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Stabilization of aeolian sand with combined use of geofiber and synthetic fluid

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Abstract: Aeolian sand is very common in arid and semi-arid regions. Without proper improvement, this soil lacks desirable engineering characteristics for use for pavement base courses, subbase courses, subgrades, and as a foundation supporting layer under buildings. A non-conventional soil stabilization technique combining synthetic fluid and geofiber as improvement additives were investigated through an extensive and systematic experimental study. Engineering characteristics of various soil-additive compositions were evaluated through CBR and large-scale direct shear tests. Beneficial effects of the additives in terms of both the CBR performance and shear strength of aeolian sand were discovered. Proper additive dosages and curing of the treated soil were found to play a significant role in achieving the desired improvemen/Asphaltt of the CBR value and peak friction angle. Comparative analysis between peak and post-peak strength of various soil/additive compositions is presented. As part of the results of this study, a relatively strong correlation between CBR and internal friction angle was established.

Subjects: Civil, Environmental and Geotechnical Engineering; Foundations and Piling; Pavement Engineering

Keywords: aeolian sand; soil stabilization; synthetic fluid; geofiber; shear strength

1. Introduction

Aeolian deposits formed by unconsolidated, poorly graded loose sand are commonly encountered in arid and semi-arid regions. The sand of such formations, without proper improvement, lacks the required engineering properties to suffice as pavement base course, subbase course, subgrade and as a foundation-support layer under buildings and various structures. Stabilization of this type of sand is one of the major geotechnical challenges in practice. Improvement of soils with the use of geofiber is fairly popular among practitioners due to low cost and ease of deployment of the technology, light weight of the additive (i.e., geofiber), and successful case histories. Recently, a combined use of geofiber and synthetic fluid to stabilize fine-grained soils has been proposed as

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Kenan Hazirbaba is an Associate Professor of Civil Engineering at the American University of Ras Al Khaimah. He received his Ph.D. from the University of Texas at Austin. As a registered professional geotechnical engineer, he worked on numerous large-scale infrastructure projects. His research interests include stabilization of marginal soils, liquefaction of shallow and deep deposits under seismic loading, and numerical studies and modeling of transport facilities and substructures.

PUBLIC INTEREST STATEMENT

Aeolian sand is very common in arid and semi-arid regions. Improving the strength and bearing capacity of this sand allows its utilization as a supporting soil for structures and infrastructure. This study investigates an innovative and cost-effective soil stabilization technology that can benefit various large-scale infrastructure projects.

a new, non-traditional technology that requires minimal installation equipment. This comprehensive experimental research investigates the applicability and feasibility of this new technology as an alternative stabilization method for aeolian sand.

In general, reinforcing cohesionless soils with geofiber improves the shear modulus, liquefaction resistance, and particle interlocking, and increases load-bearing capacity(Arteaga, 1989; Freitag, 1986; Maher & Woods, 1990). More specifically, the addition of geofiber increases the peak strength (shear, compressive, tensile), and reduces compressibility and brittleness of the soil (Gao & Zhao, 2013; Gray & Al-Refeai, 1986; Gray & Ohashi, 1983; Hazirbaba, 2018; Li, Tang, Wang, Pei, & Shi, 2014; Maher & Ho, 1994; Park, 2011; Ranjan, Vasan, & Charan, 1996; Tang, Wang, Cui, Shi, & Li, 2016; Webster & Santoni, 1997; Hazirbaba & Omarow, 2018). It is also important to note that the potential of cyclic settlement of soils may be decreased through the addition of geofibers (Hazirbaba & Omarow, 2015). The improvement of the engineering properties with the inclusion of geofiber depends on several parameters such as type, length, content, orientation and aspect ratio (length/diameter) of the geofiber, and natural soil properties (Diambra, Ibraim, Muir Wood, & Russell, 2010; Liu et al., 2011). Earlier studies by Al-Refeai (1991) reported that for fine and medium sand no appreciable increase in the stiffness of the sand could be obtained with fibers longer than 51 mm. Stabilization of sands with the geofiber contents greater than 2% by dry weight of soil (i.e., gravimetric content) showed no added benefit (Ranjan et al., 1996). Tingle, Webster, and Santoni (1999) recommended using a geofiber content between 0.6% and 1%, and they reported that a geofiber content of 0.8% is sufficient to ensure a strain hardening behavior. The addition of geofiber to the soil is usually done in a random fashion without a specific orientation; this minimizes the potential for weak shear planes to develop within the soil (Maher & Gray, 1990). Soil grain size influences the effectiveness of reinforcement; finer sand particles exhibit greater geofiber-bond strengths than coarser grained soils (Ranjan et al., 1996). The study by Lawton, Khire, and Fox (1993) showed that geofiber-reinforced soils require some amount of deformation for the strengthening effect to initiate. Kaniraj and Havanagi (2001) reported that the inclusion of geofiber increased the strength of cement-stabilized fly ash-soil samples and changed their brittle behavior to ductile behavior.

