Studying the Effect of Roughness on Soil-Geotextile Interaction in Direct Shear Test

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Abstract

One of the methods of increasing soil resistance against failure is soil reinforcement using geosynthetics. Soil-geosynthetic interactions are of great importance and are affected by friction and adhesion at their interface. Soil gradation, contact surface roughness and geotextile density are among the factors affecting soil-geotextiles interaction this study, to investigate the effects of these factors, large-scale direct shear tests have been conducted using a well and a poorly graded sand at a relative density of 80% reinforced with two geotextiles having different tensile strengths and mass per unit area. Samples were subjected to normal pressures of 12.5, 25 and 50kPa and sheared at a rate of 1 mm/min. Geotextile surface roughness was achieved by gluing two different single sized sand particles. Results show that increasing geotextile surface roughness increases shear strength at soil-geotextile interface. Geotextile tensile strength mobilization is shown to depend on soil grain size at the interface. The coarser and more angular the soil particles, the more effective the soil-reinforcement

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interactions. Geotextile tensile strength and its mass per unit area are shown to less important factors.

Keywords: Geosynthetic, Geotextile, Direct shear, Interaction, Roughness, Soil gradation.

1. Introduction

Geotextiles are classified as member of the geosynthetics which are produced and classified as woven and non-woven. Non-woven geotextiles are utilized more due to their isotropic characteristics, and have various uses including separation [1], filtration [2], [3], drainage [4], soil reinforcement [5], [6], [7], etc. The safe design of reinforced soil structures with geosynthetics requires understanding of the behavior of soil-geosynthetics at their interface [8]. Therefore, the evaluation of shear strength characteristics at soil-geosynthetic interface is an important factor in the design of soil structures [9], [10], [11], [12], [13]. Jewell et al. (1984) stated that soil-geosynthetic interactions are due to friction at soil-reinforcement interface, soil-soil in apertures and passive soil resistance in front of geogrid transverse elements. Unlike geogrids, geotextiles have only the first mechanism due to the lack of apertures [14].

In most studies, researchers have shown that the shear strength at soil-geosynthetics interface under direct shear mode is less than the shear strength of the soil, which means that friction at soil-geosynthetics interface is less than the angle of friction of the soil. In

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other words, under direct shear mode, soil-geosynthetics interface is a potential slip surface [15], [16], [17], [18].

In this study, in order to increase soil-geotextile interactions and to compensate for the reduction in shear resistance at interface as well as to exploit reinforcement tensile strength, effects of gluing sand particles to geotextile surface to increase surface roughness have been investigated. Samples were tested in direct shear mode using large scale direct shear apparatus and factors such as soil grading, geotextile tensile strength and unit weight and normal pressures investigated.

2. Laboratory equipment

The main laboratory equipment used in the present study was direct shear apparatus. One of the most influential factors affecting direct shear test results is the shear box dimensions [19]. In this research, direct shear tests for unreinforced samples were carried out according to ASTM D3080-04 which states that, the minimum length and width of the size of shear box should be 10 times and the minimum height should be 6 times the maximum soil particle [20]. Evaluation of soil-geotextile interaction under direct shear condition was evaluated in accordance with ASTM D5321-08 standard. According to the criteria of this standard, the minimum dimensions of the shear box should be 30 cm or 15 times D_{85} of soil and its height should be at least 50 mm or 6 times the largest soil particle size [21]. Thus in this research, direct shear apparatus with direct shear box dimensions of 30×30×17 cm was used. Since the upper and lower shear box sections displace during tests which reduces soil-soil contact surface, modified areas for soil-geotextile interaction computations were implemented. The apparatus is equipped with two LVDTs for recording horizontal displacement of the lower section of the shear box and the vertical deformation of the sample, a load cell to measure the shear forces and an automatic data recording system.

3. Materials

3.1. Soils

In current research, four types of sand, including two for preparation of samples and two for adherence to the geotextile surface to increase contact surface roughness were used. One of the sand used to prepare samples is non-uniform with sharp particles and the other is silica sand known as 161 Firoozkooh with uniform grading, which is used in casting and sandblast industries. For abbreviation in text, figures and diagrams S_c and S_f have been used to refer to the sharp-grained and Firoozkooh sands, respectively. The sand particle used to increase surface roughness at contact surface could not be too coarse so they could be attached to the reinforcement using adhesive, and not too fine, to make provide appropriate roughness. Accordingly, their grading was determined by trial and error and for abbreviation in text, figures and shapes P_c (coarse particles) and P_f (fine particles) is used. These sands were washed several times prior to use to have no fine particles for better attachment with adhesive.

The physical and mechanical properties of S_c and S_f sands, which comply with appropriate ASTM standards are given in Table 1 [22], [23]. Since the mechanical properties of P_c and P_f sands were not required, only their grading was determined. According to Unified Soil Classification System (USCS), fine uniform sand (S_f) was classified as SP (poorly graded sand) and the coarse non-uniform sand (S_c) as SW (well graded sand) (ASTM D 2487-11) [24], [25]. Particle size distribution curve for sands are shown in Figure. 1. In this research, a relative density of 80% was used for the preparation of samples.

