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Comparison of direct shear and simple shear responses of municipal solid waste in USA

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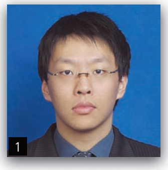

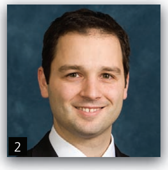

Although large-size simple shear (SS) testing of municipal solid waste (MSW) may arguably provide a more realistic estimate of the shear strength (τ) of MSW than the most commonly used direct shear (DS) testing, a systematic comparison between the shear responses of MSW obtained from the two testing methods is lacking. In this study, a large-size shear device was used to test identical MSW specimens sampled in USA in DS and SS. Eight DS tests and 11 SS tests were conducted at vertical effective stresses of 50–500 kPa. The stress–displacement response of MSW in SS testing was hyperbolic and a maximum shear stress was reached, whereas a maximum shear stress was not reached in most DS tests. The τ, effective friction angle (ϕ') and cohesion (c') of MSW were obtained from DS and SS tests by using a displacement failure criterion of 40 mm. τ in SS testing was found to be equal to or lower than τ in DS testing with ratios of τ between 73 and 101%. SS testing resulted in higher ϕ' but lower c' than DS testing. The shear strength parameters were lower than those obtained in previous studies from DS tests at 55 mm displacement.

Notation

c'	cohesion: kPa
L_L	liquid limit: %
P_I	plasticity index: %
$\gamma_{d,con}$	dry consolidated density
$\gamma_{t,con}$	total consolidated density
$\Delta\phi$	change in ϕ_{secant} over one log-cycle change of σ'_{vc}: °
ε_v	vertical strain: %
σ'_{vc}	vertical effective stress: kPa
τ	shear strength: kPa
τ_{SS}/τ_{DS}	ratio of τ between SS and DS tests
ϕ'	effective friction angle: °
ϕ_0	ϕ_{secant} at a σ'_{vc} of atmospheric pressure (101·3 kPa): °
ϕ_{secant}	secant friction angle: °

Introduction

Modern municipal solid waste (MSW) landfills may reach heights of 100 m or more, and often have steeper slopes than many conventional unreinforced earth structures. Landfill slopes need to remain stable under static and dynamic loads. One of the most critical input parameters in assessing their stability is the shear strength of MSW. Most commonly, large-size direct shear (DS) tests of MSW with a specimen diameter (or width) larger than 300 mm have been conducted (e.g. Bareither *et al.* (2012), Bray *et al.* (2009), Harris *et al.* (2006), Kavazanjian *et al.* (1999), Landva and Clark (1990), Pelkey *et al.* (2001), Singh *et al.* (2009), Zekkos *et al.* (2010a, 2013), Zhao *et al.* (2014)). Results of DS tests have been frequently used in engineering design of landfills (e.g. Kavazanjian *et al.* (2013)) and back-analysis of landfill slope failures (e.g. Eid *et al.* (2000), Jafari *et al.* (2013), Merry *et al.* (2005)). Large-size simple shear (SS) tests of MSW have been conducted as part of three studies only (Kavazanjian *et al.*, 1999; Pelkey *et al.*, 2001; Zekkos and Fei, 2017). However, SS results of geomaterials are commonly believed to represent more realistic field shearing conditions than DS results, as shown by experimental results (e.g. Hanzawa *et al.* (2007)) and numerical modelling (e.g. Dounias and Potts (1993), Tejchman and Bauer (2005)). SS is most commonly conducted in constant-volume conditions, with constant-load conditions being less common in engineering practice.

MSW is arguably one of the most anisotropic geomaterials due to the presence of fibrous waste constituents such as paper, soft plastics and wood, which tend to become horizontally oriented after compaction and upon application of a vertical load (Gotteland *et al.*, 2000; Zekkos, 2013). The orientation of large-size fibrous waste constituents after compaction and vertical load application in DS tests has been observed to be parallel to the enforced horizontal failure plane (Bray *et al.*, 2009). As a result, fibrous waste constituents oriented parallel to the failure plane result in lower shear resistance in DS compared to when constituents are oriented at an angle to the failure plane (Zekkos *et al.*, 2010a, 2013). Therefore, the shear strength of MSW obtained using DS testing of conventionally prepared specimens may be conservative. In contrast, in SS testing, the failure plane of a specimen is not pre-defined and is not necessarily parallel to the horizontal direction or primary orientation of fibrous waste constituents. Therefore, one may postulate that the shear strength of MSW in SS could be higher than in DS if the failure plane intersects fibrous waste constituents. Alternatively, the shear strength in SS could also be lower than in DS if, during SS, another plane (horizontal or not) that is even weaker than the horizontal plane tested in DS is mobilised. So far, the shear responses of MSW between SS and DS tests containing large-size fibrous waste constituents have not been directly compared.

A large shear displacement is often needed in DS to reach a peak and constant shear strength (τ) of MSW, and such large displacement may not be allowable for full-scale landfills. Thus, various failure criteria at different threshold shear displacements that vary from 40 to 100 mm have been used in the literature (e.g. Bareither *et al*. (2012), Bray *et al*. (2009), Kavazanjian *et al*. (1999), Pelkey *et al*. (2001), Zekkos *et al*. (2010a)). For example, Bray *et al*. (2009) used a 55 mm horizontal displacement as the failure criterion for interpreting 103 DS tests and developed Mohr–Coulomb strength parameters for MSW using that criterion. The authors also observed that vertical stress affected the curvature of the stress–displacement relationship. The MSW had reached peak shear stress conditions at a horizontal displacement of 55 mm at low vertical stresses between 2 and 50 kPa, but had not reached these conditions at higher vertical stresses. The stiffness and shear strength of MSW also increase with increasing time under confinement, as reported in the literature (Zekkos and Fei, 2017; Zekkos *et al*., 2008).