The use of synthetic fluid as a stabilizing additive is relatively new. Synthetic fluid molecules are formed from a wax feedstock consisting of paraffinic carbon chains. Through synthesis, these chains transform into isoparaffins that cannot reorganize into crystals; the resulting new molecules perform better from an engineering perspective (Hazirbaba, 2017). Some of the advantages of synthetic fluid are: (a) it is non-toxic and thus safe to use without health-hazard concerns; (b) it maintains its fluid form at very low temperature (i.e., sub-zero temperature); (c) it does not evaporate in hot climatic condition; and (d) it is oxidation resistant. Previous investigations reported applications of synthetic fluid for dust and erosion control (Tingle et al., 1999; Webster & Santoni, 1997).

Recent research on the combined use of geofiber and synthetic fluid for stabilizing sand and silty soils has reported promising results and a cost-effective solution for cold region construction (Hazirbaba, 2017; Hazirbaba & Connor, 2009; Hazirbaba & Gullu, 2010). Detrimental effects of the freeze-thaw process on the ground (Cox, Wood, & Hazirbaba, 2012; Yang, Dutta, Xu, Hazirbaba, & Marx, 2011; Hazirbaba, 2019) may be minimized by improving the stiffness and strength characteristics through the combined use of geofiber and synthetic fluid as stabilizing additives. Inspired from the promising results of recent research on the use of a synthetic fluid with marginal soils, this study was aimed at investigating the co-use of randomly oriented discrete-polypropylene geofiber and synthetic fluid with aeolian sand as an alternative stabilization method. Strength and bearing capacity improvements were evaluated through CBR and large direct shear box tests on reconstituted soil samples.

Table 1. Index properties of the sand (Aeolian) investigated

Index Properties of Aeolian Sand	
Specific Gravity (ASTM C128)	2.65
D_{10} (mm) (ASTM D6913)	0.11
D_{30} (mm) (ASTM D6913)	0.17
D_{60} (mm) (ASTM D6913)	0.21
C_u (ASTM D6913)	1.91
C_c (ASTM D6913)	1.25
USCS Soil Classification	SP