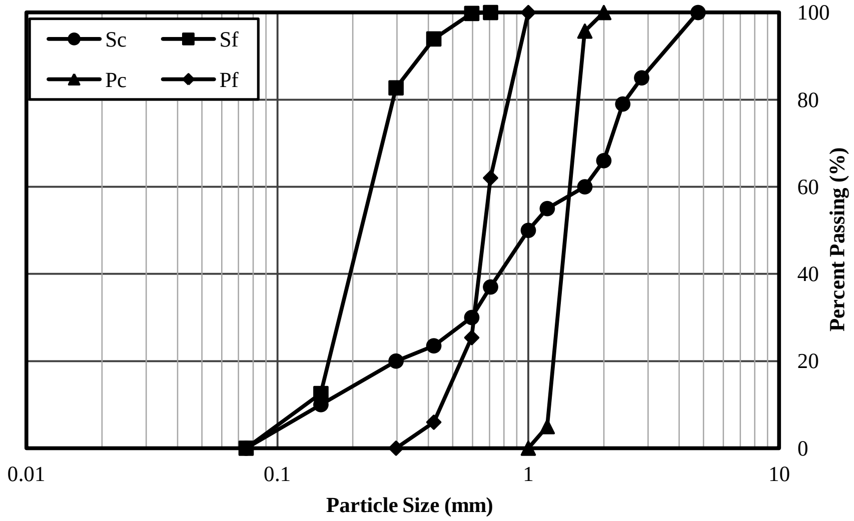

Figure 1. Soil particle size distribution curves

3.2. Geotextiles

Geotextiles used in this research were both of unwoven type having different tensile strengths and unit weights per unit area, so that the

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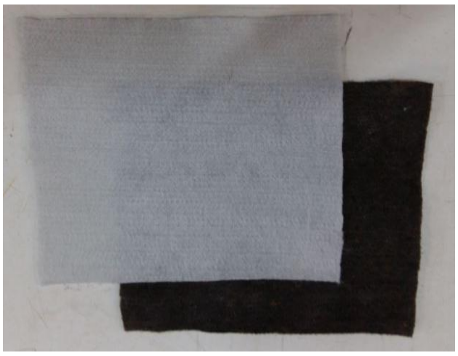
effect of these factors could also be investigated on interaction between the sand and geotextile at interface. Figure 2 shows a picture of geotextiles together with their characteristics presented on Table 2. Geotextiles are produced by Sepidbaft Company of Khorasan [26].



(a) (b)

Figure 2. Used geotextiles; a) T_1 and b) T_2

Table 1. Soils characteristics

Description	S_c	S_f	P_c	P_f
Coefficient of uniformity, Cu	11.20	1.71	1.56	1.19
Coefficient of curvature, Cc	1.43	0.96	1.14	0.97
Maximum dry unit weight (kN/m^3)	1.75	1.6	-	-
Minimum dry unit weight (kN/m^3)	1.55	1.38	-	-
Classification (USCS)	SW	SP	SP	SP
Angle of internal friction (°)	44.8	33.8	-	-
Cohesion (kPa)	0	1.3	-	-

Table 2. Geometric and physical characteristic of geotextiles

Geotextile	unit weight (gr/m^2)	Thickness (mm)	Tensile Strength (kN/m)	Puncture strength (N)	Aperture size of geotextile (mm)
T_1	500	4.7	55	1100	0.15
T_2	300	3.5	40	720	0.12

4. Sample preparation method

Richards and Scott in 1985 used a rigid piece in the lower shear box to assess soil-geotextile interactions and stated that better results

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were achieved using this method [27]. This method has also been used by many researchers [28]. If geotextile layer is not fixed, it will displace or tend to fold or wrinkle during shearing. Teflon is not a completely rigid material and particles piercing the geotextile would be able to penetrate and interact with it at their interface almost as if soil was used. Thus in this study, a piece of Teflon 30×30×8 cm was used to fit in the lower shear box, similar to a study by Abdi and Mamani in 2015 [29]. Geotextiles were cut 30×30 cm and glued to the surface of the Teflon as shown in Figure. 3. Subsequently soil was poured in the upper shear box and compacted to a relative density of 80% as shown in Figure. 4. In order to attach P_c and P_f sand particles to geotextiles T_1 and T_2, the upper surface of the geotextile attached to the Teflon was covered with glue and placed in boxes with the aforementioned sands. Then, they were placed under dead weights for three days for the adherence to be complete (Figure 5). Figure 6 shows roughened geotextiles. Authors are well aware of the fact that gluing particles to geotextiles is not a practical method of increasing soil-geotextile interactions. This method was adopted because of its simplicity and cost effectiveness which would produce a geo-composite with both filtration and reinforcement capabilities. Various geo-composites have been introduced and studied by researchers [30], [31]. For abbreviation in the text and on the figures samples are referred to as T_1P_c, T_2P_c, T_1P_f and T_2P_f, meaning geotextiles T_1 and T_2 coarsened with sands P_c and P_f.

In order to compact the soil layers in the upper shear box, a metal tamper 10×10 cm was used and the number of blows required to

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achieve the required relative density were determined with trial and error in preliminary tests. In order to reduce the friction, contact surfaces of the upper and lower shear boxes were lubricated. After pouring and compaction of the soil in the upper shear box, the loading plate was placed and normal load applied. Since shear mode of failure is most likely in the upper soil layers in reinforced soil structure, low vertical pressures of 12.5, 25 and 50 kPa were used in all experiments [32]. After sample preparations, horizontal and vertical measuring sensors were attached together with a 5 ton capacity load cell. Shear force was applied at a rate of 1 mm/min and experiments were carried out as strain controlled up to a maximum horizontal displacement of 15 mm (5% shear displacement). After each test, adherence between geotextiles, Teflon and sand particles were assessed and replaced if damaged. A total of 42 large scale shear tests were performed, and the coding $S_iT_jP_k$ used means the S_i sand is reinforced with geotextile T_j roughened with P_k particles. For example $S_cT_1P_c$ refers to "coarse sand + geotextile 1+ coarse particles".