In this study, a large-size shear device capable of executing both DS and SS tests was utilised to test replicates of MSW specimens. Eight DS tests and 11 SS tests were conducted, and the experimental results were compared to investigate differences in the evaluated shear strength parameters of MSW based on DS and SS tests at different vertical effective stresses and displacement (or strain) failure criteria.

Methodology

Two samples of MSW that had been disposed of for approximately 1 year were collected from pits excavated at the surface of the Lamb Canyon landfill in California and the Austin community landfill in Texas, USA, and were shipped in sealed drums to the laboratory. The field composition of each waste sample was first characterised by sieving and manual separation according to the procedures recommended by Zekkos *et al*. (2010b). The specimens were tested for field composition, but only the four major waste constituents – that is, the <20 mm fraction, which is soil-like material, and the >20 mm fraction, which consists of paper, soft plastics and hard objects (primarily wood and hard plastic) – were included. The remaining constituents were omitted because they were insignificant in terms of volume and weight. The compositions and moisture contents of the tested California and Texas specimens are listed in Table 1. The <20 mm fraction of the samples was characterised according to the Unified Soil Classification System (ASTM, 2011a) and was classified as silty sand (SM) with 30% fines of high plasticity (P_I = 19, L_L = 65) for the Texas waste and

Table 1. Compositions and moisture contents of the California and Texas solid wastes

	Texas waste	California waste
<20 mm material: % dry	79·1	72·0
<20 mm material soil classification	Silty sand (SM) with 30% fines of high plasticity	Poorly graded sand with silt (SP-SM) with 10% fines of low plasticity
Paper: % dry	10·6	5·0
Soft plastics: % dry	6·0	4·3
Hard objects: % dry	4·3	18·7
Moisture content: % dry	26–31	29–35
Moisture content of <20 mm material: % dry	27 (% dry)	29

poorly graded sand with silt (SP-SM) with 10% fines of low plasticity (P_I = 15, L_L = 44) for the California waste. Additional specimens were also prepared using exclusively the <20 mm fraction from the California landfill (California <20 mm only). The maximum dimension of >20 mm constituents included in the specimens was not greater than one-sixth of the diameter of the specimen for stiff constituents (wood and stiff plastics) and one-fourth of the diameter for flexible constituents (paper and soft plastics), based on the recommendations of Bray *et al*. (2009).

A prototype large-size shear device was used in this study; its detailed configuration and performance were described by Zekkos and Fei (2017). Briefly, the device comprises two independent control and data-logging units for the vertical and horizontal axes. Each unit has a microstepper motor for load application and a load cell and a displacement transducer for load and displacement measurements. Specimens for SS testing were prepared inside a set of stacked Teflon-coated shear rings of 300 mm inner diameter and 150 mm total height that can slide on top of each other in the horizontal direction with minimal friction and allow lateral deformation during shearing (Figure 1(a)). Typically, a sheared SS specimen exhibited a ‘slinky’ shape in the horizontal direction (Figure 1(b)).

The specimen container for DS tests consisted of two parts of a similar height of 75 mm each. The lower part was a rectangular box of 300 × 400 mm^2 inner dimensions. The upper part was a stack of shear rings identical to those used for SS tests, which were instead locked together to remain stationary as one unit. The stacked shear rings were attached to a rectangular interface plate, which had an opening of 300 mm inner diameter and similar outer dimensions as the lower rectangular box. The interface plate and shear rings were supported by a frame and were lifted vertically to create a gap of about 4 mm between the plate and lower box (Figure 1(c)). Specimens for DS testing were prepared following the same procedure as SS testing; the upper and lower parts were prepared together in one piece. During shearing in DS, horizontal load was

