EFFECT OF SAND CHARACTERISTICS ON SAND/GEOTEXTILE INTERFACE FRICTION

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Abstract: Design procedures for reinforced soil structures, such as reinforced soil walls and steep slopes, require quantification of interaction behaviour at the soil/reinforcement interface. The sand/reinforcement interaction is determined by conducting large-scale direct shear and pull-out tests which are rather costly. Therefore, a methodology was developed for obtaining interface friction angle values from the results of triaxial compression tests using conventional equipment. In the present research, the effectiveness of this methodology is investigated for various sands and geotextiles. Six clean uniform sands differing in grain shape (subangular or rounded grains) and/or grain size as well as one non-woven and three woven geotextiles with or without apertures, were used in this experimental investigation. Triaxial compression tests were conducted on specimens with a diameter of 70 mm and a height of 144 mm consisting of dry and dense sands reinforced with 4 and 5 horizontal geotextile disks. For comparison purposes, interface direct shear tests were conducted on selected sand/geotextile interfaces. Triaxial compression tests yielded bilinear failure envelopes for sand reinforced with 5 geotextile layers. Reinforced sands with subangular grains present higher shear strength than reinforced sands with rounded grains. The grain size of sand has no remarkable effect on shear strength of reinforced sand. For geotextiles without apertures, the grain size of sand has no consistent effect on δ/φ ratio (interface friction angle / angle of internal friction of sand). For geotextiles with apertures, a relationship was found between δ/φ ratio and A/D_{50} ratio (aperture size of geotextile / mean grain size of sand), giving maximum δ/φ values for A/D_{50} values approximately equal to 1.9, which is in agreement with the results from other investigations. In general, the interface friction angle values obtained from triaxial compression tests are in agreement with the values obtained from interface direct shear tests.

Keywords: soil reinforcement, geotextile, sand, shear strength, interface friction, laboratory test.

INTRODUCTION

Design procedures for reinforced soil structures require quantification of the interaction behaviour at the soil – reinforcement interface which is accomplished by conducting large scale laboratory direct shear and pull-out tests and is expressed in terms of an apparent friction angle, δ (Koerner 1994). These experimental procedures require the use of specially designed and constructed large-size direct shear or pull-out boxes and specialized personnel and are rather costly. Therefore, a methodology for obtaining δ values from the results of laboratory tests using conventional triaxial compression testing equipment was developed, triaxial compression tests were conducted on reinforced sand samples (Atmatzidis *et al.* 1992, Atmatzidis & Athanasopoulos 1994) and the experimental investigation was supplemented with results from a linear elastic analysis of similar reinforced sand samples under triaxial loading conditions (Atmatzidis *et al.* 1994). The triaxial compression testing techniques used in these investigations for estimating values of the interface friction angle, appear to offer a feasible alternative to conventional pull-out and direct shear tests.

It is, therefore, of merit to investigate the effectiveness of this methodology for a wide range of sands with different characteristics and geotextiles manufactured with different processes and having different properties and to compare the results obtained using standardized direct shear tests. Toward this end, triaxial compression tests were conducted on samples consisting of various sands reinforced with different woven and non-woven geotextiles. Preliminary results of this investigation for one sand reinforced (a) with non-woven geotextiles manufactured using different processes (Markou & Sirkelis 2003) and (b) with standard grade and high strength woven geotextiles (Markou & Sirkelis 2004), were presented and were compared with the results obtained from large scale interface direct shear tests (Markou & Droudakis 2005). These results were found to be in quantitative and qualitative agreement with results from other investigations using different testing methods (Markou & Sirkelis 2003, 2004) and to be comparable to the results of interface direct shear tests (Markou & Droudakis 2005). Reported herein are the results of triaxial compression tests conducted on sands differing in grain shape and/or grain size, reinforced with woven and non-woven geotextiles and the comparison of these results with those obtained from interface direct shear tests performed on selected sand – geotextile interfaces, within the scope of this experimental investigation.

EXPERIMENTAL PROCEDURES

Conventional laboratory triaxial compression equipment without any modifications was used to conduct tests on geotextile reinforced sands in order to investigate the mechanical behaviour of the composite material and to evaluate the interface friction angle, δ. For comparison purposes, direct shear tests were performed with a conventional shear box on selected interfaces between sands and geotextiles. The tests were conducted using six clean uniform sands in dry and dense condition with grain sizes limited between ASTM sieve sizes Nos. 4 and 10, 16 and 20, 20 and 30, 30 and 40, and 40 and 100. From the properties of sands presented in Table 1, it can be seen that the sands also differ in grain shape since three of them (designated as S 4-10, S 16-20 and S 20-30) consist of subangular grains while the other three (designated as R 20-30, R 30-40 and R 40-100) are standard Ottawa quartz sands with rounded grains. The values of angle of internal friction, φ, of the sands in dry and dense condition, are also shown in Table 1. These φ values are used for normalizing the computed values of the interface friction angle, δ.

