste compared with F-NC at both low and high σ_n [Figs. 3(a and b)]. These observations suggest that shear resistance increased with waste decomposition.

Relationships of vertical strain versus horizontal displacement at low σ_n exhibit both dilative and contractive behavior [Fig. 3(c)], whereas relationships at high σ_n only exhibit contractive behavior [Fig. 3(d)]. At low σ_n, a change from continuously increasing vertical strain with horizontal displacement to a constant strain or decreasing strain relationship was measured for F-WI, F-P25, D-WI, LD, MD, and HD. In particular, minor dilative behavior ($0.00 >$ vertical strain > -0.02) was measured for F-P25, D-WI, MD, and HD. In contrast, continuous contractive behavior with increasing horizontal displacement was measured for F-NC, abiotic, and biotic for all σ_n. A compilation of vertical strain versus horizontal displacement data for all wastes tested in this study is included in Figs. S1–S3.

The dilative behavior at low σ_n was strongest for F-P25 and D-WI and less for MD and HD. The behavior in F-P25 is attributed to the larger fraction that is soil, gravel, and inert material (>85%, Table 2) combined with a higher γ_d obtained after compression (Table 4). These properties created a denser and more soil-like material compared with the other wastes. D-WI, MD, and HD were the more decomposed wastes derived from F-WI (compared with LD). The enhanced decomposition of these wastes, which decreased the biodegradable constituents (Table 3) and increased the soil-like and inert fractions (e.g., D-WI in Table 1), was probably the reason for the dilative behavior of these wastes at low σ_n.

The contractive behavior for F-NC, abiotic, and biotic wastes is attributed to the initial low γ_d (Table 4) combined with the compressible nature of the waste composition. The lowest shear stresses were consistently measured for these three wastes for the range of σ_n used in this study [e.g., Figs. 3(a and b)]. This lower shear resistance is attributed to the lower fraction of soil-like, gravel, and inert waste, which decreases the frictional resistance of the materials present in the shear plane of the direct shear test (described subsequently).

Two direct shear tests were conducted on F-NC at both 60 and 90 kPa [e.g., the lines numbered 1 and 2 in Figs. 3(b and d)]. Repeat tests were used to evaluate the shear stress and vertical strain response from the initial test at $\sigma_n = 90$ kPa, which contrasted with data at other σ_n. Shear stress versus displacement relationships for F-NC from both tests at $\sigma_n = 60$ and 90 kPa were used to determine a single set of shear strength parameters (described subsequently).

Stark et al. (2009) compared MSW shear strength data from laboratory tests with data back-calculated from failed waste slopes and suggested that shear stress measured in direct shear at displacements > 60 mm can be representative of MSW peak shear strength. For tests conducted in this study, shear strength was selected at a horizontal displacement of 56 mm [Figs. 3(a and b)], which is equivalent to a horizontal displacement of 20% of the specimen diameter. This shear strength criterion is comparable to the recommendation in Stark et al. (2009) and was selected to provide a consistent shear strength criterion applicable to all shear stress versus horizontal displacement data. For some direct shear data [e.g., F-WI in Fig. 3(b)], determining shear strength prior to shear stress reaching an ultimate stress may underestimate shear strength. However, evaluating MSW shear strength at large horizontal displacements was not possible with equipment used in this study.

Friction Angle Dependency on Normal Stress

To assess possible dependency of friction angle on normal stress, as well make comparisons with literature (e.g., Zekkos et al. 2010), secant friction angle (ϕ_s) plotted versus σ_n for the wastes tested in