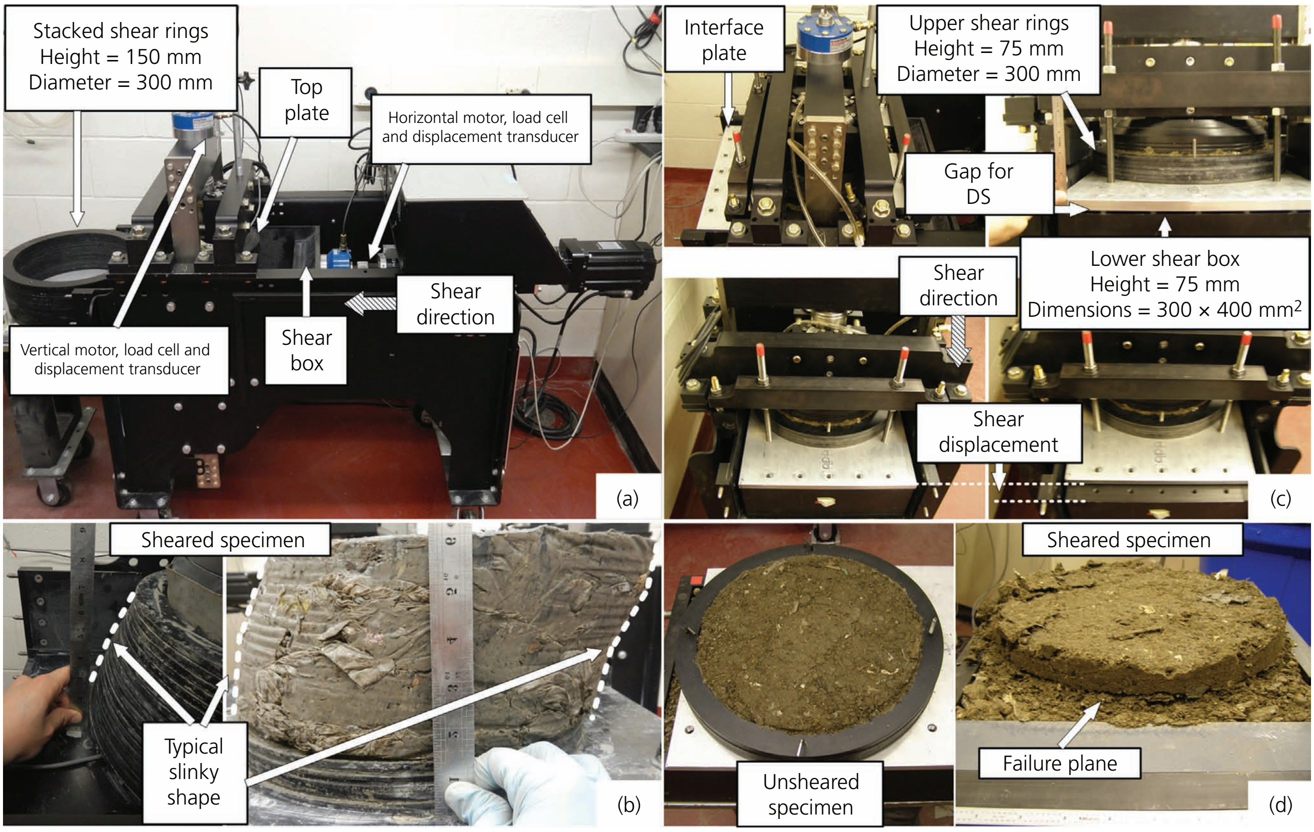

Figure 1. Schematic diagrams of test set-ups for DS and SS tests: (a) device for SS tests; (b) a sheared SS specimen; (c) device for DS tests; (d) unsheared and sheared DS specimens. LVDT, linear variable differential transformer

applied to the lower box while the upper plate was fixed. Since the MSW in the upper part had a smaller footprint (a circle of 300 mm diameter) than the MSW in the lower part (a rectangle of 300 × 400 mm^2), the MSW was always sheared against MSW along the pre-defined horizontal shearing plane – that is, the failure plane (Figure 1(d)). Therefore, a correction to the cross-sectional area of a specimen in DS was unnecessary.

The specimen heights for DS and SS tests were all around 150 mm and the specimen diameters were 300 mm. By conducting both DS and SS tests on the same MSW material with similar dimensions and using the same device, differences in waste composition variability, preparation procedures and sizes of the specimens between DS and SS tests were minimised. As a result, differences in test results induced by DS and SS testing techniques were compared directly.

Specimens of the Texas waste were prepared with minimal compaction effort by simply placing the waste carefully in the container. California specimens were compacted in four layers by dropping a 98 N hammer from a height of 0·9 m, 18 times per layer, to achieve a high dry unit weight following the procedure described by Zekkos *et al*. (2012). For each waste sample, identical specimens using the same compaction effort were prepared for SS and DS tests. Compaction effort between the Texas and California samples was different to investigate its influence on the respective DS and SS responses. Each specimen was compressed for 23 ± 1 h at a target vertical effective stress (σ'_{vc}) between 50 and 500 kPa to a height of 100 ± 10 mm prior to shearing. The target σ'_{vc} was approximately representative of the top 50 m of MSW in a landfill that is also often susceptible to shear failure (Zekkos *et al*., 2006).

All DS and SS tests were conducted under constant-load conditions. ASTM D 3080-11 (ASTM, 2011b) was followed for DS testing. Although no specific ASTM standard is available for SS testing under constant load, because it is not a common testing configuration, both ASTM D 3080-11 (ASTM, 2011b) and ASTM D 6528-07 (ASTM, 2007) for SS testing in constant volume were used as guidance. All specimens were sheared at a constant and slow shearing displacement rate of 0·45 ± 0·05 mm/min. During the shearing phase of each test, horizontal and vertical applied forces and displacements were recorded. In order to facilitate direct comparison between the results of DS and SS tests of MSW, shear displacement was used in the analysis instead of shear strain, which is not known in DS testing. Subsequently, the shear stress (τ) was calculated as the horizontal load divided by the cross-sectional area of the (upper) specimen, vertical strain (ε_v) was calculated as the vertical displacement during shearing divided by the specimen height immediately prior to shearing and the secant friction angle (ϕ_{secant}) was calculated according to the equation (Duncan *et al.*, 2014)

$$1.\quad \phi_{\text{secant}} = \tan^{-1}\left(\frac{\tau}{\sigma'_{\text{vc}}}\right)$$

Two shear displacements, 10 and 40 mm, were selected as failure thresholds to evaluate the influence of failure criteria on testing results. The former threshold is considered very conservative, while the latter is closer to, but still at lower displacement than, the criterion adopted by Bray *et al.* (2009) in DS – that is, 55 mm – because of testing limitations in achieving larger horizontal displacements. Note that the 10 and 40 mm horizontal displacements in this study are equivalent to approximately 9 and 36% shear strains in SS tests, which are similar to the failure criteria used in previous SS tests (Kavazanjian *et al.*, 1999; Zekkos and Fei, 2017).

A Mohr–Coulomb failure envelope was derived for each waste sample in DS and SS tests at 10 and 40 mm displacements, respectively. The effective friction angle (ϕ') and cohesion (c') of each waste sample were calculated according to the equation (Zekkos and Fei, 2017)

$$2.\quad \tau = c' + \sigma'_{\text{vc}} \times \tan\phi'$$

The influence of σ'_{vc} on ϕ_{secant} of each waste sample is described according to the equation

$$3.\quad \phi_{\text{secant}} = \phi_0 - \Delta\phi \times \log\left(\frac{\sigma'_{\text{vc}}}{p_{\text{a}}}\right)$$

where ϕ_0 is the ϕ_{secant} at a σ'_{vc} of atmospheric pressure (p_{a} = 1 atm = 101·3 kPa) and $\Delta\phi$ is the change in ϕ_{secant} over one log-cycle change of σ'_{vc}.