5. Interaction coefficient and Enhanced interaction coefficient

Many researchers have used "interaction coefficient, C_i" which is the ratio of "reinforced soil shear strength to unreinforced soil shear strength" as a measure of soil-geosynthetic interaction [33], [34], [35], [36]. In present paper, "enhanced coefficient of interaction, i" has been introduced, which is defined as the ratio of "soil-modified geotextile.

shear strength to soil-geotextile shear strength at interface" and is as follows

$$i = \frac{C_a + \sigma_n \tan \delta_r}{C_a + \sigma_n \tan \delta_a} \quad \textbf{(1)}$$

In this equation, δ_r, is the interaction friction angle at soil-modified geotextile interface; δ_a, is the interaction friction angle at soil-geotextile interface; C_a, apparent adhesion between soil and geotextile and σ_n, is the applied normal pressure. As the soils investigated were cohesion less, the above equation is simplified as:

$$i = \frac{\tan \delta_r}{\tan \delta_a} \quad (2)$$

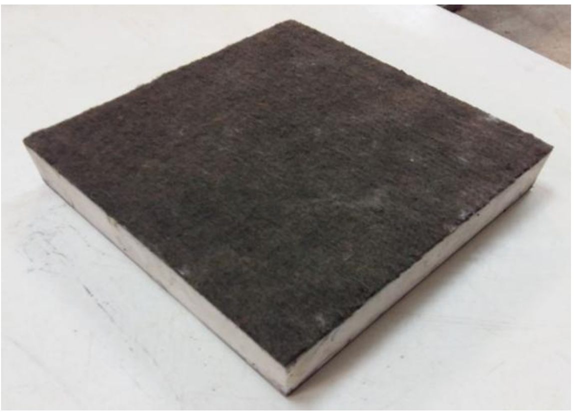

Figure 3. Teflon with attached geotextile

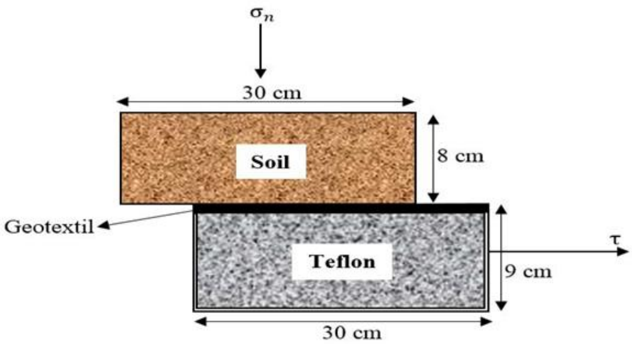

Figure 4. Geotextile position

Fgure 5. Method of roughening geotextiles

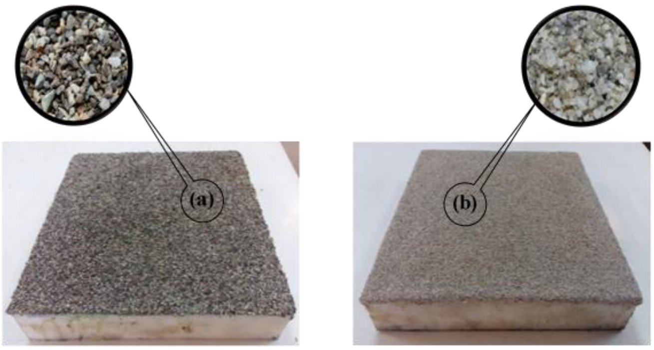

Figure 6. Coarsened geotextile; surface with sands: a) P_c and b) P_f

6. Results and analyses

6.1. Unreinforced sand samples

Shear stress-horizontal displacement variations and Failure envelopes of the unreinforced S_c and S_f sand samples used in the research are shown in Figures 7 and 8. Under a specific normal pressure, the S_c compared to S_f shows greater shear stresses with increased shear displacement due to their coarse grading and the

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presence of non-uniform and angular shaped particles. The S_c samples at shear displacement of about 10 mm reach their maximum shear strength, but the S_f sand samples with smaller and uniform particles at lower shear displacement of less than 5 mm reached their maximum shear strength. S_f samples have reached their final and stable conditions in a maximum displacement of 15 mm, whereas S_c samples show a decreasing trend and have not reached their final condition. The internal friction angle of the S_c and S_f sands investigated are 44.8 and 33.8 degrees respectively, and the apparent cohesion of S_f sand is low and negligible.