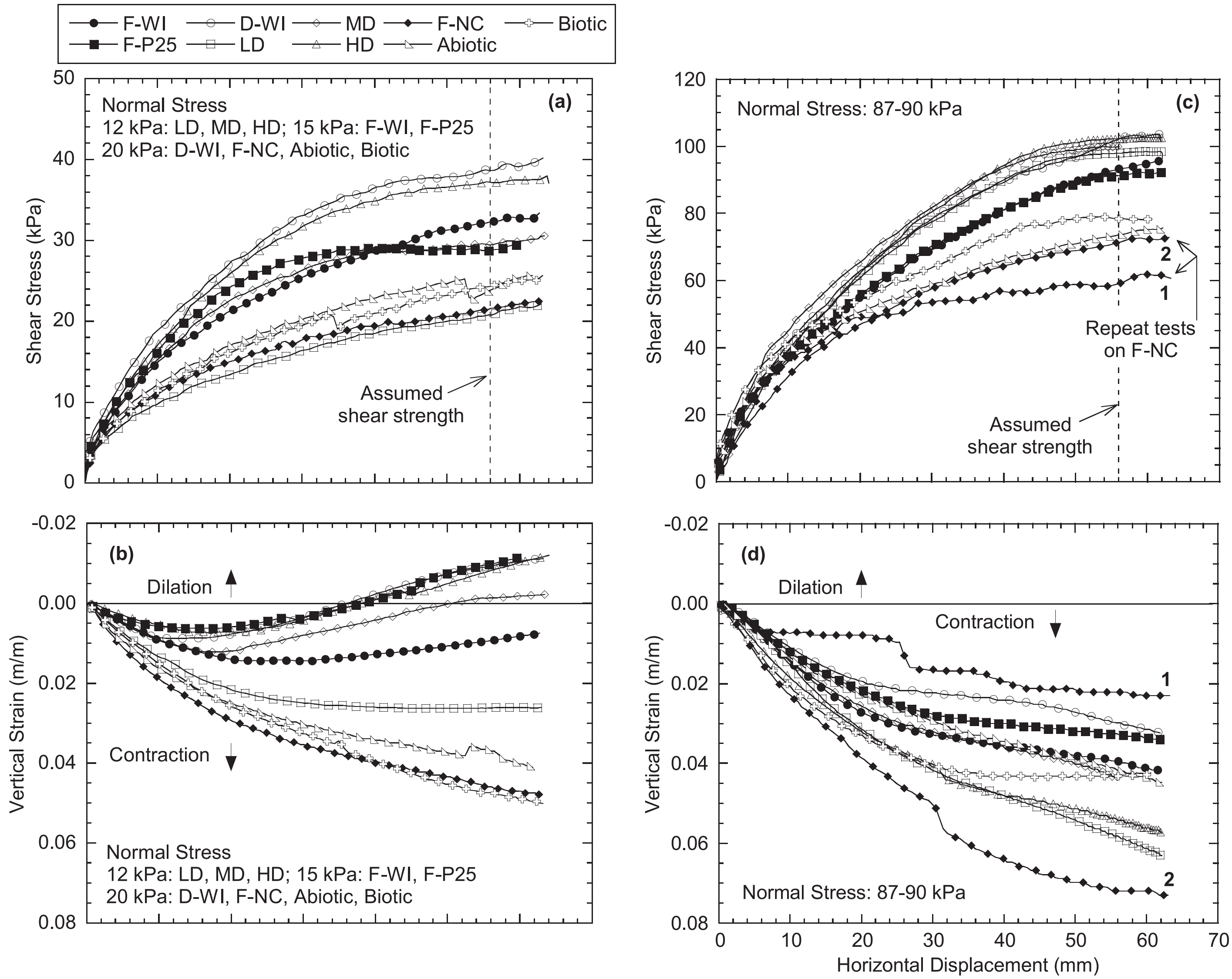

Fig. 3. Relationships between (a) shear stress and (b) vertical strain versus horizontal displacement at low normal stress (12–20 kPa) and between (c) shear stress and (d) vertical strain versus horizontal displacement at high normal stress (87–90 kPa); 5% of data points shown

this study is shown in Fig. 4. Secant friction angles were computed for each σ_n as the arctangent of the ratio of shear strength to σ_n. ϕ_s decreases with increasing σ_n, supporting the general consensus that the friction angle of MSW is σ_n dependent (Bray et al. 2009; Zekkos et al. 2010). The regression line from Zekkos et al. (2010) shown in Fig. 4 was derived from direct shear tests conducted as part of their study, as well as data compiled from eight additional studies. The close comparison between the regression lines from Zekkos et al. (2010) and direct shear tests in this study (Fig. 4) suggests that the testing and data analysis conducted in this study is comparable to previous research.

Strength Envelopes

Relationships between shear strength and σ_n for all nine wastes tested in this study are shown in Fig. 5. An average linear failure envelope is fitted to shear strength versus σ_n for each waste to obtain a friction angle (ϕ) and cohesion intercept (c), which are typically used to characterize the strength behavior of MSW. A summary of ϕ, c, and coefficient of determination (R^2) for the failure envelopes of the individual wastes is provided in Table 4. The friction angle ranges from 29 to 44°, c ranges from 7 to 26 kPa, and all failure envelopes have $R^2 > 0.88$, indicating that a linear representation of the strength envelope is reasonably accurate in the stress range (12–90 kPa) evaluated in this study. A composite failure envelope is also shown in Fig. 5; this envelope was regressed through all of the shear strength versus σ_n data collected in this study. The composite failure envelope has $\phi = 37°$, $c = 20$ kPa, and $R^2 = 0.73$ and is applicable for normal stress ranging between 12 and 90 kPa.

Shear strength parameters (ϕ and c) of the composite failure envelope are statistically significant at the 5% level (p statistics $<$ 0.05) and agree with previously recommended shear strength parameters for MSW. Kavazanjian et al. (1995) recommend a bilinear failure envelope with $c = 24$ kPa and $\phi = 0°$ for $\sigma_n < 30$ kPa, and $c = 0$ kPa and $\phi = 33°$ for $\sigma_n > 30$ kPa. Van Impe (1998) recommends a trilinear failure envelope with $c = 20$ kPa and $\phi = 0°$ for $\sigma_n < 20$ kPa, $c = 0$ kPa and $\phi = 38°$ for σ_n between 20 and 60 kPa, and $c \geq 20$ kPa and $\phi = 30°$ for $\sigma_n > 60$ kPa. Stark et al. (2009) recommend $c = 6$ kPa and $\phi = 35°$ for $\sigma_n < 200$ kPa. Finally, Bray et al. (2009) recommend $c = 15$ kPa and $\phi = 36°$ and present