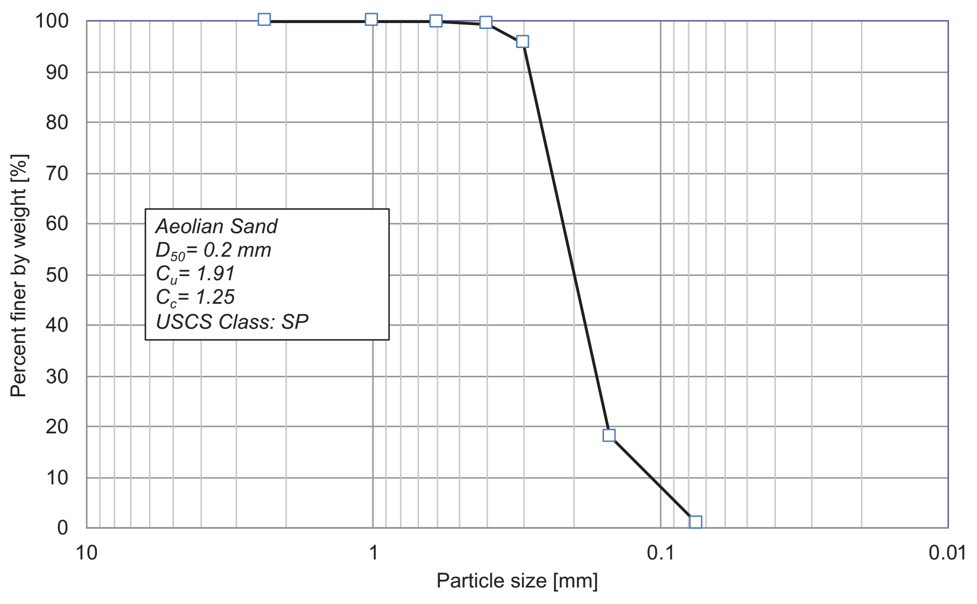


Figure 1. Grain size distribution of aeolian sand.

2. Experimental program and methodology

2.1. Materials

The soil used in this research was an aeolian sand, which is commonly encountered in the Arabian Gulf region. Basic index properties of the sand were determined according to pertinent ASTM procedures, and are listed in Table 1. The particle size distribution of the sand is shown in Figure 1. It is classified as poorly graded sand (SP) according to USCS classification.

Fibrillated-polypropylene type geofiber was used as a stabilization additive. Discrete fiber elements were cut into 51 mm length. Polypropylene geofiber is common in soil reinforcement projects because of its availability, resistance to ultraviolet degradation, chemical stability, and reasonably high strength characteristics (Fletcher & Humphries, 1991). The index properties of the geofiber used are listed in Table 2. Based on previous investigations, the effective gravimetric dosages investigated in this study were: 0.25%, 0.50%, and 0.75%.

The second additive was synthetic fluid. The fluid is colorless with a clear and bright appearance. It has a specific gravity of 0.863 and a viscosity index of 70. The index properties of this fluid are shown in Table 3. The dosage rate was set at 2% based on trial mixes and earlier field and laboratory experiences (e.g., Hazirbaba, 2017; Hazirbaba & Gullu, 2010).

Table 2. Index properties of the geofiber (as provided by the manufacturer)

Property	Test Method	Fiber Type
		Fibrillated
Material	ASTM D4101 Group 1/Class 1/Grade 2	Polypropylene, 99%
Shape	-	Flat-Narrow (2mm wide)
Color	-	Black
Moisture	-	Nil
Specific gravity	ASTM D792	0.91
Carbon black content	ASTM D1603	0.5%, minimum
Tensile strength (kPa)	ASTM D2256	206,843
Tensile elongation	ASTM D2256	20%, maximum
Length used (mm)	Measured	51

Table 3. Index properties of the synthetic fluid used (as provided by the manufacturer)

Property	Value
Color	Clear, bright
Specific gravity	0.863
Viscosity index	70
Viscosity, cSt at 40 °C	10.7
Viscosity, cSt at 100 °C	2.6
Flash point, °C	175
Pour point, °C	−33

2.2. Testing program and procedures

Tests were performed on samples of the sand at the following categories: (a) natural sand with no additives; (b) sand with varying geofiber content; and (c) sand with geofiber and synthetic fluid together.

CBR testing is routinely used in mechanistic design as an indicator of strength and bearing capacity of a subgrade soil, subbase, and base course material in road and airfield pavements. The CBR of a soil is the ratio obtained by dividing the stress required to cause a standard piston to penetrate 2.54 mm, 5.08 mm, 7.62 mm, 10.16 mm, and 12.70 mm into the soil by a standard penetration stress at each depth of penetration (ASTM D 1883). The CBR is an index value comparing the strength of the soil to that of crushed rock (Liu & Evett, 2003). Some general ratings of soils to be used as subgrade, subbase

Table 4. Ratings of soils for roads and runways according to CBR values (Asphalt Institute, 1962; Bowles, 1978)