6.2. Sand samples reinforced with geotextile

Variations of shear stress-shear displacement and failure envelopes obtained for sands S_c and S_f reinforced with geotextiles T_1 and T_2 together with failure envelopes for unreinforced samples are shown in Figures 9 to 12. Results show that reinforcing sands with geotextiles has reduced deformation characteristics of the samples such that maximum shear strengths are achieved at smaller shear displacements with initial slope of curves being sharper than unreinforced samples. It can also be observed that in these samples shear displacements at failure increase with increase in normal pressures. Geotextile reinforced sands display initially hardening and subsequently softening behavior which for particularly S_f samples becomes more evident with increase in normal pressures. Considering failure

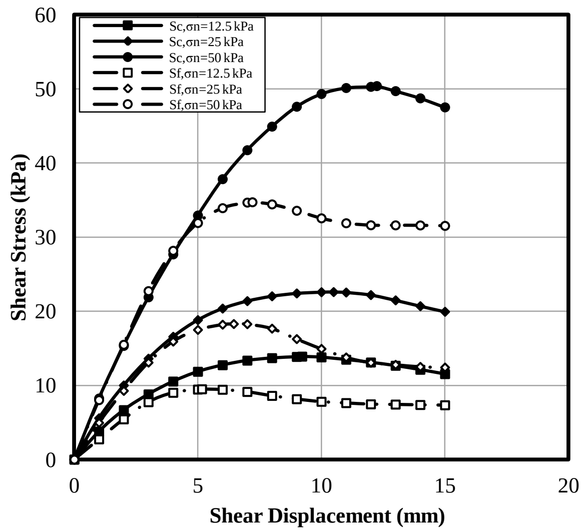

Figure 7. Shear stress-shear displacement curves for unreinforced S_c and S_f sands

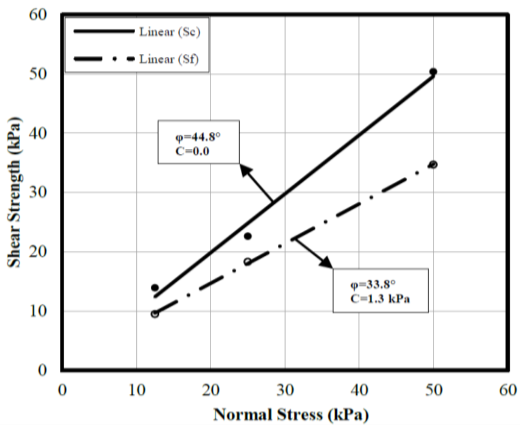

Figure 8. Failure envelopes for unreinforced S_c and S_f sands.

envelopes and by comparing interaction angles at interface of reinforced samples with internal friction angles of the unreinforced sand samples, it is observed that interaction angles obtained are smaller that friction angles (i.e. 3.6 to 5.5 degree (i.e. 8 to 12.5%) reduction for S_c and 3.6 degree (i.e. 10.7%) reduction for S_f sand). The reductions are attributed to weak interactions at soil-geotextile interface. Presence of geotextile prevents effective soil-soil interactions. These effects have also been reported by Athanasopoulos (1996), Chenggang (2004), and Liu et al. (2009) [37], [38], [39].

Considering the results for both sands and bearing in mind that for all samples reinforced with T_1 having greater tensile strength, weaker interactions have been achieved with soil particles. Thus, it may be concluded that geotextile tensile strength does not have a significant effect on soil-reinforcement interactions. In these samples interactions are more influenced by soil frictional and geotextile deformation characteristics and angle of interactions depends on geotextile surface texture. It is noteworthy that the interaction between sand-geotextile is dependent on the average sand particle size [40]. The lack of effective soil-geotextile interactions is mainly due to the fact that under direct shear mode, geotextile is not put in tension and thus its tensile strength is not mobilized. Lack of influence of geotextile tensile strength on soil-geotextile interactions has previously been reported by Tuna and Altun in 2012 [41].

For both the reinforced soils it can be observed that mass/unit area of the geotextiles have an inverse relation with interaction friction angle. This relationship for S_f reinforced samples is less vivid which is attributed to the fine and uniform soil particles which penetrate the fabric of the geotextile. Based on the results of current research and the observations reported by other researchers that have used geotextiles with lower and higher mass/unit areas, it can be concluded that probably there is an optimum relation between mass/unit area and soil particle size. If the mass per unit area of the geotextile is too high, it would prevent effective interaction between particles on both sides, and if this property is too low, soil particles penetrate the geotextile and its fibers can provide sufficient restraint for the particles [8], [41], [42].

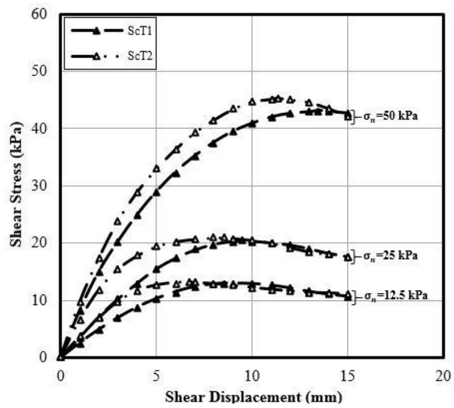

Figure 9. Shear stress versus shear displacement curves for S_cT_1 and S_cT_2

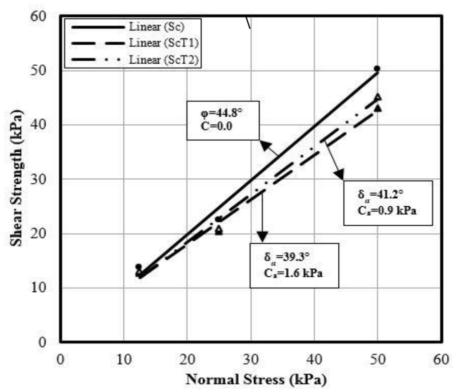

Figure 10. Failure envelopes for S_cT_1 and S_cT_2

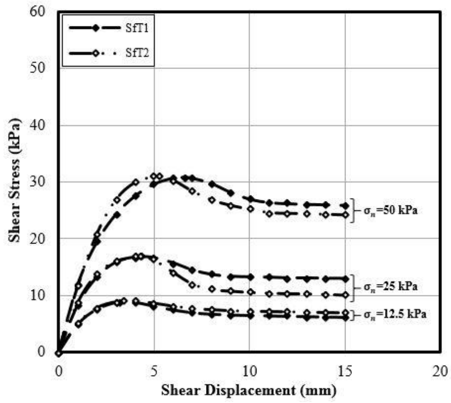

Figure 11. Shear stress versus shear displacement curves for S_fT_1 and S_fT_2.