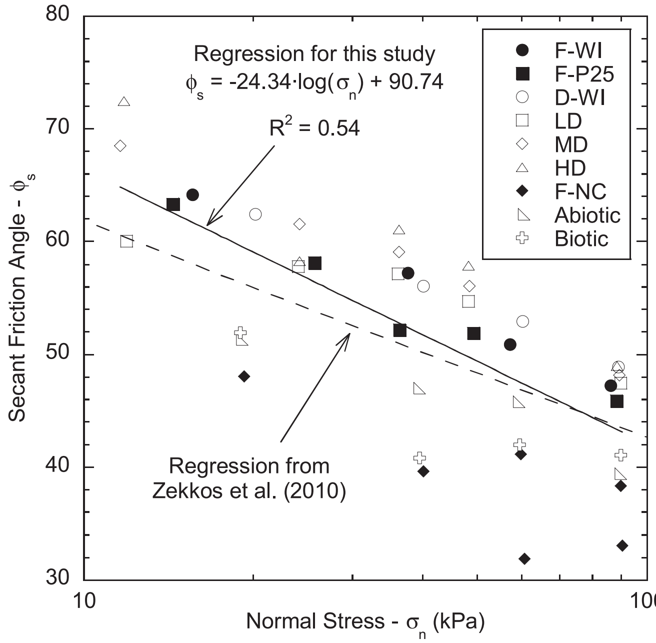

Fig. 4. Relationship between secant friction angle and normal stress; all secant friction angles computed with shear stress at horizontal displacement = 56 mm; regression equation is not presented in Zekkos et al. (2010)

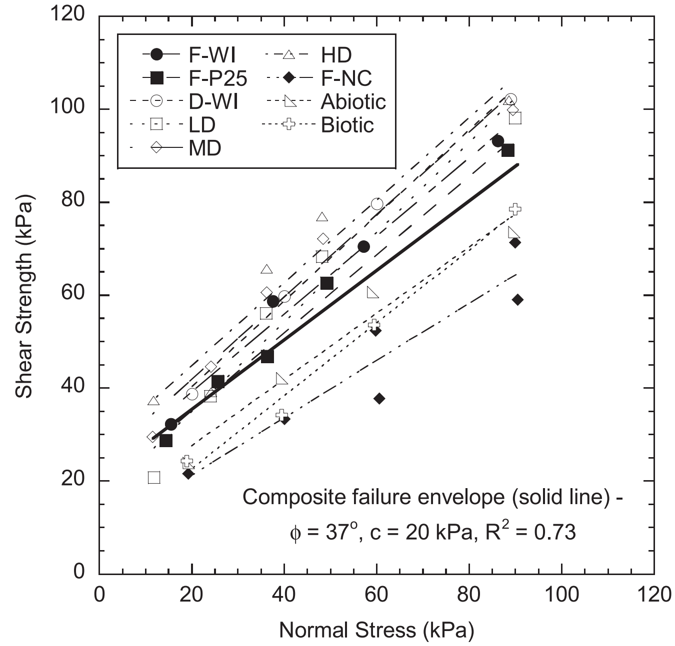

Fig. 5. Failure envelopes of shear strength versus normal stress for all nine wastes tested in this study; the composite failure envelope is regressed through all data; shear strength = shear stress at 56-mm horizontal displacement

a method for adjusting ϕ based on σ_n. For the σ_n range in this study, ϕ ranges between 36 and 40° based on recommendations in Bray et al. (2009). These four sets of recommended strength parameters are largely in agreement with one another, as well as with the composite failure envelope derived from tests conducted in this study (Fig. 5).

Effects of Waste Composition

Relationships between ϕ and the percent waste composition of (a) soil-like, gravel, and inert waste, (b) paper and cardboard, and (c) plastic are shown in Fig. 6. Data in Fig. 6 from this study include F-WI, F-P25, D-WI, and F-NC because a material-specific waste characterization was only conducted on these four wastes. A larger fraction of the soil-like, gravel, and inert waste corresponds to larger ϕ, whereas a larger fraction of either paper and cardboard or plastic waste corresponds to a smaller ϕ. Solid lines in Fig. 6 are linear least-square regressions and dashed lines are ± 1 SD (σ) of the regressions. Parameters of the regression lines in Fig. 6 are statistically significant (i.e., p statistics < 0.05) and indicate that a correlation between ϕ and material specific waste composition exists. However, the low R^2 of the regression lines (0.25–0.28) suggest there is limited practicality in predicting ϕ based on a single waste fraction.

Inert waste contains materials such as glass, ceramics, and roof shingles, which when combined with soil-like waste and gravel create a waste matrix that is more aggregate than fibrous. The higher ϕ measured for MSW with larger fractions of soil-like, gravel, and inert waste [Fig. 6(a)] are comparable to ϕ of cohesionless soils such as sands and gravels (e.g., Bareither et al. 2008). Benson and Khire (1994) report that the addition of high-density polyethylene plastic strips to sand, ranging from 1 to 4% by weight, increased ϕ relative to ϕ of clean sand. Borgatto et al. (2009) report an increase in both ϕ and c for mechanically biologically treated MSW (79% granular material) when including a 4% flexible plastic fraction. For wastes evaluated in this study, a larger ϕ was measured for D-WI compared with F-P25 (Table 3), which contained a larger plastic fraction, but lower soil, gravel, and inert fraction (Table 1). The plastic contained in D-WI probably provided additional reinforcement to yield a larger ϕ. Thus, for MSW composed predominantly of soil, gravel, and inert material, relatively small (e.g., 4–10% or less) plastic contents can provide fibrous reinforcement and additional shear strength (i.e., higher ϕ). However, an increasing plastic content as shown in Fig. 6(c) has the opposite effect of decreasing ϕ.