CBR%	General Rating	Uses	Classification System	
			Unified	AASHTO
0–3	Very poor	Subgrade	OH, CH, MH, OL	A5, A6, A7
3–7	Poor to fair	Subgrade	OH, CH, MH, OL	A4, A5, A6, A7
7–20	Fair	Subbase	OL, CL, ML, SC, SM, SP	A2, A4, A6, A7
20–50	Good	Base, subbase	GM, GC, SW, SM, SP, GP	A1b, A2-5, A3, A2-6
>50	Excellent	Base	GW, GM	A1a, A2-4, A3

and base courses of roads and airfield runways corresponding to various ranges of CBR values are presented in Table 4 (Asphalt Institute, 1962; Bowles, 1978). The CBR test is an economical and simple tool for measuring strength gain and improvement in soils. CBR tests in this study were performed in accordance with ASTM D 1883. CBR performance of each soil sample was evaluated at each of the penetration depths (i.e., 2.54 mm, 5.08 mm, 7.62 mm, 10.16 mm, and 12.70 mm). For a reliable CBR value, an average of minimum two CBR tests is recommended (Yoder & Witczak, 1975). Thus, in this study two replicate samples were tested for each of the CBR value reported (i.e., each reported CBR value is presenting the average value of the two tests).

For the evaluation of strength, direct shear testing was preferred. Among the advantages of direct shear testing are: the soil sample is sheared on a prescribed plane, consolidation is one-dimensional, the shear deformation is approximately plane strain, and the test operation is relatively easy (Nakao & Fityus, 2008; Sadek, Najjar, & Freiha, 2010; Takada, 1993). However, the results of direct shear test are sensitive to the size of the soil specimen. In general, smaller size direct shear box tends to overestimate the friction angle (Cerato & Lutenegger, 2006). To overcome the size effect, and more realistically and reasonably mimic in situ conditions, a large-scale direct shear apparatus, with a box of 300 mm x 300 mm in plane x 180 mm in depth, was used in this research (Figure 2). The equipment is fully instrumented with automatic data logging and a computer interface unit. One of the unique features of the direct shear apparatus used in this study is the ability to account for the side friction. Side friction is measured by suspending (floating) the upper (stationary) half of the shear box on load cells using threaded rods. By deducting side friction from the applied normal load, the stress is accurately computed at the shear-friction zone; only the true force is measured as the friction associated with the moving half is excluded. The tests in this study were performed in general accordance with ASTM D3080.