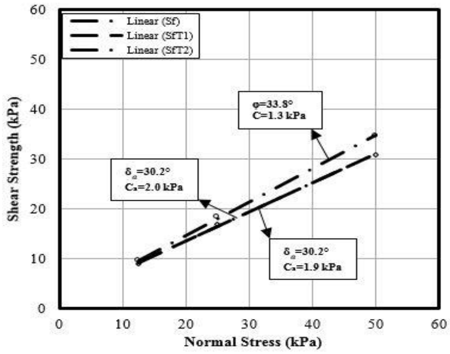

Figure 12. Failure envelopes for S_cT_1 and S_cT_2

6.3. Sand samples reinforced with roughened geotextiles

According to Figures 13 to 20, which show shear stress-shear displacements variation and failure envelopes for S_c and S_f samples reinforced with geotextiles and roughened geotextiles, it can be observed that roughening geotextile surface with sand particles has resulted in improving interactions at interface. Overall samples of S_c sand reinforced with roughened geotextiles show greater shear strengths compared to equivalent S_f samples which is due to differences in their particle size, shape and distributions. Also, for a particular reinforced sand, samples that have been roughened with coarser P_c particles compared to smaller P_f particles have resulted in larger shear strengths. In both series of samples, the effect of roughness is strongly influenced by normal pressures, such that in sample subjected to normal pressures of 12.5 and 25 kPa no significant changes can be observed. But by increasing normal pressure to 50 kPa, greater resistance to shearing has been achieved. This effect is attributed to the greater confinement and thus better interactions between sand particles and geotextile surfaces which has resulted in preventing particle dislodgments. Mosallanezhad et al in 2016 investigating performance of a new reinforcement system to increase interactions at soil-geogrid interface have also reported significant increase in shear strength which is significantly influenced by normal pressures [43]. Makkar et al. in 2017 investigating the performance of a 3-D geogrid reinforced sand under direct shear reported 16 to 22% increase in interface shear strength [44].

Results show that tensile strengths and different specific weight of T_1 and T_2 geotextiles are not very influential factors on maximum shear resistances at interfaces. For example, according to Figure 13, for sand S_c reinforced with geotextile T_1 and roughened with particles P_c and P_f and subjected to normal pressure of 50 kPa, maximum shear strengths of 43, 46 and 53 kPa were obtained, respectively. For the same sand, but reinforced with geotextile T_2 the maximum shear strengths were 45, 49 and 54 kPa, respectively (Figure. 14), which do not show much difference with samples reinforced with geotextile T_1.

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The summary of the interaction angles measured for reinforced and roughened reinforced sand samples are presented in Tables 3 and 4 for S_c and S_f samples, respectively. It is observed that by reinforcing sand S_c with geotextile T_1 and T_2, the internal friction angles have decreased from 44.8 degrees to 39.3 (i.e. 12.2%) and 41.2 degrees (i.e. 8%), respectively, and for equivalent S_f sand decreased from 33.8 degrees to 30.2 degrees (i.e. 10.7%). By roughing the surface of geotextile T_1 with P_c and P_f particles, the angles of interactions for S_c sand samples obtained were 41.6 and 46.1 degrees, and for the roughened geotextile T_2 were 43.9 and 46.5 degrees, respectively. It can be said that roughing the surface of geotextile with sand particles has compensated for the reduction in shear resistance due to mobilization of geotextile.

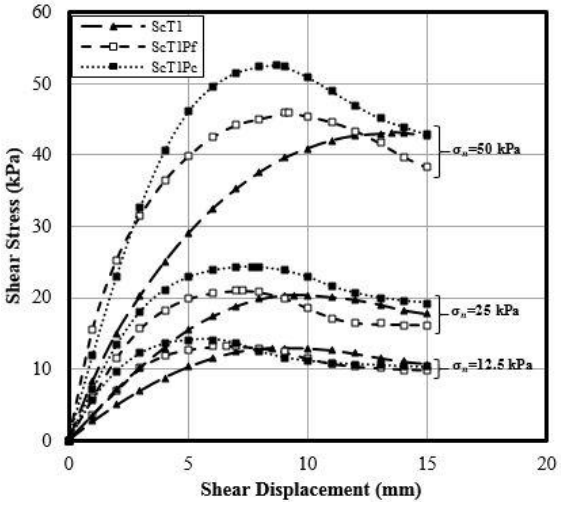

Figure 13. Shear stress versus shear displacement curves for S_cT_1, $S_cT_1P_c$ and $S_cT_1P_f$.