Landva and Clark (1990) conducted a direct shear test on stacked plastic bags and report $\phi = 9°$. They attributed the lower friction angles of their fresh MSW to a high abundance of plastic bags. Gabr et al. (2007) report ϕ for plastic = 18° and ϕ for paper = 33°. The low ϕ for plastic measured in these two studies agree with the trend in Fig. 6(c). Thus, assuming plastic is oriented in the direction of applied shear stress (i.e., common orientation in direct shear), high plastic contents can reduce ϕ of MSW because of the low internal frictional resistance of plastic.

The paper specific ϕ reported by Gabr et al. (2007) does not support a continuous decreasing trend in ϕ with increasing fraction of paper and cardboard [Fig. 6(b)]. However, Pelkey et al. (2001) report that ϕ for shredded and stacked dry computer paper ranges between 21 and 26°. The lower ϕ range for paper reported by Pelkey et al. (2001) does support the trend in Fig. 6(b), in that an increasing contribution of paper decreases ϕ of MSW. Paper and cardboard particles in a waste matrix consisting predominantly of soil, gravel, and inert material likely provide fibrous reinforcement similar to that described for plastic. However, the tensile strength of paper and cardboard will depend on water content, and the reinforcement component will likely diminish as waste is wetted (e.g., in bioreactor landfills).

Waste composition data in Fig. 6 were combined with the remaining material-specific characterization data from this study

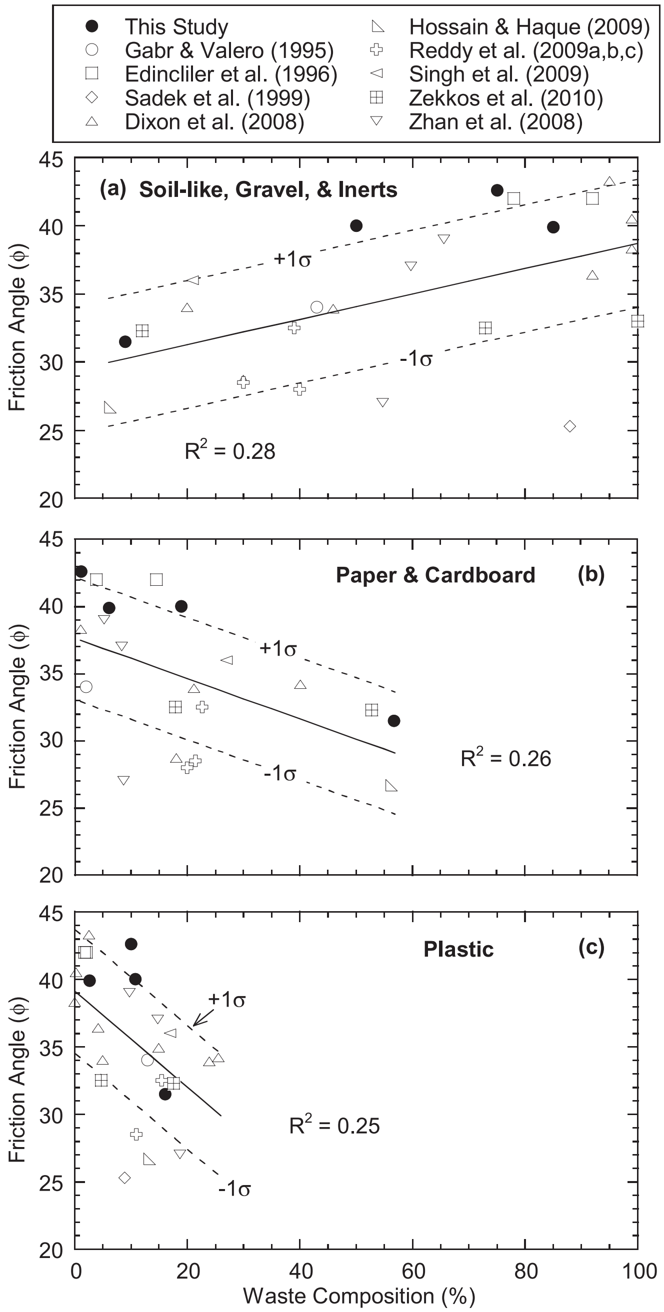

Fig. 6. Relationships between friction angle and waste composition for the percent contribution of (a) soil-like, gravel, and inert waste, (b) paper and cardboard, and (c) plastic; solid lines are linear regressions and dashed lines are ± 1 SD(σ)