Results and discussion

The σ'_{vc}, total and dry as-consolidated unit weights ($\gamma_{\text{t,con}}$ and $\gamma_{\text{d,con}}$), and τ, ϕ_{secant} and ε_{v} for all the tests presented in this study

Table 2. Summary of target vertical effective stresses, unit weights, shear strengths, secant friction angles and vertical strains of all specimens at 10 and 40 mm displacements

Test	As-consolidated specimen			Displacement = 10 mm			Displacement = 40 mm		
	σ'_{vc}: kPa	$\gamma_{\text{t,con}}$: kg/m^3	$\gamma_{\text{d,con}}$: kg/m^3	τ: kPa	ϕ_{secant}: degrees	ε_{v}: %	τ: kPa	ϕ_{secant}: degrees	ε_{v}: %
Texas SS									
1	48	1136	859	16·1	18·5	2·2	23·0[a]	25·6	5·6[a]
2	97	1303	991	35·6	20·1	2·1	43·1	23·9	5·3
3	197	1356	1026	59·8	16·9	2·1	77·3	21·4	5·7
4	394	1673	1272	116·8	16·5	1·6	140·7	19·7	4·4
Texas DS									
5	97	1310	1013	38·2	21·5	2·9	59·0[a]	31·4	7·0[a]
6	197	1486	1148	55·8	15·8	2·6	80·0[a]	22·1	8·0[a]
7	397	1636	1270	82·8	11·8	1·6	110·5	15·5	2·9
California SS									
8	47	1249	924	23·0	26·1	1·6	27·2	30·1	2·5
9	98	1342	991	45·0	24·8	1·4	55·3	29·6	2·3
10	198	1440	1063	76·8	21·2	1·6	97·7	26·3	3·6
11	394	1555	1147	135·4	19·0	1·6	165·9	22·8	4·5
California DS									
12	99	1381	1027	57·4	30·1	1·3	75·4	37·2	1·5
13	196	1439	1069	91·7	25·1	1·8	117·0	30·9	4·1
14	497	1537	1140	155·5	17·4	0·9	190·0	20·9	1·5
	394			132·5[b]			163·5[b]		
California <20 mm only SS									
15	99	1633	1300	62·4	32·4	0·6	74·4	37·1	0·3
16	199	1602	1273	88·8	24·1	1·2	112·5	29·5	2·4
17	497	1756	1397	171·9	19·1	1·5	235·1	25·3	3·8
California <20 mm only DS									
18	99	1688	1317	73·3	36·4	0·3	82·8	39·8	0·0
19	498	1818	1416	187·9	20·7	1·9	253·0	26·9	4·9
	199			101·9[b]			125·2[b]		

[a] Shear strength and vertical strain at 40 mm displacement extrapolated from test results between displacements of 0 and 35 mm
[b] Shear strength interpolated from available DS data for comparison with corresponding SS shear strength at the same displacement and σ'_{vc}

are listed in Table 2. Stress–displacement and vertical strain–displacement responses of MSW specimens in DS and SS tests are plotted in Figure 2. In all the DS and SS tests, the MSW exhibited a displacement (strain) hardening behaviour without an obvious post-peak reduction in τ. The stress–displacement response of waste specimens in SS tests followed a hyperbolic trend and reached a plateau with a maximum τ at a shear displacement of between 20 and 35 mm. In contrast, τ in most DS tests continued to increase with increasing shear displacement, and the maximum τ was not reached even at displacements of