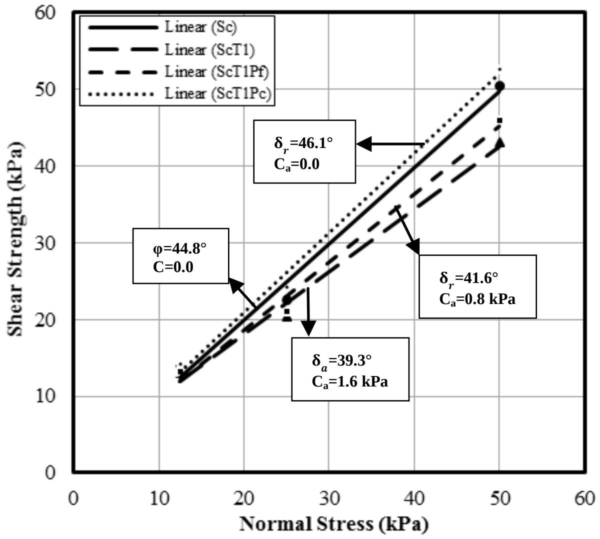

Figure 14. Failure envelopes for S_c, S_cT_1, $S_cT_1P_c$ and $S_cT_1P_f$.

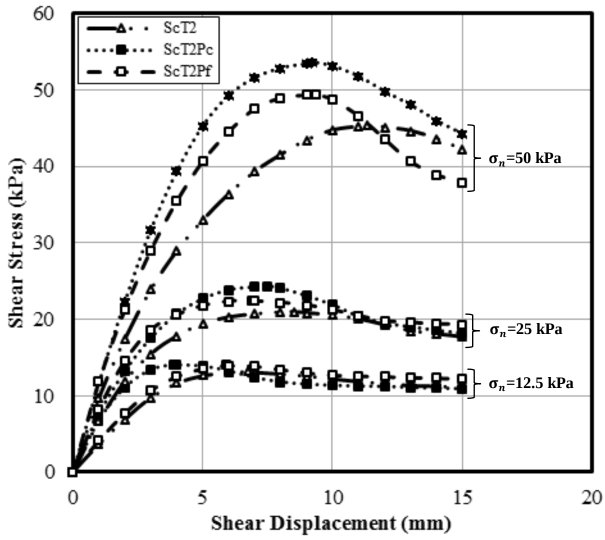

Figure 15. Shear stress versus shear displacement curves for S_cT_2, $S_cT_2P_c$ and $S_cT_2P_f$.

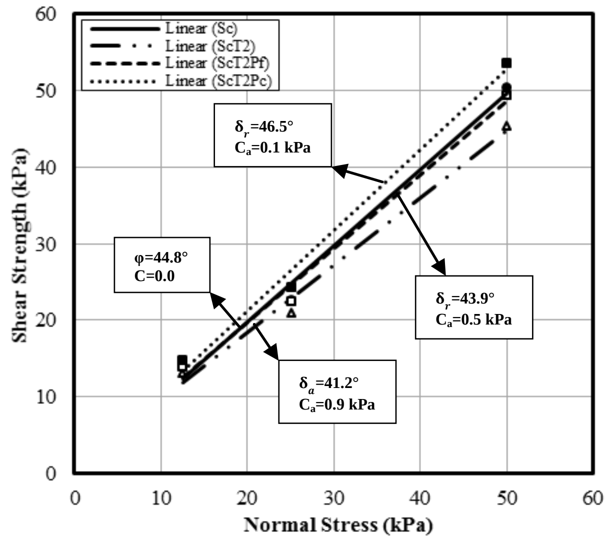

Figure 16. Failure envelopes for S_c, S_cT_2, $S_cT_2P_c$ and $S_cT_2P_f$.

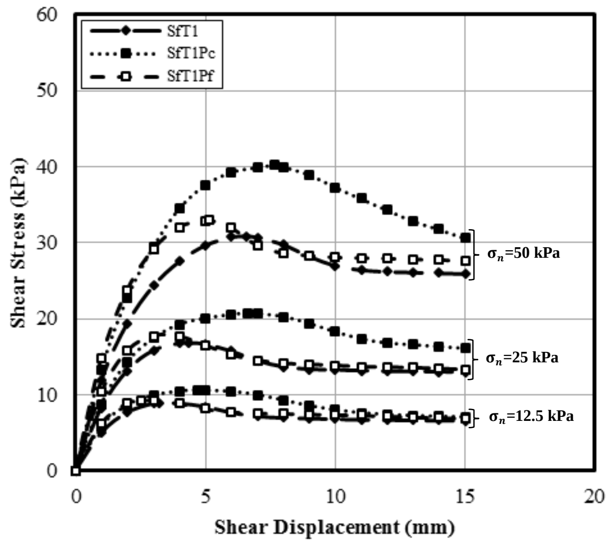

Figure 17. Shear stress versus shear displacement curves for S_fT_1, $S_fT_1P_c$ and $S_fT_1P_f$.

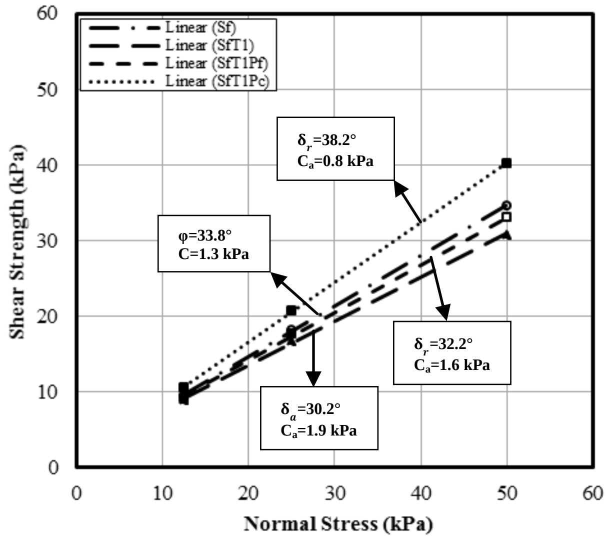

Figure 18. Failure envelopes for S_f, S_fT_1, $S_fT_1P_c$ and $S_fT_1P_f$.