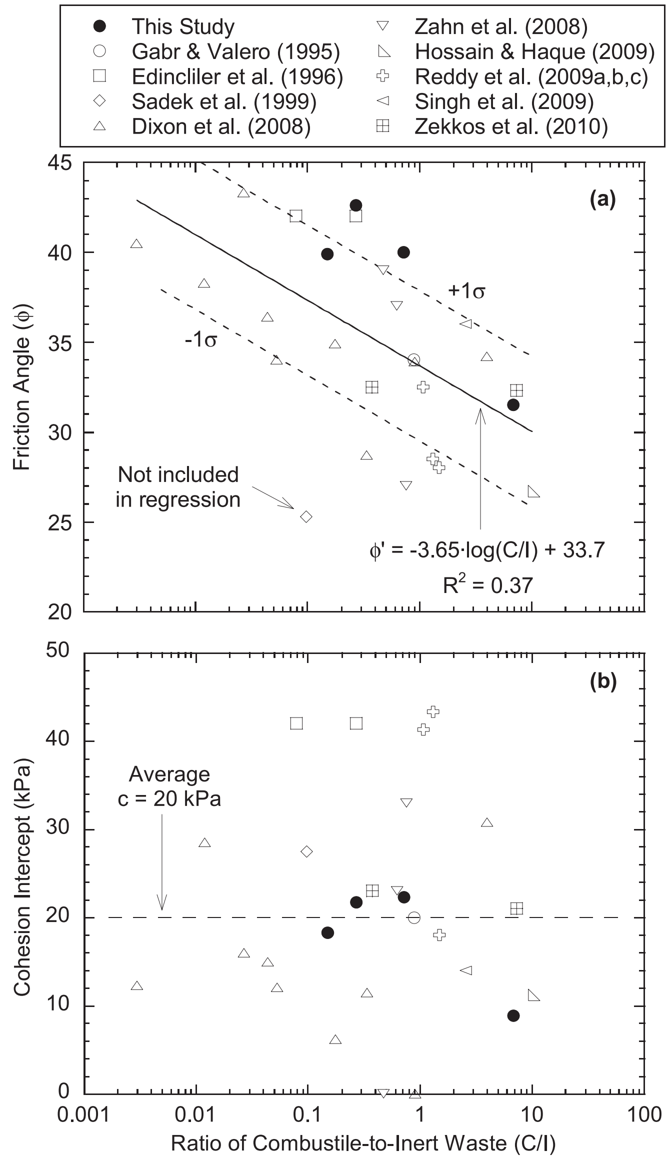

Fig. 7. Relationships between (a) friction angle and (b) cohesion intercept versus the ratio of combustible-to-inert waste; combustible waste includes paper, cardboard, plastic, wood, textiles, and organic waste; inert waste includes soil-like, gravel, glass, metal, and miscellaneous inert materials

and literature (i.e., percent contributions of wood, organic waste, metal, and textiles) to create a composite indicator of waste composition. The composite indicator is the ratio of combustible-to-inert (C/I) waste, where combustible waste includes paper, cardboard, plastic, wood, textiles, and organic waste, and inert waste includes soil-like, gravel, glass, metal, and miscellaneous inert material. Thus, combustible waste is qualitatively defined as the noninert MSW fraction that likely combusts when incinerated at 550°C (i.e., loss on ignition test to quantify volatile solids).

Relationships between ϕ and c versus C/I are shown in Fig. 7. Regression parameters for the semilogarithmic regression line in Fig. 7(a) are statistically significant (i.e., p statistics < 0.05). Larger ϕ correspond to lower C/I that have larger contributions of inert waste and smaller ϕ correspond to higher C/I that have larger contributions of paper, cardboard, plastic, and other bulky waste constituents. The relationship between c and C/I in Fig. 7(b) shows significant scatter with an average $c = 20$ kPa for the entire data set. Similar scatter exists between c and material specific waste composition.

The correlation between ϕ and C/I supports the ϕ trends with waste composition in Fig. 6. A substantially different ϕ is expected for wastes comprising the two extremes of C/I presented in Fig. 7(a): for predominantly inert waste with $C/I \leq 0.05$, $\phi \approx 36$–44°; and for predominantly combustible waste with $C/I \geq 5$, $\phi \approx 26$–34°. An upper bound $\phi = 43°$ and lower bound $\phi = 26°$ are recommended constraints for the semilogarithmic equation (Fig. 7) based on data from this study and that compiled from literature. For C/I ranging between 0.05 and 5, a broad range in ϕ exists in the data. This range in ϕ (~26–44°) can be attributed not only to variability in waste composition, but to variability in testing methods and conditions, waste processing, unit weight, specimen size, and data analysis, which also influence the shear strength properties of MSW (e.g., Bray et al. 2009; Stark et al. 2009).

The ϕ versus C/I correlation is developed from ten independent laboratory investigations of MSW shear strength: eight studies used direct shear and two used triaxial compression (Table 1). Thus, ϕ in Fig. 7 are predominantly from direct shear and represent a conservative measure of expected field behavior where fibrous particles are parallel to the shear plane and do not considerably increase shear resistance (Zekkos et al. 2010). The lower bound trend-line of the ϕ versus C/I regression [i.e., -1σ in Fig. 7(a)] may be more appropriate for estimating ϕ for landfill design as this trend-line accounts for error in the regression analysis. The data point from Sadek et al. (1999) was not included in the ϕ versus C/I regression [Fig. 7(a)]. Although waste evaluated by Sadek et al. (1999) was 88% soil-like, gravel, and inert material, ϕ did not agree with the material-specific trends [e.g., Fig. 6(a)].