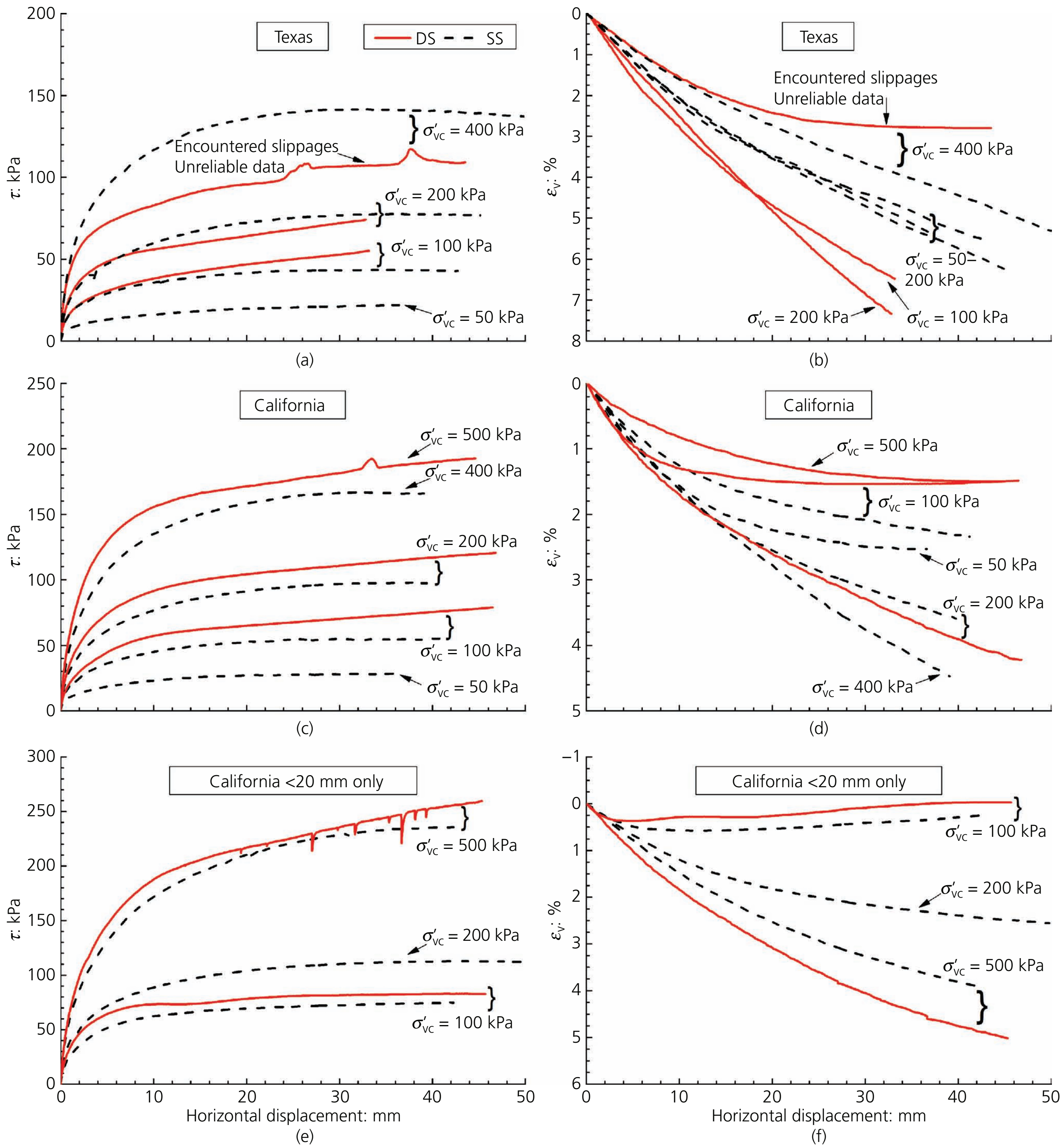

Figure 2. Shear responses of MSW specimens with horizontal displacement in DS (continuous lines) and SS (dashed lines) tests: (a) shear stress and (b) vertical strain of Texas waste; (c) shear stress and (d) vertical strain of California waste; and (e) shear stress and (f) vertical strain of California <20 mm only waste

40 mm (Figures 2(a), 2(c) and 2(e)). This observation is consistent with previous DS studies in the literature (e.g. Bareither *et al*. (2012), Zekkos *et al*. (2010a)). The only exception was a Texas specimen at $\sigma'_{vc} = 400$ kPa, which encountered slippages along shearing interfaces; these data were not considered representative of the MSW response and were not used in subsequent analysis (marked in Figures 2(a) and 2(b)). Because of the different stress–displacement responses of waste in DS and SS tests, the selected displacement failure criterion obviously affects the shear strength parameters of MSW obtained by the two testing methods.

Except for two California MSW specimens that consisted of only <20 mm fraction (California <20 mm only) at $\sigma'_{vc} = 100$ kPa (Figure 2(f)), the vertical strain for the test specimens increased with increasing shear displacement, indicating predominantly contractive behaviour of MSW in DS and SS tests (Figures 2(b), 2(d) and 2(f)). The uncompacted Texas MSW (Figure 2(b)) had higher vertical strain during shearing than the compacted California MSW (Figures 2(d) and 2(f)). The California <20 mm only specimens (Figure 2(f)) had overall the lowest vertical strain during shearing at each σ'_{vc} compared with the other specimens.

Mohr–Coulomb failure envelopes for different waste samples at 10 and 40 mm displacements are shown in Figures 3(a) and 3(b), and ϕ' and c' calculated as per Equation 2 are given in Table 3. The values of ϕ' and c' obtained at 10 and 40 mm displacements are compared in Figure 4. The value of ϕ' at 40 mm was between 1·3 and 7·1° higher than at 10 mm for all three waste samples in both DS and SS tests (Figure 4(a)). The cohesion of the MSW obtained at 40 mm horizontal displacement was practically the same or higher than that at 10 mm (Figure 4(b)).

Overall, the failure criterion at 10 mm displacement resulted in significantly lower shear strength parameters than the

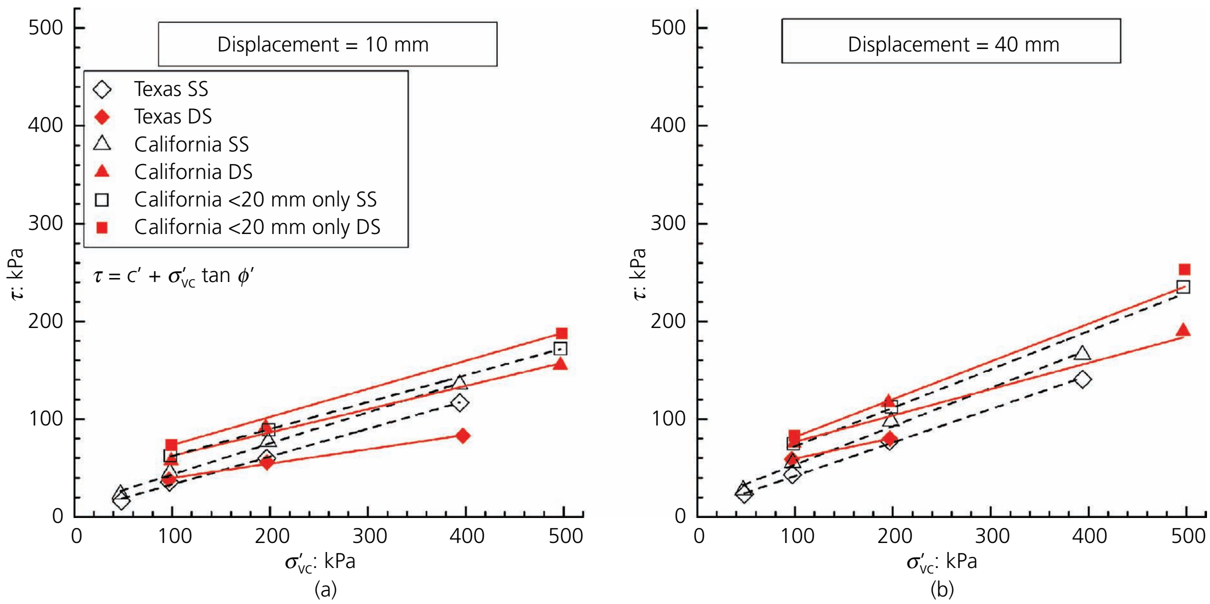

Figure 3. Relationships between vertical effective stress (σ'_{vc}) and shear resistance (τ) of specimens at (a) 10 mm displacement and (b) 40 mm displacement

Table 3. Summary of composition and shear response parameters for each type of waste in SS and DS tests at 10 and 40 mm displacements