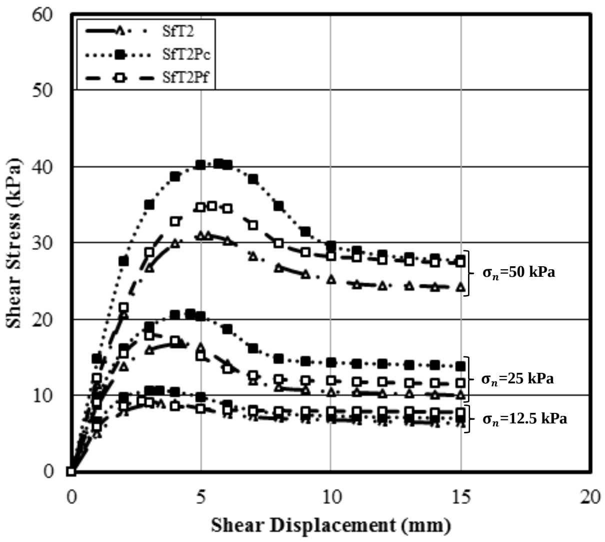

Figure 19. Shear stress versus shear displacement curves for S_fT_2, $S_fT_2P_c$ and $S_fT_2P_f$.

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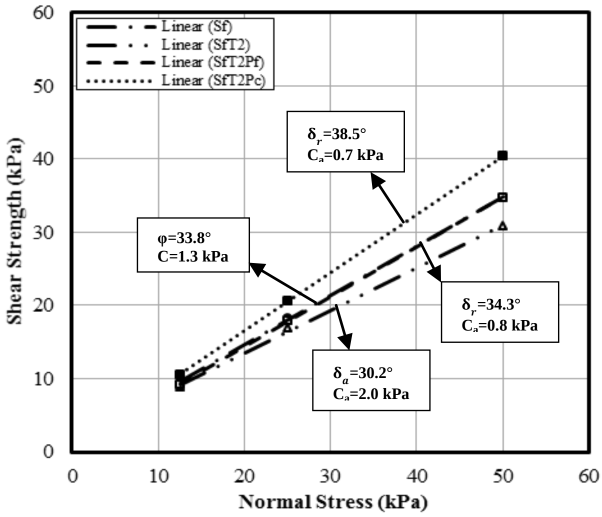

Figure 20. Failure envelopes for S_f, S_fT_2, $S_fT_2P_c$ and $S_fT_2P_f$.

Table 4. Summary of direct shear test results for sand S_c, S_cT_1, S_cT_2, $S_cT_1P_c$, $S_cT_1P_f$, $S_cT_2P_c$ and $S_cT_2P_f$.

Sample	σ_n=12.5 kPa			σ_n=25 kPa			σ_n=50 kPa			φ (°)	δ_a (°)	δ_r (°)	% Increase
	τ_{max}	C_i	i	τ_{max}	C_i	i	τ_{max}	C_i	I				
S_c	13.89	1.00	-	22.60	1.00	-	50.40	1.00	-	44.8	-	-	-
S_cT_1	12.98	0.93	1.00	20.40	0.90	1.00	43.14	0.86	1.00	-	39.3	-	-
$S_cT_1P_f$	13.21	0.95	1.02	21.02	0.93	1.03	45.85	0.91	1.06	-	-	41.6	6
$S_cT_1P_c$	14.20	1.02	1.09	24.26	1.07	1.19	52.56	1.04	1.22	-	-	46.1	17
S_cT_2	13.15	0.95	1.00	20.96	0.93	1.00	45.38	0.90	1.00	-	41.2	-	-
$S_cT_2P_f$	13.98	1.01	1.06	22.43	0.99	1.07	49.40	0.98	1.09	-	-	43.9	6.2
$S_cT_2P_c$	14.78	1.06	1.12	24.30	1.08	1.16	53.58	1.06	1.18	-	-	46.5	12.9

Note: $S_cT_iP_j$ means reinforced sand S_c with geotextile T_i roughened with P_j particles

Table 5. Summary of direct shear test results for sand S_f, S_fT_1, S_fT_2, $S_fT_1P_c$, $S_fT_1P_f$, $S_fT_2P_c$ and $S_fT_2P_f$.

Sample	σ_n=12.5 kPa			σ_n=25 kPa			σ_n=50 kPa			φ (°)	δ_a (°)	δ_r (°)	% Increase
	τ_{max}	C_i	i	τ_{max}	C_i	i	τ_{max}	C_i	i				
S_f	9.49	1.00	-	18.29	1.00	-	34.71	1.00	-	33.8	-	-	-
S_fT_1	8.90	0.94	1.00	16.79	0.92	1.00	30.84	0.89	1.00	-	30.2	-	-
$S_fT_1P_f$	9.27	0.98	1.04	17.72	0.97	1.06	32.98	0.95	1.07	-	-	32.2	6.6
$S_fT_1P_c$	10.57	1.11	1.19	20.72	1.13	1.23	40.18	1.16	1.30	-	-	38.2	26.5
S_fT_2	8.98	0.95	1.00	16.90	0.92	1.00	30.93	0.89	1.00	-	30.2	-	-
$S_fT_2P_f$	9.22	0.97	1.03	17.90	0.98	1.06	34.79	1.00	1.13	-	-	34.3	13.6
$S_fT_2P_c$	10.59	1.12	1.18	20.63	1.13	1.22	40.41	1.16	1.32	-	-	38.5	27.5