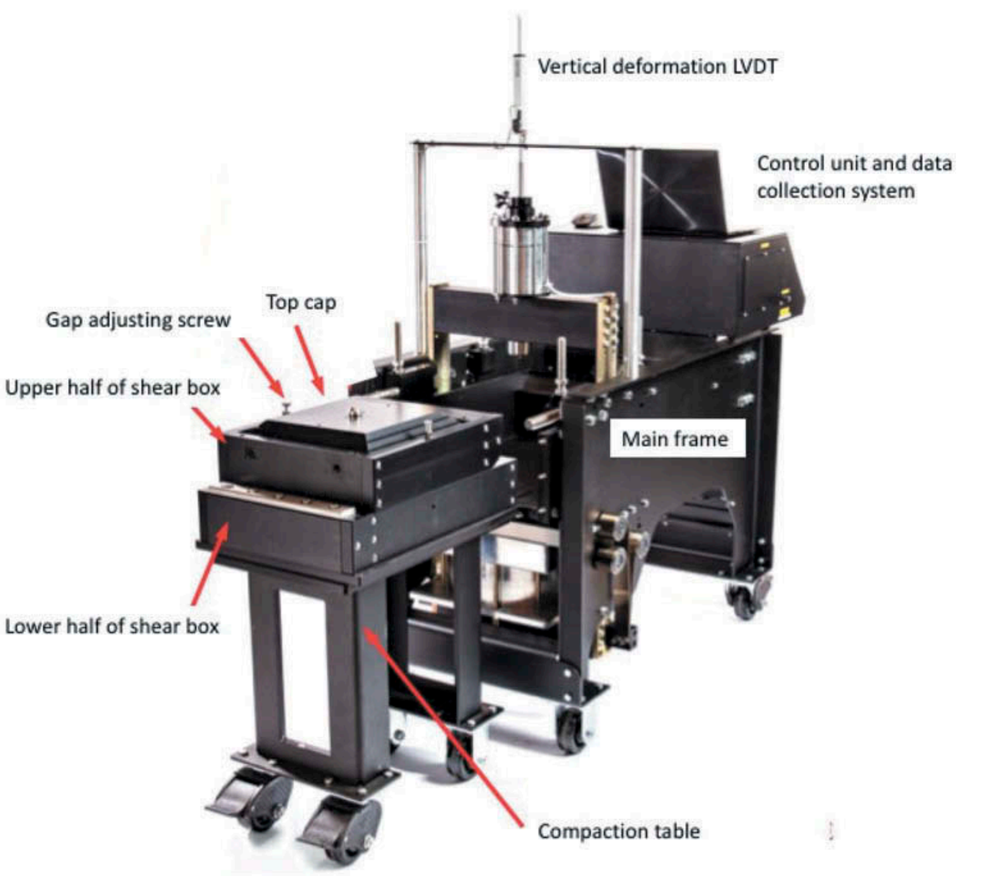


Figure 2. A photo of the large direct shear box testing system used in this study.

2.3. Sample preparation

Sample preparation is an important step in the testing of reinforced soils. The two critical factors affecting sample preparation are moisture control and mixing procedures (Hazirbaba & Gullu, 2010; Tingle et al., 1999). In this study, samples were obtained by thoroughly mixing dry soil with the water and synthetic fluid at the targeted amounts. The mixing of soil with water and synthetic fluid was done in a plastic container by hand. To achieve equilibrium of moisture and uniform moisture distribution throughout the sample, soil-fluid mixtures were stored in the sealed container for about 18 h prior to compaction. It is important to introduce geofibers to the mixture at the final step to avoid clumping of the soil-fiber mix. Thus, geofibers at the targeted gravimetric content were added just before compaction. Extreme care was taken during the mixing process to ensure a uniform mixture. For CBR testing, the soil was compacted in accordance with ASTM D1557.

The Modified Proctor procedure was adopted for preparing samples of direct shear tests. A round tamp weighing 5.25 kg was used and the sample was compacted in five layers. After compaction of each layer, the layer surface was roughened to ensure a good contact with the overlying layer and prevent the forming of a weak inter-layer shear plane.

3. Results and discussion

3.1. CBR baseline testing and sensitivity to moisture content

To establish a baseline for evaluating the effects of additives, the sand in its natural form (i.e., without any additives) were tested. First, the compaction characteristics were determined. The results of the Modifed Proctor tests are presented in Figure 3. The data show a typical trend for sandy soils; the maximum dry density of the sand, when compacted with water only, was found to be about 16.7 kN/m^3 at an optimum range of 6% to 8% moisture content. The sensitivity of CBR values to varying water content was investigated through a separate series of tests at 6%, 7%, and 8% water content, as shown in Figure 4. Although the results of compaction tests yielded similar dry density values within the range of water content between 6% and 8%, the CBR performance at each depth of penetration consistently indicates greater values for the sand compacted with 7% water content. Maximum CBR values were obtained at 5.08 mm penetration as follows: 27 with 7% water content; 24 with 8% water content; and 20 with 6% water content.

3.2. Effect of the synthetic fluid on CBR performance

Synthetic fluid is added to the sand at 2% gravimetric dosage rate, as discussed above in the experimental program and methodology section. The water content, in this case, was reduced by the amount of the added synthetic fluid (i.e., 2%) for each of the composition evaluated within the optimum range. Thus, the following compositions were formed and tested under this category: 2%

Figure 3. Compaction (Modified Proctor) characteristics of aeolian sand.