Waste	$\%_{paper} + \%_{soft\ plastic}$: % dry	Displacement = 10 mm				Displacement = 40 mm			
		ϕ': degrees	c': kPa	$\Delta\phi$: degrees	τ_{SS}/τ_{DS}	ϕ': degrees	c': kPa	$\Delta\phi$: degrees	τ_{SS}/τ_{DS}
			SS						
Texas	16·6	15·7	5·8	3·0	0·93–1·41	18·6	9·0	6·6	0·73–1·27
California	9·3	17·6	11·5	8·1	0·78–1·02	21·4	14·3	8·1	0·73–1·01
California <20 mm only	0	15·4	34·7	18·6	0·85–0·91	22·0	33·5	16·4	0·90–0·93
			DS						
Texas	16·6	8·3	25·2	15·9		9·6	44·3	25·8	
California	9·3	13·4	38·7	18·2		15·5	54·3	23·4	
California <20 mm only	0	16·0	44·8	22·5		23·1	40·4	18·4	

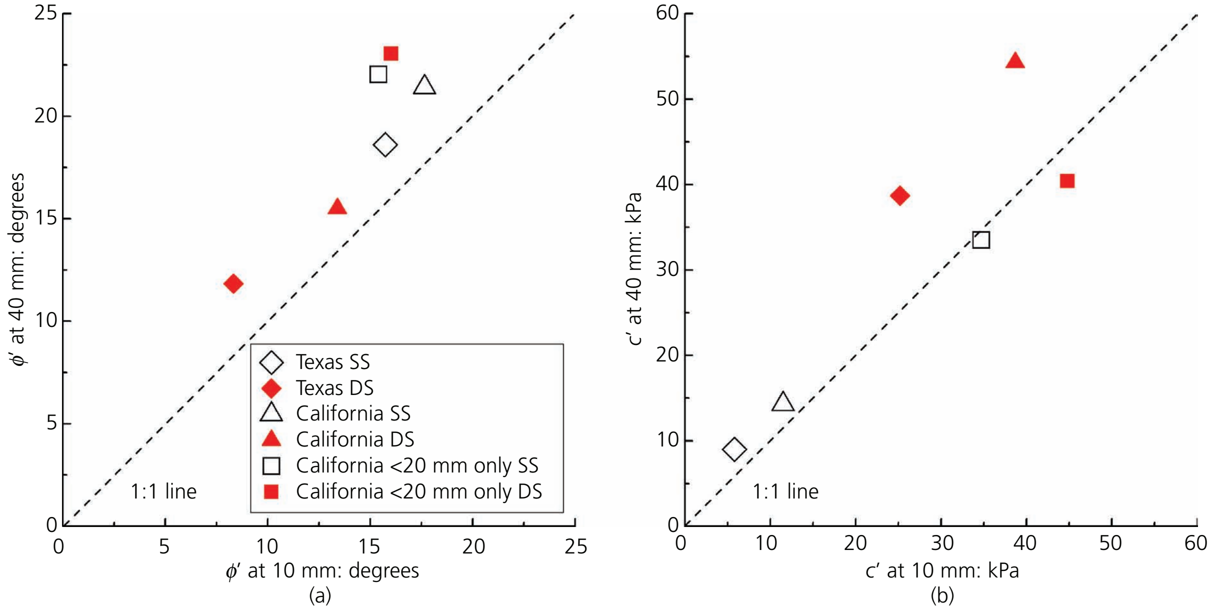

Figure 4. Comparison of shear strength parameters of MSW obtained at 10 and 40 mm displacements: (a) effective friction angle (ϕ'); (b) cohesion (c')

40 mm displacement criterion. This difference is important because, for the testing set-up used in this study, 10 mm displacement is equal to nearly 10% shear strain of MSW in SS, which is the failure criterion for SS testing that has been used in engineering practice (Kavazanjian *et al.*, 1999, 2013; Zekkos and Fei, 2017). The ϕ' and c' for SS tests are not expected to increase appreciably at displacements larger than 40 mm, as the stress–displacement curves reached plateaus (Figures 2(a), 2(c) and 2(e)). On the contrary, since the shear resistance of MSW in DS tests is expected to continue to increase at displacements larger than 40 mm (Figures 2(a), 2(c) and 2(e)), the failure criterion at 40 mm displacement results in lower shear strength estimates compared with studies that used a 55 mm displacement or higher failure criterion (Bareither *et al.*, 2012; Bray *et al.*, 2009; Kavazanjian *et al.*, 1999). Therefore, in general, interpreted shear strength in DS will be higher than interpreted shear strength in SS testing.

The values of ϕ', c' and τ of the MSW obtained from DS and SS tests at failure criteria of 10 and 40 mm displacements are compared in Figure 5. For specimens consisting of only California <20 mm material, ϕ' was practically the same in DS and SS tests (Figure 5(a)) and the c' in DS tests was around 10 kPa higher than in SS tests (Figure 5(b)). This results in a ratio of τ between SS and DS tests (τ_{SS}/τ_{DS}) between 0·85 and 0·90 at σ'_{vc} of 100–500 kPa (Figure 6(a)). Thus, the two testing methods yielded comparable results when testing MSW specimens without >20 mm fibrous waste constituents, and the shear strength parameters obtained in SS tests were marginally lower. The observation that SS results in lower shear strength than DS has been reported in the literature for various soils without fibrous waste constituents (Dounias and Potts, 1993; Hanzawa *et al.*, 2007).

On the other hand, MSW specimens that consisted of a mixture of <20 mm material and >20 mm fibrous waste constituents exhibited higher ϕ' (Figure 5(a)) and lower c' (Figure 5(b)) in SS tests than in DS tests at the same displacement level. However, as shown in Figure 6(a), the ratios of τ between SS and DS tests for Texas and California wastes at 40 mm displacement ranged between 0·73 and 0·97 and 0·73 and 1·01, respectively – that is, the SS shear strength was lower than the DS shear strength. The ratios were also dependent on σ'_{vc}.