Table 1. Soil properties

Sand	Grain shape	Grain sizes (mm)			Void ratios		Shear strength	
		D_{max}	D_{50}	D_{min}	e_{max}	e_{min}	Friction angle, φ (^{o})	Rel. density, D_r (%)
S 4-10	Subangular	4.75	3.00	2.00	0.81	0.51	45.0	76
S 16-20	Subangular	1.18	1.00	0.85	0.92	0.58	48.5	92
S 20-30	Subangular	0.85	0.71	0.60	0.96	0.62	47.0	83
R 20-30	Rounded	0.85	0.71	0.60	0.77	0.46	36.0	82
R 30-40	Rounded	0.60	0.51	0.43	0.85	0.52	35.0	92
R 40-100	Rounded	0.43	0.25	0.15	0.79	0.52	37.0	90

Four different commercially available geotextiles were used during this investigation. These geotextiles were selected in order to test non-woven and woven products with or without apertures. More specifically, one thermally bonded non-woven polypropylene geotextile (TYPAR SF 56), one standard grade woven polypropylene geotextile without apertures (BONAR SG 80/80), one woven polyethylene geotextile with apertures (NICOLON 66447) and one woven polyester with PVC coating geotextile with apertures (HUESKER HaTe 50.145), were tested. These geotextiles are designated as SF 56, SG 80/80, N 66447 and H 50.145, respectively. Pertinent geotextile properties, according to the manufacturers, are presented in Table 2.

Table 2. Geotextile properties

Geotextile	Manufacturing process	Thickness (mm)	Mass per unit area (g/m^2)	Aperture size, A (mm)	Tensile test results	
					Max. tensile load (kN/m)	Extension at max. load (%)
SF 56	Non-woven	0.54	190.0	------	12.8	65
SG 80/80	Woven	1.35	360.0	------	82.0 / 86.0 *	20 / 11 *
H 50.145	Woven	1.15	225.0	1.20	32.0 / 32.0 *	15 / 18 *
N 66447	Woven	0.90	194.4	0.77	2.2/2.0 kN/5cm *	27 / 22 *

* Machine direction / Cross machine direction

Triaxial compression testing

Triaxial compression tests were conducted using samples with a diameter of 70 mm and an overall height of 144 mm. A schematic representation of the reinforced sand samples with 5 horizontal geotextile layers is shown in Figure 1a. The geotextile reinforcement discs had a diameter equal to the diameter of the sample and were placed at equal distances perpendicular to the axis of the sample. The sands were compacted using a special hand operated tamper and extreme care was taken in order to produce sand layers with constant density. All tests were conducted at a relative density of the sands between 76% and 99%. Tests were conducted with confining pressures, σ_3, equal to 10, 25, 50, 100, 200 and 400 kPa and at a constant rate of axial displacement equal to 0.6 mm/min. Duplicate tests were conducted with 4 geotextile reinforcement disks, arranged as shown in Figure 1b in order to determine the effect of the reinforcement disc placed at the mid-height of the sample. This was dictated by consistent observations indicating that slippage between sand and geotextile occurred definitely at least on this reinforcement disc. Reinforced sample configurations the same as that of Figure 1 have been used previously (Atmatzidis *et al.* 1992, Atmatzidis *et al.* 1994, Atmatzidis & Athanasopoulos 1994, Markou & Sirkelis 2003, Markou & Sirkelis 2004, Markou & Droudakis 2005) in an attempt to separate the effect of the central reinforcement layer and to estimate values for the interface friction angle, δ, using the computation method described below.