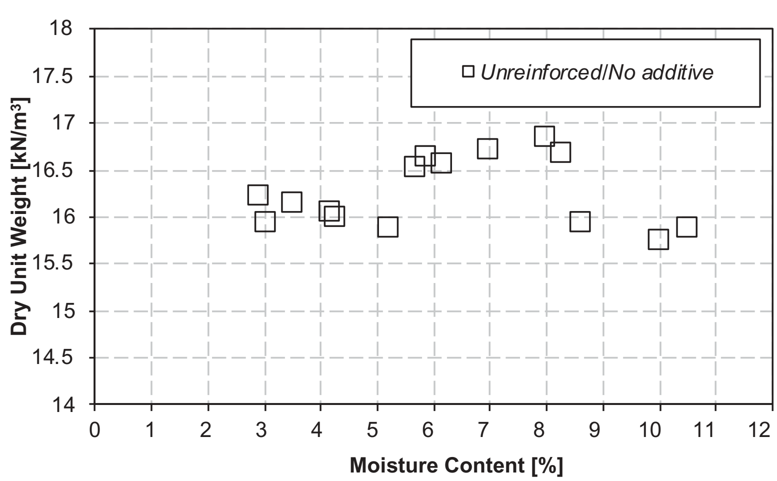
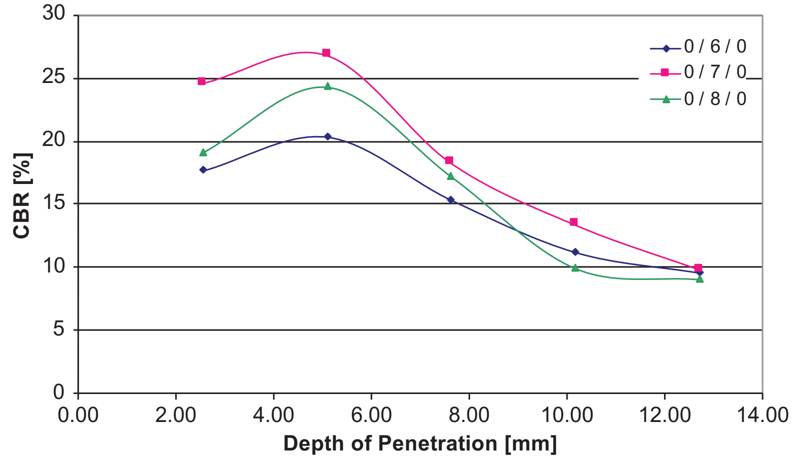


Figure 4. CBR performance sensitivity of untreated aeolian sand to moisture content within the optimum range.