The ranges of shear strength values of MSW obtained from DS and SS testing in this study were compared with those reported in the literature using large-size MSW specimens (dimension ≥300 mm) (Figure 6(b)). Bray *et al.* (2009) recommended a best-fit shear strength envelope for MSW based on the synthesis of 103 laboratory large-size DS testing by using a failure criterion of a shear displacement of 55 mm. The recommended values are higher than the τ values obtained at 40 mm displacement in this study, particularly at higher normal stresses (>100 kPa).

Kavazanjian *et al.* (1999) conducted SS testing on specimens reconstituted using different proportions of <20 and >20 mm fractions of MSW sampled from the Operating Industries Inc. Landfill in California, and τ at 10% shear strain in SS tests was reported. Pelkey *et al.* (2001) tested synthetic waste through SS testing and reported peak τ for all specimens. As shown in Figure 6(b), the results of SS testing on MSW in these studies are comparable to the results of SS testing presented in this study. Overall, τ obtained from DS testing was higher than that from SS testing, although the composition and compaction effort of the MSW specimens and σ'_{vc} values were not identical between studies. Additional investigation is needed to

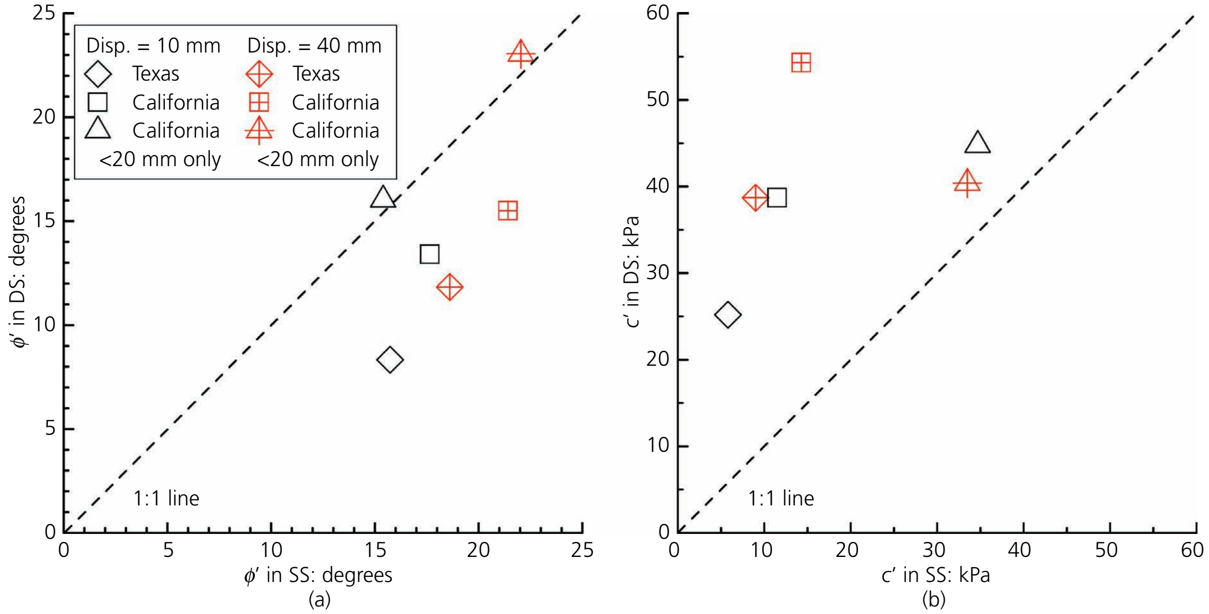

Figure 5. Comparison of shear strength parameters of MSW in SS and DS tests: (a) effective friction angle (ϕ'); (b) cohesion (c'). Disp., displacement

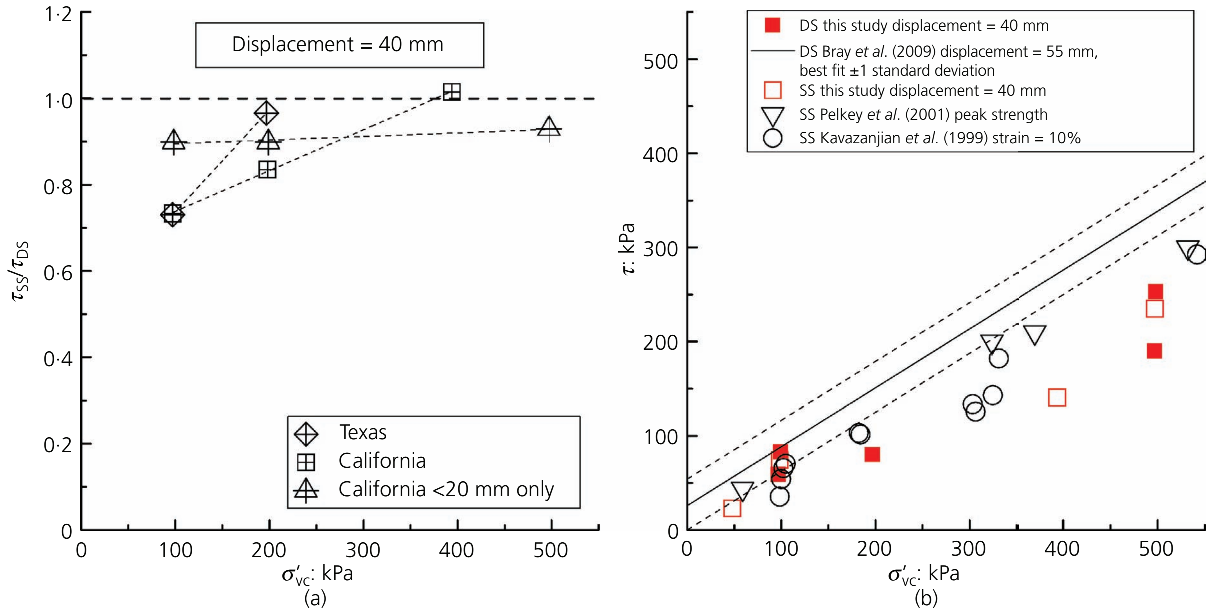

Figure 6. Relationships between vertical effective stress (σ'_{vc}) and (a) ratio of shear strength between SS and DS tests (τ_{SS}/τ_{DS}) at 40 mm displacement and (b) shear strength (τ) obtained from SS and DS tests in this study and in the literature based on different failure criteria

elucidate the influences of composition, compaction effort and σ'_{vc} of MSW on the difference in τ between SS and DS testing.