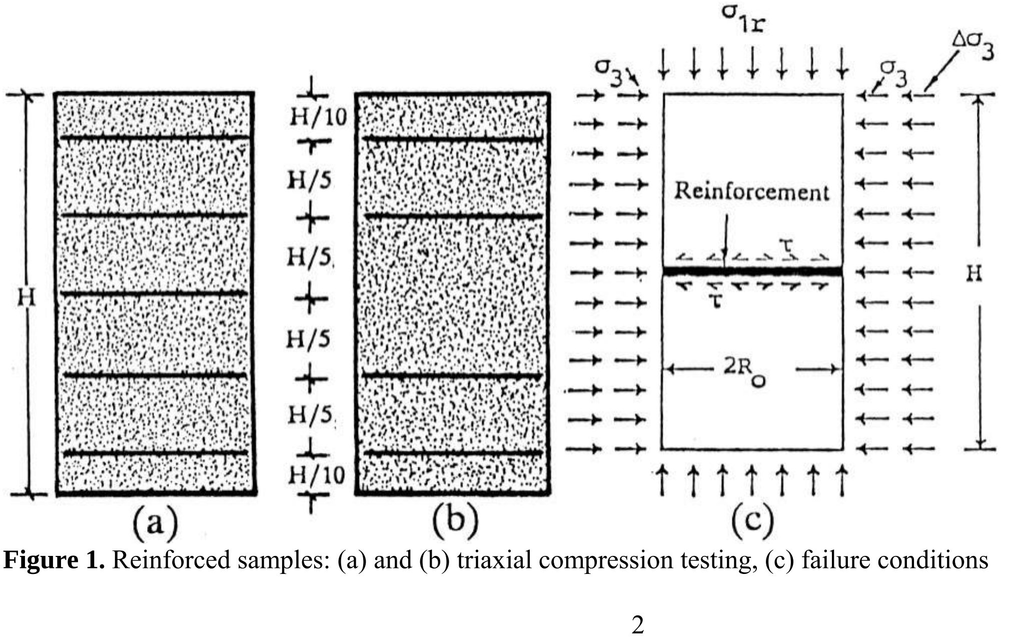
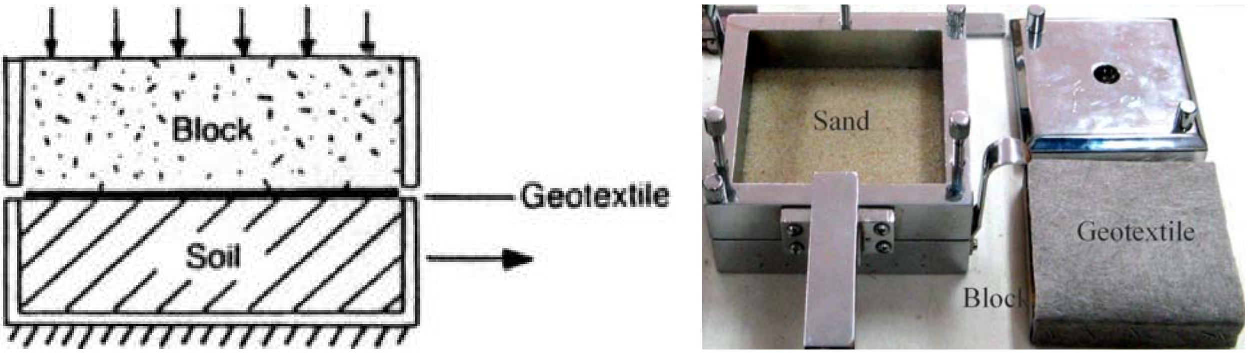


Figure 1. Reinforced samples: (a) and (b) triaxial compression testing, (c) failure conditions

Direct shear testing

The direct shear tests for the evaluation of the interface friction angle, δ, were conducted using a direct shear machine of controlled displacement with conventional square shear box (100 mm x 100 mm). This shear box was preferred because, according to Koerner (1994), shear boxes of these dimensions are felt to be satisfactory for geotextiles and geomembranes, while shear boxes of 300 mm x 300 mm size, although required in many cases according to ASTM Standard D 5321-92, are appropriate for geonets, geogrids and many geocomposites and are considered to be excessive for geotextiles and geomembranes. The sample configuration used in sand – geotextile interface direct shear testing, is shown schematically in Figure 2a and is depicted in Figure 2b. The dry sand was placed and compacted in the lower part of the shear box. The geotextile sheet was placed and fixed on a wooden block and, then, the block with the geotextile sheet was placed in the upper part of the shear box in contact with sand. The sands were compacted using a hand operated tamper and care was taken in order to produce sand layers with constant density. All tests were conducted at a relative density of the sands between 85% and 95%, with normal stresses, σ_n, equal to 100, 200 and 400 kPa, at a constant rate of shearing equal to 0.25 mm/min and were completed after failure of the sand – geotextile interface (peak value of shear force).