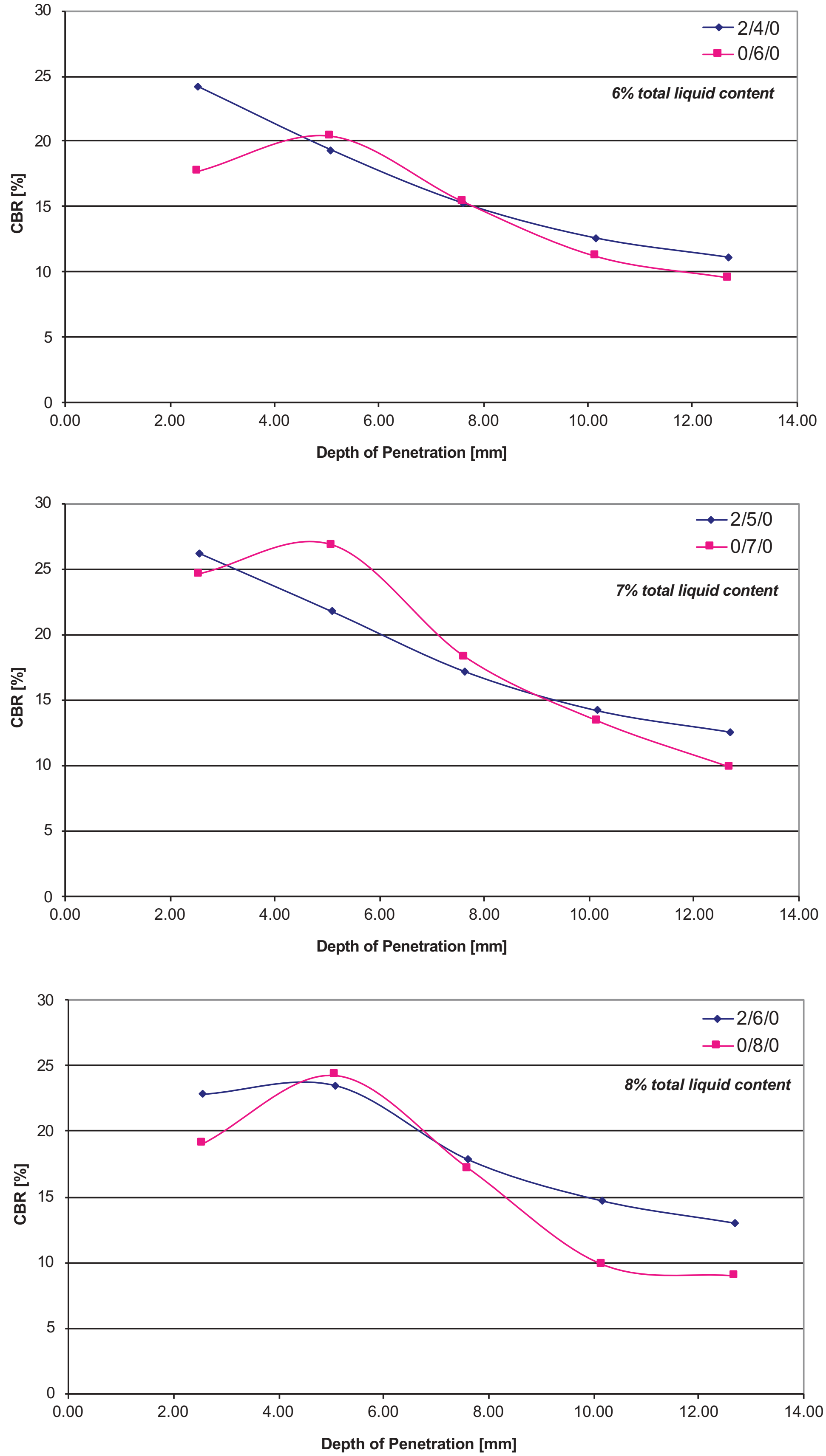


synthetic fluid with 4% water (overall liquid content of 6%); 2% synthetic fluid with 5% water (overall liquid content of 7%); and 2% synthetic fluid with 6% water (overall liquid content of 8%). The results of these tests are shown in Figure 5. For comparison and analysis, each category is presented with the results of the untreated/unreinforced sand. Replacing the water with synthetic fluid appears to have not caused a substantial change in the CBR performance; very comparable values of CBR were obtained. In general, the CBR performance of the sand containing synthetic fluid was found to be slightly better at depth of penetration greater than 7.62 mm. The ability to use synthetic fluid in lieu of water without compromising the CBR performance is a great advantage for hot climate project locations where aeolian sand is commonly encountered. Evaporation of water is one of the main challenges in projects of hot climatic conditions, and this can add to the overall project cost, especially when large volumes of soil are to be compacted. Characteristically, the synthetic fluid does not evaporate and thus it can provide a significant reduction in project cost along with flexibility in schedule (i.e., it eliminates the need to wait out the peak temperatures of the day). Figure 6 shows the comparison of CBR results for the sand containing synthetic fluid. The design CBR values (i.e., the greater value obtained at 2.54 mm and 5.08 mm penetration) range between 19 and 26. The maximum value of 26 was obtained from the soil having 2% synthetic fluid and 5% water whereas the minimum value of 19 was from the soil with 2% synthetic fluid and 4% water. It is also interesting to note that the soil with 2% synthetic fluid and 6% water exhibited slightly better performance at all depths of penetration except at 2.54 mm.