Relationships between ϕ and c versus initial waste water content and γ_d are shown in Fig. 8. Water contents reported in Sadek et al. (1999) were not identified as computed on a wet or dry weight basis, whereas all other water contents are on a dry weight basis. Adjusting water contents in Sadek et al. (1999), assuming either an initial wet or dry weight basis, only changes the water contents ± 0.3–6.8%. This range does not influence the scatter in Fig. 8 and thus no correlation exists between ϕ or c and water content for MSW. Negligible effect of water content on MSW shear strength parameters has been reported by Sadek et al. (1999), Vilar and Carvalho (2004), and Reddy et al. (2009a, b).

Scatter also exists in the relationships between ϕ and c versus γ_d [Figs. 8(b and d)]. A modest trend of increasing ϕ and c with increasing γ_d is observed in data from this study. However, the lower γ_d are for F-NC, abiotic, and biotic wastes, which had a considerably different waste composition compared with other wastes evaluated in this study. These lower γ_d are attributed to larger fractions of paper and plastic and corresponding lower fractions of soil-like, gravel, and inert waste (e.g., F-NC in Table 2). Thus, the correlations between ϕ and waste composition (Figs. 6 and 7) are believed more relevant for explaining differences in ϕ compared with γ_d when there exists considerable variability in waste composition.

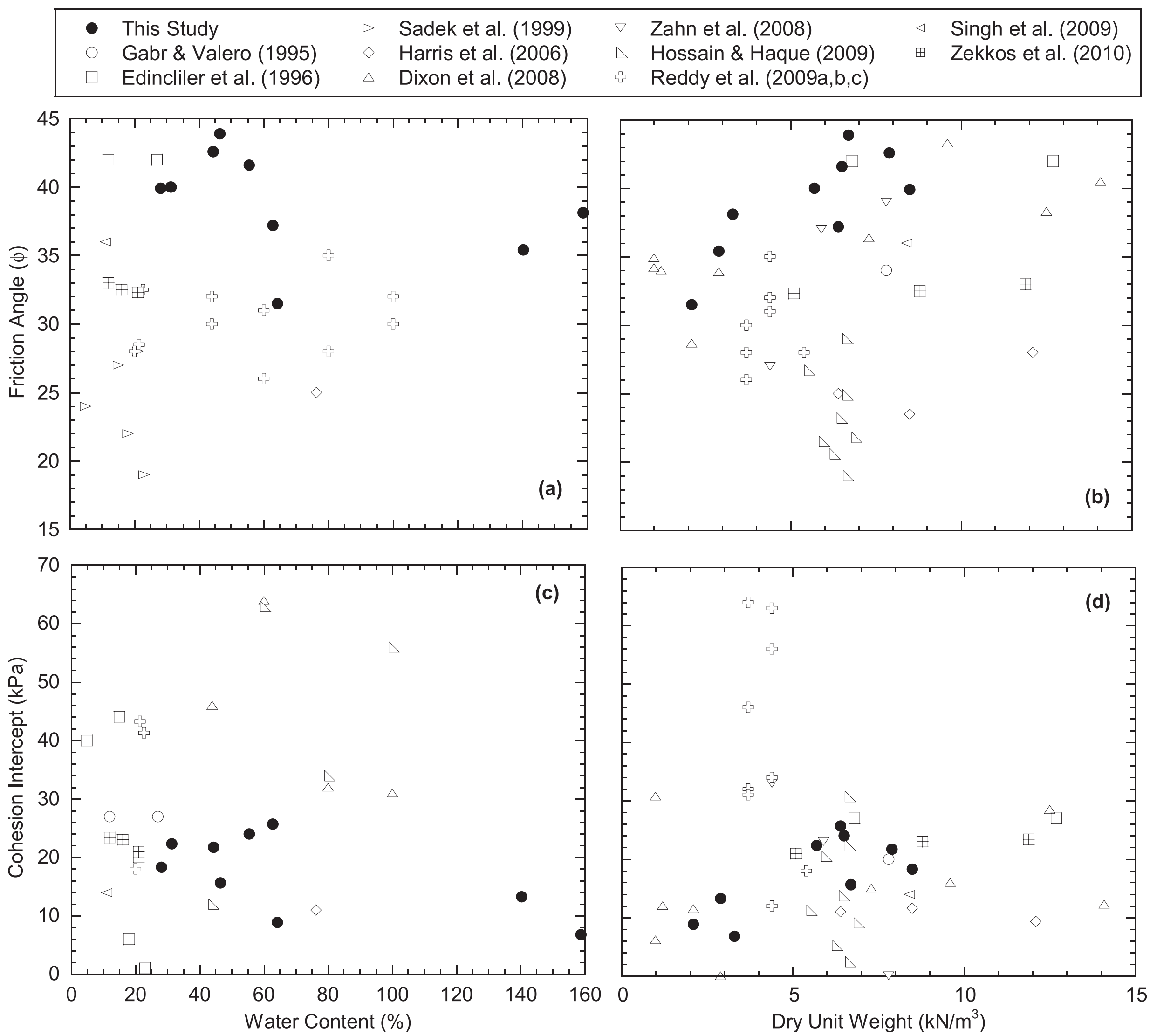

Fig. 8. Relationships between friction angle versus (a) water content and (b) dry unit weight and cohesion intercept versus (c) water content and (d) dry unit weight; water content and dry unit weights are initial properties of the test specimens (not all references listed in the legend are used in both water content and dry unit weight plots)