(a) (b)

Figure 2. Shear box 100 mm x 100 mm and sample configuration for sand/geotextile interface direct shear testing

INTERFACE FRICTION ANGLE COMPUTATION METHOD

A method developed for computing values of the apparent angle of friction, δ, from the results of triaxial compression tests (Atmatzidis *et al.* 1992, Atmatzidis *et al.* 1994, Atmatzidis & Athanasopoulos 1994), was used in this investigation. More specifically, the "equivalent" confining stress increase, $\Delta\sigma_3$, concept (Ingold 1982) attributes the observed shear strength increase, due to reinforcement, to the development of an additional confining pressure, $\Delta\sigma_3$, as shown in Figure 1c for failure conditions. This additional confining pressure, $\Delta\sigma_3$, is considered uniformly distributed over the entire cylindrical surface of the reinforced soil sample and can be expressed, for failure conditions, as (Gray & Al-Refeai 1986):

$$\Delta\sigma_3 = \frac{\sigma_3}{\sigma_1} \bullet \Delta\sigma_1 \qquad (1)$$

Where σ_3 is the same minor principal stress for tests on reinforced and unreinforced soil in kPa, σ_1 is the major principal stress at failure of the unreinforced soil in kPa and $\Delta\sigma_1$ is the major principal stress difference at failure between reinforced and unreinforced soil in kPa. Therefore, the contribution of the geotextile disc at the mid-height of the samples (Figure 1a) to the shear strength increase was quantified by determining the corresponding confining stress increase, $\Delta\sigma_3$. This was achieved by (a) conducting triaxial compression tests with the same confining pressure, σ_3, for unreinforced sand and sand reinforced as shown in Figures 1a and 1b, (b) determining $\Delta\sigma_{3,5\,l}$ and $\Delta\sigma_{3,4\,l}$ for five and four layers of reinforcement, respectively, by applying Equation 1 and (c) setting $\Delta\sigma_3 = \Delta\sigma_{3,5\,l} - \Delta\sigma_{3,4\,l}$. The value of the apparent angle of friction, δ, was then computed in degrees by applying Equation 2 (Atmatzidis *et al.* 1992, Atmatzidis et al. 1994, Atmatzidis & Athanasopoulos 1994):

$$\tan\delta = \frac{\Delta\sigma_3}{\sigma_{1r}} \bullet \frac{3H}{2R_0} \qquad (2)$$

Where R_0 is the radius of the reinforcement disc in cm, H is the overall height of the sample in cm and σ_{1r} is the major principal stress at failure in kPa, which was set equal to the axial stress at failure of the sand sample reinforced with five layers of geotextile.

RESULTS AND DISCUSSION

Shown in Figure 3 are the failure envelopes obtained by triaxial compression testing of the reinforced sands with 5 layers of all the geotextiles tested. It can be observed that the triaxial compression tests yielded bilinear envelopes for