Note: $S_fT_iP_j$ means reinforced sand S_f with geotextile T_i roughened with P_j particles

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6.4. Effects of increasing geotextile roughness on soil-geotextile interaction

According to the summary of the results presented in Tables 4 & 5 and aforementioned diagrams, it is observed that the reinforcing sands S_c and S_f with geotextiles has resulted in reducing soil-geotextile interactions at their interface. It can be seen from Tables 4 & 5 that for reinforced samples interaction angles (δ_a) have actually been reduced to less than soil angles of friction and thus decreased shear strengths. However, roughening geotextile surfaces by means of gluing particles P_c and P_f not only have compensated the reductions in interactions they have actually resulted in interaction angles that are greater than soils friction angles. In all reinforced samples, the increase in roughness has caused an increase in the angle of interaction, in such a way that the failure envelop of the sand-roughened geotextile with P_c particles are always higher than non-reinforced samples. Abdi and Safdari Seh Gonbad in 2018 have also shown that attachment of elements as anchors to geogrids significantly enhances soil-geogrid interactions in direct shear mode [45].

It is observed that the improved interaction coefficients obtained for both soils reinforced with roughened geotextiles are greater than 1, and their values increase with the increase in normal pressure and particularly those subjected to 50 kPa. Higher normal pressures cause greater confinements and thus improved soil-geotextile interactions. Coarser P_c particles in comparison with P_f particles having larger surface areas that can be covered with glue and thus show more resistance to shear at soil-roughened geotextile interface. Probability of these particles being dislodged during shearing is also less than finer P_f particles.

6.5. Effects of tensile strength and unit weight of roughened geotextile on interactions

By comparing the values of the enhanced interaction coefficients determined for the samples of S_c and S_f sands reinforced with roughened geotextiles T_1 and T_2 with the same particles (i.e. P_c or P_f) and subjected to the same normal pressures, it can be said that these factors are not very determinant on soil-geotextile interactions and therefore shear resistance of the reinforced soils. Ineffectiveness of the aforementioned factors are due probably to the facts that geotextiles get compressed under normal pressures which subsequently reduces the ability of soil particles penetrating the fabric as well as geotextile tensile strength not being mobilized in direct shear mode. It is worth noting that applying adhesive to the geotextiles surfaces also reduces pores that prevent the effective penetration and interaction of sand particles with geotextile fibers.

6.6. Impact of soil particle size distribution interactions with roughened geotextiles

Increase in enhanced interactions through sticking P_c particles to the geotextile surface has been more pronounced than equivalent samples in which P_f particles were used which is probably the result of coarser and angular P_c particles. Roughening geotextiles T_1 and T_2 with P_c particles used for reinforcing sand S_c has increased interaction angles from 39.3 to 46.1 and 46.5 degrees showing improvements of 17.3 to 18.3% respectively. The interaction angles of sand S_f reinforced with roughened geotextiles T_1 and T_2 respectively where also increased from 30.2 to 38.2 and 38.5 degrees respectively showing enhancements of 26.5 and 27.5%. In all samples not only roughening geotextile surfaces have compensated for the reduction in interaction angles because of reinforcing with geotextiles, but also have resulted in interactions angles even greater sand only samples. The values of the enhanced interaction coefficients of the studied soils were found to vary between a minimum of 1.02 and maximum of 1.22 for the S_c, and a minimum of 1.03 and maximum of 1.31, for the S_f sand respectively.

In contrast to maximum shear strengths, angles of interactions determined for S_f reinforced samples were often higher than equivalent S_c samples. Enhancement ratios for all S_f reinforced samples except $S_fT_2P_f$ were greater than S_c samples. These effects have been attributed to finer S_f particles have penetrated the geotextile as well as the spaces between P_c and P_f particles stuck to reinforcement surfaces thus causing more effective interactions and therefore greater shear strength enhancements. Higher shear strengths and greater angles of interactions achieved for S_c-roughened geotextiles was most probably due to coarser more angular particles and higher greater sand shear strengths. Thus it can be concluded that the coarser the particles used for roughening geotextile surface in comparison with soil average particle size, the greater the interaction enhancements.

7. Conclusions

- Increasing the roughness through gluing sand particles to the geotextile surface, resulted in enhancing shear strengths at soil-geotextile interface in both sands investigated.
- The degree of interaction enhancements has a direct relation with normal pressures, which is probably due to increased penetration and interlocking between S_f and S_c sand particles with particles of P_c and P_f glued to geotextile surfaces.
- Tensile strength of geotextiles have no effect on enhancing interactions at interface which is probably due to the fact that

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geotextiles are not effectively put in tension in direct shear mode and subsequently their tensile strength is not effectively mobilized.

- The unit weight of geotextiles is also found not to have a substantial influence on interactions. It is recommended that this factor has to be investigated in more detail as geotextile roughness was rather reduced due to their surfaces being covered with glue.
- The coarser the attached particles to geotextile surfaces in comparison with soil particles, the higher the enhancement coefficients.
- The values of the enhanced coefficient ratio for samples reinforced with roughened geotextile surfaces varied between 1.02 to 1.23 and 1.03 to 1.31 for sands S_c and S_f respectively.

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