Effects of Waste Decomposition

The effect of waste decomposition on shear strength parameters of MSW (ϕ or *c*) has been assessed via volatile solids (VS) (Hossain and Haque 2009), as well as the ratio of cellulose + hemicellulose to lignin ([C + H]/L) (Gabr et al. 2007). VS and [C + H]/L are commonly used parameters to quantify MSW decomposition and both generally decrease with increasing waste decomposition (Mehta et al. 2002). Additionally, these metrics relate to the composite MSW and can be measured without separating MSW into material groups. In a bioreactor landfill, where waste decomposition is a primary objective, using VS or [C + H]/L to quantify the state of decomposition is common (e.g., Mehta et al. 2002), as waste characterization via material separation becomes difficult with increasing decomposition.

The relationship between ϕ and VS for wastes tested in this study and data from the literature is shown in Fig. 9. Dashed lines in Fig. 9 indicate the general trends in ϕ versus VS for data from this study and data from Hossain and Haque (2009). Data from this study suggest an increase in ϕ with decreasing VS, whereas data from Hossain and Haque (2009) suggest the opposite. Trends from both studies approximately overlap for VS $> 85\%$; these high VS are representative of fresh MSW collected from transfer stations.

MSW tested by Hossain and Haque (2009) was collected from a transfer station and decomposed in laboratory reactors to produce wastes at different states of decomposition (Table 1). Their initial waste (VS $= 94\%$, $\phi = 27°$) contained high fractions of paper and cardboard (56%) and plastic (13%) and a low fraction of soil-like, gravel, and inert waste (6%), which combined to yield a low ϕ. Hossain and Haque (2009) attributed the decrease in ϕ with decrease in VS (Fig. 9) to loss of paper because of decomposition and corresponding increase in plastic content. This change in composition reportedly increased the plastic-on-plastic sliding surfaces in the failure plane and decreased ϕ.

Data from the other five studies shown in Fig. 9 more closely agree with the general trend of increasing ϕ with decrease in VS supported by this study. Waste from these other studies was all exhumed from a landfill, except for the synthetic waste identified in Fig. 9, which was a laboratory prepared mixture (Reddy et al. 2009c). These exhumed wastes all had a soil-like and inert waste content that was larger than that of the waste used by Hossain and Haque (2009). Similarly, wastes tested in this study that yielded higher ϕ at lower VS all contained significant contributions of soil-like and inert waste (Table 2, note that LD, MD, and HD were prepared from F-WI). This increase in ϕ with decrease in VS attributed to the influence of soil-like and inert materials is similar to waste composition effects on ϕ [Figs. 6(a) and 7(a)]. The compiled data in Figs. 6(a), 7(a), and 9 all support a similar compositional dependence of ϕ for MSW (i.e., ϕ increases with increasing soil-like and inert material) when fibrous particles are aligned predominantly parallel to the direction of applied shear stress.

The effect of [C + H]/L on ϕ is shown in Fig. 10 and also shows contrasting trends between data from this study and data from Gabr et al. (2007). Although the initial waste composition was not reported by Gabr et al. (2007), the trend of decreasing ϕ with decreasing [C + H]/L (i.e., enhanced waste decomposition) was attributed to an increasing plastic content. Thus, the contrasting trends of ϕ versus VS (Fig. 9) and ϕ versus [C + H]/L (Fig. 10) are attributed to the same mechanism, i.e., frictional resistance of MSW decreases because of an increasing plastic content in the absence of a significant fraction of soil-like and inert waste [i.e., as shown in Fig. 6(c)]. This observation suggests that there may not be a unique relationship between ϕ and waste decomposition and that changes in ϕ with decomposition depend on the initial waste composition and subsequent changes to that composition (e.g., increasing soil content from interim cover).

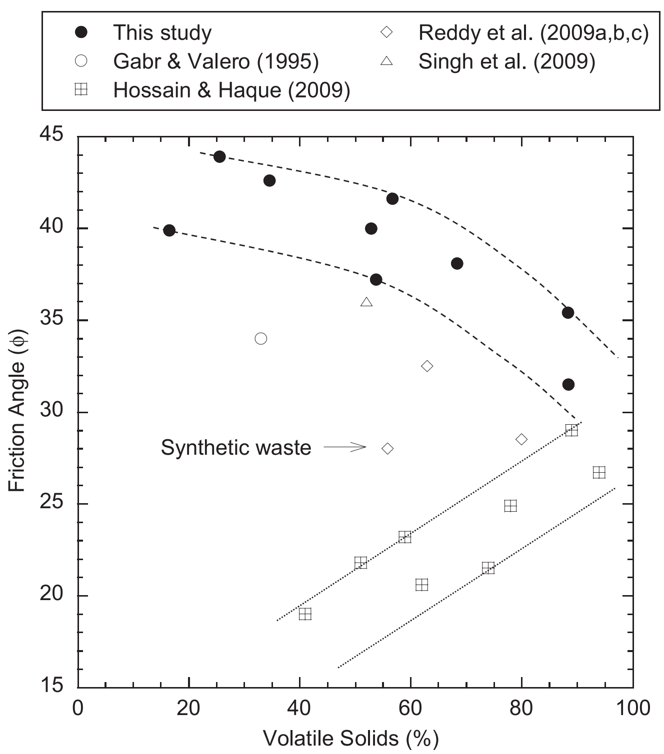

Fig. 9. Relationship between friction angle and volatile solids; dashed lines indicate separate general trends in data from this study and data from Hossain and Haque (2009)