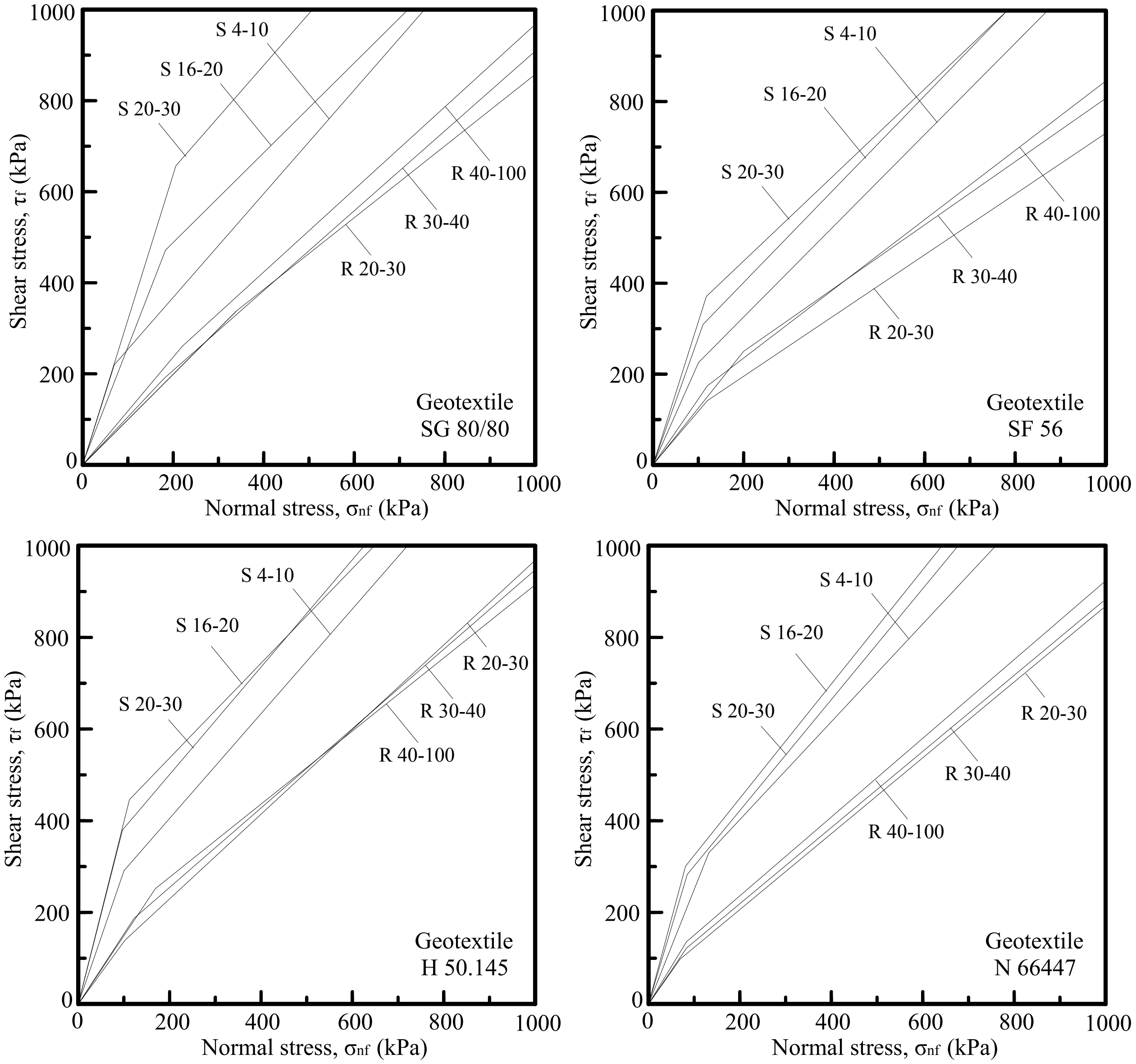


Figure 3. Failure envelopes from triaxial compression tests on sands reinforced with 5 geotextile layers

the composite material, which is in good agreement with the observations of other investigators (e.g. Gray *et al.* 1982, Gray & Al-Refeai 1986). The reinforced sands present higher shear strength than unreinforced sands, for all the geotextiles tested. It is also observed (Figure 3) that reinforced sands with subangular grains present higher shear strength than reinforced sands with rounded grains, which can be attributed to the higher angles of internal friction of the sands with subangular grains compared to those of the sands with rounded grains (Table 1). On the contrary, sand grain size does not have a consistent effect on shear strength of reinforced sand with the exception of S 4-10 which always presents lower shear strength than S 16-20 and S 20-30 sands, probably due to the slightly lower friction angle in comparison with the other two sands with subangular grains (Table 1). The break point of the bilinear envelopes corresponds to critical values of interface normal stress, σ_{vcr}, ranging from 70 kPa to 330 kPa. The values of σ_{vcr} depend on the type and the mechanical properties of the geotextiles. In the part of the bilinear failure envelopes before the break point, failure of the composite material is due to slippage of the geotextile with regard to the surrounding soil. Therefore, values of friction angle δ were computed using Equation 2, for all tests conducted with the confining pressures, σ_3, that resulted in Mohr circles tangent to this part of the bilinear failure envelopes.

The values of the apparent friction angle, δ, computed using Equation 2 for samples tested in triaxial compression, generally indicate a dependence of δ on the applied normal stress to the sand – geotextile interface. However, the actual interfacial normal stress cannot be evaluated reliably and the applied confining pressure, σ_3, can be considered as a good qualitative indicator of the interface normal stresses developing during the triaxial compression test. Accordingly, it can be concluded that the value of the friction angle δ generally decreases with increasing normal stress (increasing σ_3) in agreement with the results of other studies (Ingold 1982). For simplicity reasons, only the average values of friction angle δ and friction coefficient, tan δ, obtained from all samples tested in triaxial compression, are presented in Table 3. These values of δ were also normalized with regard to the angle of internal friction, φ, of the sands and the resulting values of friction efficiency, δ/φ, are also presented in Table 3. For the geotextiles without apertures (SF 56 and SG 80/80), the values of δ/φ range generally between 0.61 and 1.02 and are

Table 3. Values of apparent friction angle and friction coefficient from triaxial compression tests