In addition, ϕ_{secant} of the waste specimens decreased with increasing σ'_{vc} in both DS and SS tests, but the decrease was more pronounced in DS testing (Figure 7). As shown in Figure 8, $\Delta\phi$ calculated according to Equation 3 for DS tests was always higher than in SS tests. Thus, the impact of σ'_{vc} on ϕ_{secant} of DS specimens is higher than that for SS specimens. This suggests that MSW shows higher non-linearity in DS testing than in SS testing with respect to increasing σ'_{vc}. The values of $\Delta\phi$ for DS tests obtained in this study agree with the values reported by Bray *et al.* (2009) for MSW.

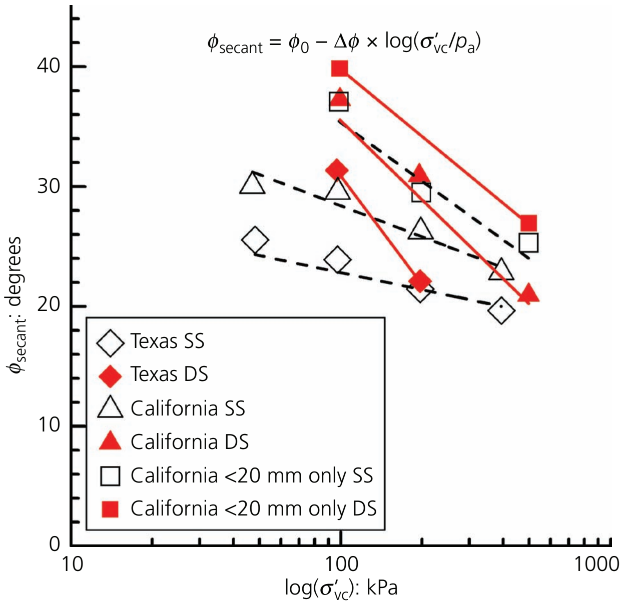

Figure 7. Relationship between vertical effective stress (σ'_{vc}) in logarithmic scale and secant friction angle (ϕ_{secant}) at 40 mm displacement of waste specimens

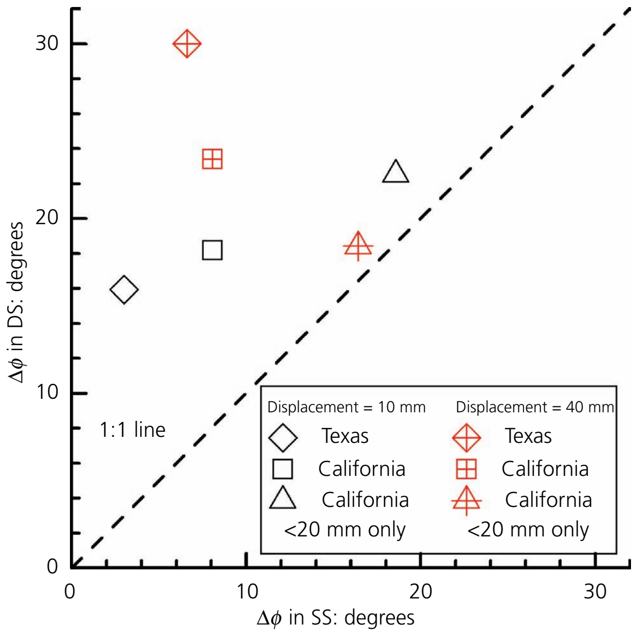

Figure 8. Comparison of change of secant friction angle of MSW with vertical effective stress ($\Delta\phi$) in SS and DS tests

Conclusions

Results of eight DS tests and 11 SS tests on three waste samples at vertical effective stresses (σ'_{vc}) between 50 and 500 kPa have been presented. The stress–displacement (or strain) response of waste in SS tests followed a hyperbolic trend and reached a maximum τ at shear displacement of 20–35 mm, whereas τ in most DS tests increased with increasing shear displacement and the maximum τ was commonly not reached even at displacements of 40 mm. Three parameters describing the shear response of waste, the effective friction angle (ϕ'), cohesion (c') and change in secant friction angle (ϕ_{secant}) with σ'_{vc} ($\Delta\phi$), are obtained for DS and SS tests by using displacement failure criteria of 10 and 40 mm, respectively. The failure criterion at 10 mm displacement resulted in significantly lower shear strength parameters than the 40 mm displacement criterion. The 40 mm criterion in DS resulted in lower parameters compared with previous DS studies that used a shear displacement of 55 mm as the failure criterion. The shear response parameters in DS and SS tests were compared to evaluate the differences between the two testing methods. SS testing resulted in higher ϕ' but lower c' of MSW than DS testing at the same shear displacement. The ratios of τ between DS and SS tests were influenced by the inclusion of large-size fibrous waste constituents. When only <20 mm material of MSW was tested, SS testing yielded similar or slightly lower τ than DS testing, between 85 and 90%, and the ratio of τ was independent of σ'_{vc}. When large-size fibrous waste constituents were included, SS testing yielded, in some cases, even lower τ than DS testing (as low as 73%), and the ratio of τ at 40 mm appeared to be dependent on σ'_{vc}. It was also observed that ϕ_{secant} was less influenced by an increase in σ'_{vc} in SS testing than in DS testing. Overall, the interpreted SS shear strength (at 10% shear strain) resulted in lower shear strength than in DS (at 55 mm horizontal displacement or higher). These observations are consistent with the stress–displacement (or stress–strain) relationships observed in previously reported DS and SS tests.

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