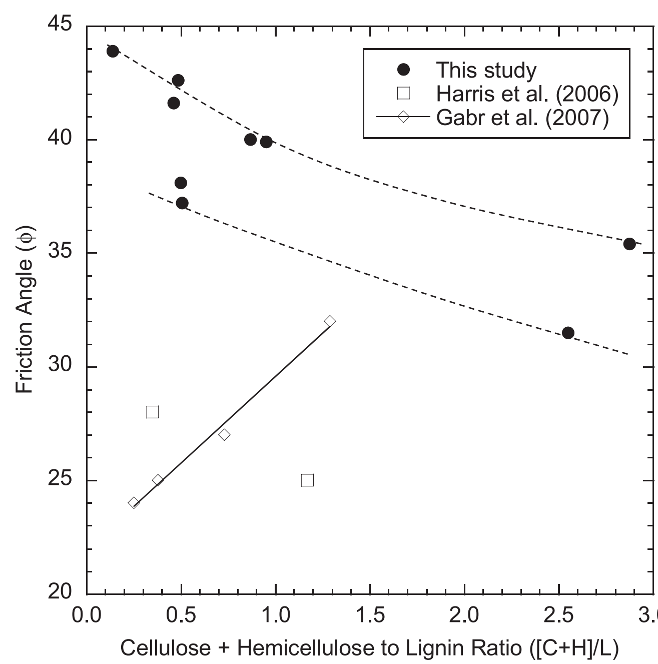

Fig. 10. Relationship between friction angle and cellulose + hemicellulose to lignin ratio ([C + H]/L); dashed lines indicate the general trend in data from this study whereas the solid line is linearly regressed through data from Gabr et al. (2007)

Other researchers have also attributed the effects of waste decomposition on ϕ to changes in waste composition. Harris et al. (2006) report larger shear strength for more decomposed MSW (data shown in Fig. 10), attributed to additional reinforcement from an increase in fibrous-type materials. Zhan et al. (2008) report an increase in ϕ with waste age, where older wastes had larger contributions of soil-like material and smaller contributions of paper and plastic. Reddy et al. (2009b) report larger ϕ for decomposed waste exhumed from a bioreactor landfill relative to fresh waste collected from the working face (Reddy et al. 2009a). The decomposed MSW with larger ϕ also had more soil-like material and less paper compared with the fresh MSW. The ϕ reported in these studies agree with trends in Fig. 6 and suggest, along with data presented from this study, that the effect of decomposition on ϕ is a function of the initial waste composition.

Conclusions

Direct shear tests were conducted on municipal solid waste (MSW) collected from two sources to evaluate the effects of waste composition and decomposition on shear strength. Fresh waste from both sources was decomposed in laboratory anaerobic reactors to produce wastes at different states of decomposition. All direct shear tests were conducted in a 280-mm-diameter shear ring. Shear strength of MSW measured in direct shear increased with horizontal displacement and typically approached an ultimate shear strength toward the limit of the direct shear horizontal displacement capacity (≈62 mm). Shear stress at horizontal displacement = 56 mm (20% of the specimen diameter) was designated as the shear strength.

The following conclusions are derived from this study:

- A friction angle (ϕ) of 37° and cohesion intercept (*c*) of 20 kPa are appropriate general shear strength parameters for MSW in conventional and bioreactor landfills when normal stress ranges between 12 and 90 kPa. These strength parameters are also similar to recommendations in the literature.
- In direct shear tests with fibrous particles oriented predominantly in the direction of applied shear stress, an increasing fraction of soil-like, gravel, and inert waste increases ϕ of MSW, whereas ϕ decreases, in general, with increasing fractions of paper and cardboard or plastic waste. The composite waste composition can be represented with a ratio of combustible-to-inert waste, which can be used to estimate ϕ based on a semi-logarithmic relationship.
- No relationship was found between *c* and waste composition, and no relationships were found between ϕ or *c* and waste water content.
- Data presented in this study support a general trend of increasing ϕ with waste decomposition, quantified as either volatile solids or the ratio of cellulose + hemicellulose to lignin.
- Contrasting relationships between ϕ and waste decomposition in the literature and this study are attributed to the initial waste composition. The trend of increasing ϕ with waste decomposition appears valid for MSW that includes daily cover soil and/or significant inert material.

Acknowledgments

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Supplemental Data

Figs. S1–S3 include shear stress and vertical strain versus horizontal displacement for each direct shear test conducted as part of this study and are available online in the ASCE library (www.ascelibrary.org).

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