Sand	Geotextile SF 56			Geotextile SG 80/80			Geotextile H 50.145			Geotextile N 66447		
	δ (°)	tanδ	δ/φ	δ (°)	tanδ	δ/φ	δ (°)	tanδ	δ/φ	δ (°)	tanδ	δ/φ
S 4-10	38.9	0.81	0.86	39.1	0.81	0.87	35.7	0.72	0.79	34.2	0.68	0.76
S 16-20	32.3	0.63	0.67	29.5	0.57	0.61	28.4	0.54	0.59	26.0	0.49	0.54
S 20-30	35.6	0.72	0.76	34.4	0.68	0.73	32.0	0.62	0.68	28.0	0.53	0.60
R 20-30	33.4	0.66	0.93	33.4	0.66	0.93	43.3	0.94	1.20	41.7	0.89	1.16
R 30-40	40.7	0.86	1.16	33.2	0.65	0.95	42.2	0.91	1.21	42.5	0.92	1.21
R 40-100	37.9	0.78	1.02	36.2	0.73	0.98	41.5	0.88	1.12	41.0	0.87	1.11

in good agreement with the typical range of friction properties of geotextiles, which are equal to 60 – 100% of soil friction (Koerner 1994). The values of δ/φ obtained for the interfaces between sands with rounded grains and geotextiles with apertures (H 50.145 and N 66447), are higher than 1.00 and range from 1.11 to 1.21. These high δ/φ values can be attributed to the interlocking of sand grains in geotextile apertures. Values of δ/φ considerably higher than 1.00 were also reported by Athanasopoulos (1993) for sands in contact with a geotextile with apertures. The relatively low δ/φ values obtained for S 16-20 and S 20-30 sands can be considered as mobilized values indicating that maximum δ/φ values were not reached in these tests.

Typical results of interface direct shear tests between the SG 80/80 geotextile and the R 20-30 sand are shown in Figure 4. The results of tests were used to plot Figure 4b, in order to evaluate the interface shearing resistance between the geotextile and the sand. As it is typically shown in Figure 4b, the interaction behaviour can be described by a linear Mohr – Coulomb failure envelope presenting very low adhesion values (up to 9.5 kPa). These adhesion values may be considered negligible for practical applications. From the slope of the failure envelopes resulted from interface direct shear tests, the values of apparent interface friction angle, δ, and friction coefficient, tanδ, were estimated and are presented in Tables 4 and 5. It may be easily observed that the values of friction angle δ are constant (independent

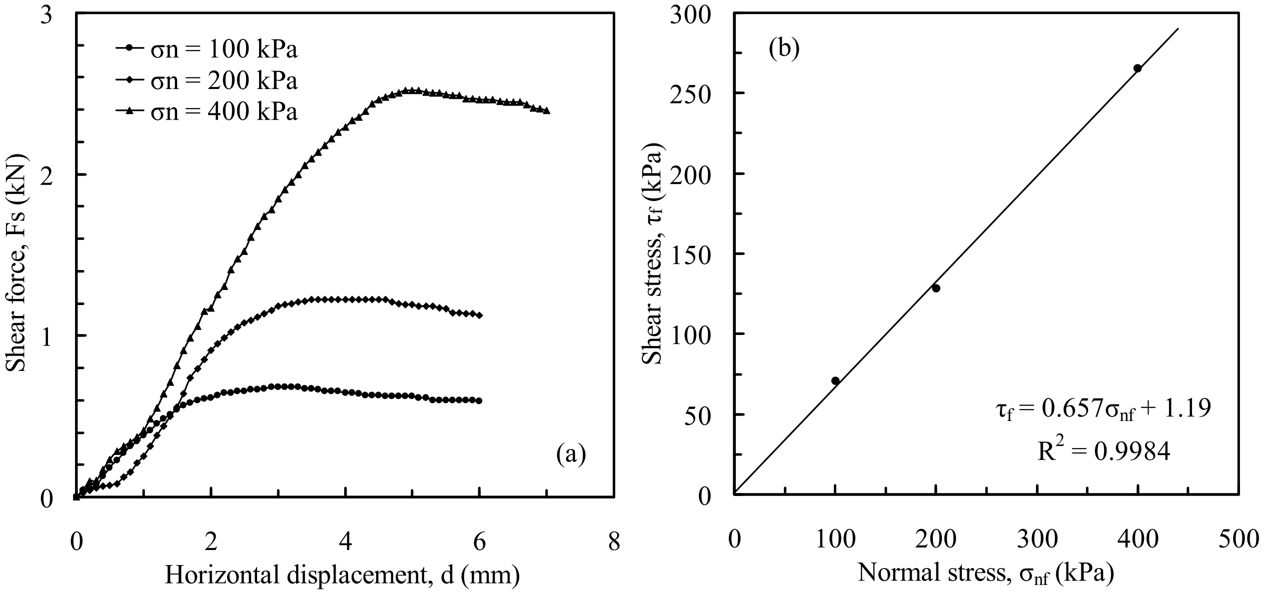


Figure 4. Results for R 20-30 sand / SG 80/80 geotextile interface from direct shear tests
(a) shear force versus horizontal displacement, (b) failure envelope

Table 4. Effect of sand grain shape and test type on sand/geotextile interface friction

Geotextile	Sand	Triaxial compression test			Direct shear test			Difference between tests in:		
		δ (°)	tanδ	δ/φ	δ (°)	tanδ	δ/φ	δ (°) *	δ (%) ‡	tanδ (%) §
SF 56	R 20-30	33.4	0.66	0.93	31.3	0.61	0.87	-2.1	-6.7	-8.2
	S 20-30	35.6	0.72	0.76	37.0	0.75	0.79	+1.4	+3.8	+4.0
SG 80/80	R 20-30	33.4	0.66	0.93	33.3	0.66	0.93	-0.1	-0.3	0.0
	S 20-30	34.4	0.68	0.73	38.0	0.78	0.81	+3.6	+9.5	+12.8
H 50.145	R 20-30	43.3	0.94	1.20	34.4	0.68	0.96	-8.9	-25.9	-38.2
	S 20-30	32.0	0.62	0.68	42.0	0.90	0.89	+10.0	+23.8	+31.1
N 66447	R 20-30	41.7	0.89	1.16	35.6	0.72	0.99	-6.1	-17.1	-23.6
	S 20-30	28.0	0.53	0.60	39.4	0.82	0.84	+11.4	+28.9	+35.4

* $\delta_{\text{direct shear}} - \delta_{\text{triaxial compression}}$
‡ (Difference in δ) / $\delta_{\text{direct shear}}$
§ $(\tan\delta_{\text{direct shear}} - \tan\delta_{\text{triaxial compression}}) / \tan\delta_{\text{direct shear}}$

Table 5. Effect of sand grain size and test type on sand/geotextile interface friction

Geotextile	Sand	Triaxial compression test			Direct shear test			Difference between tests in:		
		δ (°)	**tanδ**	**δ/φ**	**δ (°)**	**tanδ**	**δ/φ**	**δ (°) ***	**δ (%) ‡**	**tanδ (%) §**
SF 56	R 20-30	33.4	0.66	0.93	31.3	0.61	0.87	-2.1	-6.7	-8.2
	R 30-40	40.7	0.86	1.16	32.5	0.64	0.93	-8.2	-25.2	-34.4
	R 40-100	37.9	0.78	1.02	35.4	0.71	0.96	-2.5	-7.1	-9.9
SG 80/80	R 20-30	33.4	0.66	0.93	33.3	0.66	0.93	-0.1	-0.3	0.0
	R 30-40	33.2	0.65	0.95	33.9	0.67	0.97	+0.7	+2.1	+3.0
	R 40-100	36.2	0.73	0.98	33.9	0.67	0.92	-2.3	-6.8	-8.9

* $\delta_{\text{direct shear}} - \delta_{\text{triaxial compression}}$

‡ (Difference in δ) / $\delta_{\text{direct shear}}$

§ $(\tan\delta_{\text{direct shear}} - \tan\delta_{\text{triaxial compression}}) / \tan\delta_{\text{direct shear}}$

from the interfacial normal stress) and are lower than the values of friction angle φ of the tested sands. The average values of friction angle δ and friction coefficient tanδ obtained from triaxial compression tests, are also compared to the values obtained from direct shear tests in Tables 4 and 5. The friction angle δ values obtained from triaxial compression tests are smaller or larger than the ones obtained from interface direct shear tests. For geotextiles without apertures, δ and tanδ values obtained from the two tests are comparable, since the differences between them range from 0.3% to 9.5% (0.1° – 3.6°) and from 0.0% to 12.8%, respectively, and can be considered as low. The only exception is R 30-40 sand – SF 56 geotextile interface, where the large difference between the two tests is attributed to the very high values of δ and tanδ obtained from triaxial compression tests. On the contrary, the results of the two tests are not comparable for geotextiles with apertures, since differences in δ and tanδ as high as 29% and 38%, respectively, are observed (Table 4). These high differences are attributed to (a) the low δ and tanδ values obtained from triaxial compression test in S 20-30 sand, which are considered as mobilized and not as maximum, and (b) the high δ and tanδ values obtained from triaxial compression tests on R 20-30 sand, possibly due to a more effective interlocking of sand grains in geotextile apertures in comparison with that in direct shear tests.

The results of triaxial compression and direct shear tests conducted with two sands having the same grain size and differing in grain shape are shown in Table 4. It is observed that the values of δ and tanδ are higher in sand with subangular grains than in sand with rounded grains. This observation does not apply to the triaxial compression tests conducted with the two geotextiles with apertures, due to the reasons described in the previous paragraph. On the contrary, friction efficiencies δ/φ are higher in sand with rounded grains than in sand with subangular grains. Presented in Table 5 are the results of triaxial compression and direct shear tests conducted with geotextiles without apertures in contact with three sands having the same grain shape and differing in grain size. It can be seen that grain size of sand has no consistent effect on friction angle δ and friction coefficient tanδ as well as on friction efficiency δ/φ. For geotextiles with apertures, the effect of sand grain size on friction efficiencies δ/φ and tanδ/tanφ is quantified using the aperture ratio, A/D_{50}, defined as the ratio of aperture size of geotextile to the mean grain size of sand. The aperture sizes, A, of geotextiles are shown in Table 2 and the mean grain sizes of sands are presented in Table 1. Due to the different aperture sizes of the two geotextiles used, the results obtained from triaxial compression tests on the three sands with rounded grains and the two geotextiles with apertures are combined and presented in Figure 5. It is evident that there is a relationship between friction efficiencies and aperture ratio and that the maximum value of friction efficiency is developed for an optimum value of aperture ratio approximately equal to 1.9. This optimum value is in agreement with the value of 1.6 reported by Athanasopoulos (1993) and lies between the values of 1.0 and 3.1 reported by Juran *et al.* (1988) and Bauer & Mowafy (1990), respectively.

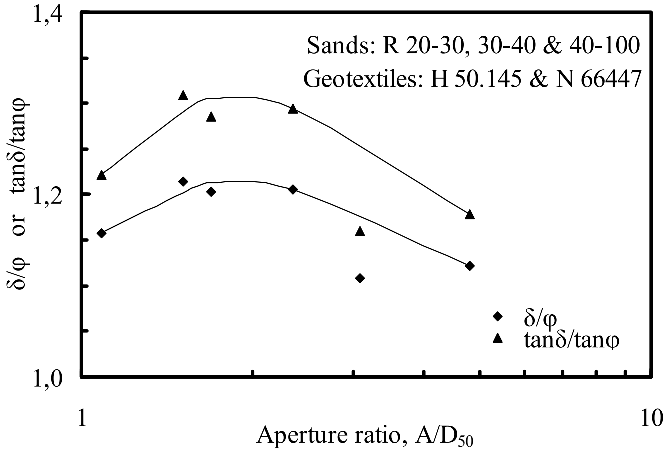


Figure 5. Effect of aperture ratio on friction efficiency values

CONCLUSIONS

Based on the results of this investigation and within the limitations posed by the number of tests conducted and the materials used, the following conclusions may be advanced:

- Triaxial compression tests yield bilinear failure envelopes for the geotextile-reinforced sands. Reinforced sands with subangular grains present higher shear strength than reinforced sands with rounded grains, which is attributed to the difference in angle of internal friction between sands with subangular and rounded grains.
- For geotextiles without apertures, the values of the apparent friction angle at the sand – geotextile interface obtained by triaxial compression tests, may be smaller or slightly larger than the angle of internal friction of the sand in contact with the geotextile. For geotextiles with apertures, triaxial compression tests yield values of interface friction angle higher than friction angle of sand, in agreement with the results of other investigators.
- The values of apparent friction angle and friction coefficient from triaxial compression tests are in quantitative agreement with the values obtained by interface direct shear tests, for geotextiles without apertures.
- Although the values of interface friction angle and friction coefficient are generally higher in sands with subangular grains than in sands with rounded grains, friction efficiency values are higher in sands with rounded grains than in sands with subangular grains.
- For geotextiles with apertures, the aperture ratio (aperture size of geotextile / mean grain size of sand) affects the value of friction efficiency and, according to the experimental results reported herein, the maximum value of friction efficiency is developed for an optimum value of aperture ratio approximately equal to 1.9, in agreement with the results of other investigations.
- The triaxial compression testing techniques used in this investigation for estimating values of the apparent friction angle at sand – geotextile interfaces, appear to offer a feasible alternative to conventional pull-out and direct shear tests.

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