3.3. Effect of geofiber on CBR performance

To evaluate the effect of geofiber on CBR performance and determine the optimum dosage rate, a series of tests was conducted with varying geofiber content. Samples of soil containing 0.25%, 0.50%, and 0.75% gravimetric dosages of geofiber were prepared at 7% water content without synthetic fluid. This water content was selected as an average value between the range of optimum (6% to 8%) where the maxim dry densities were obtained from compaction testing, as discussed above. The results of these tests were grouped by the geofiber content and are displayed in Figure 7. For comparison, the results of the unreinforced soil were also included. The CBR performance of the sand without inclusion of geofiber indicate a typical soil response with higher CBR values initially (i.e., at 2.54 mm or 5.08 mm). At greater depths of penetration, however, less soil resistance, and possibly failure, is encountered. This typical trend is reversed by the inclusion of adequate geofiber. The transition in soil response starts at 0.25% geofiber content. At this geofiber content, the soil-geofiber engagement works best in the range of 5.08 mm to 10.16 mm penetration depth. The geofiber content is not sufficient to develop the required tensile strength to withstand further depth of penetration. The results of 0.5% and 0.75% geofiber content indicate more soil resistance, and thus larger

Figure 5. CBR performance of aeolian sand with and without synthetic fluid.



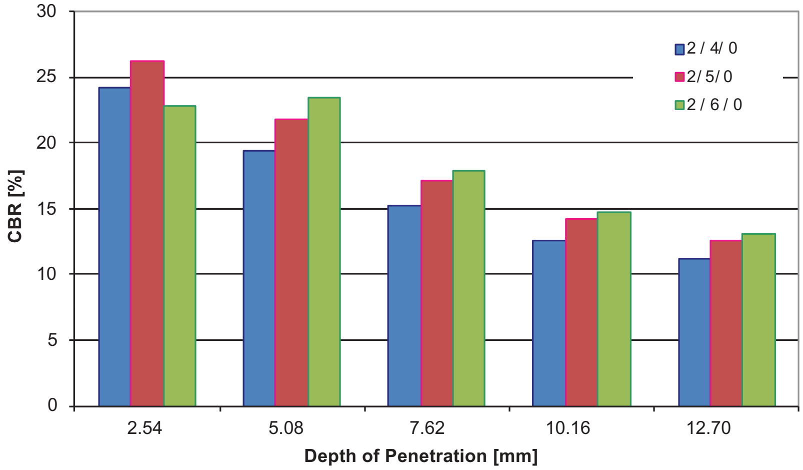


Figure 6. Comparative CBR performance of aeolian sand with synthetic fluid.

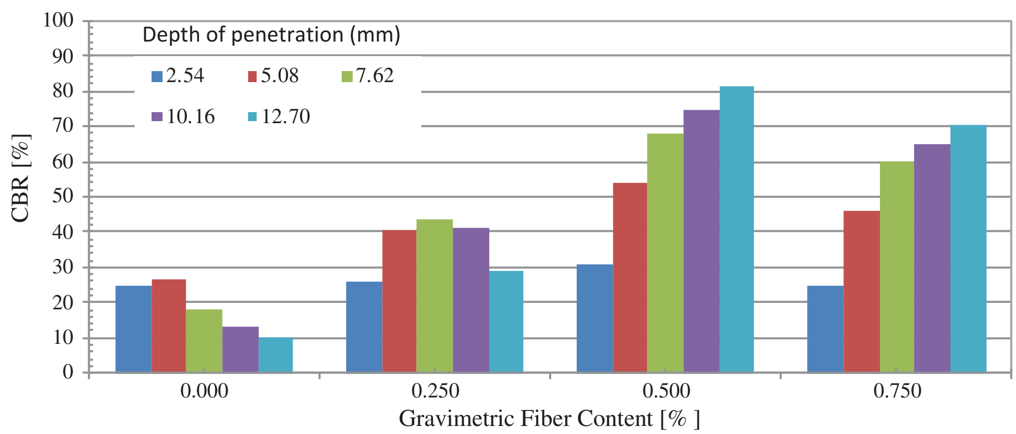


Figure 7. Comparative CBR performance of aeolian sand with geofiber.

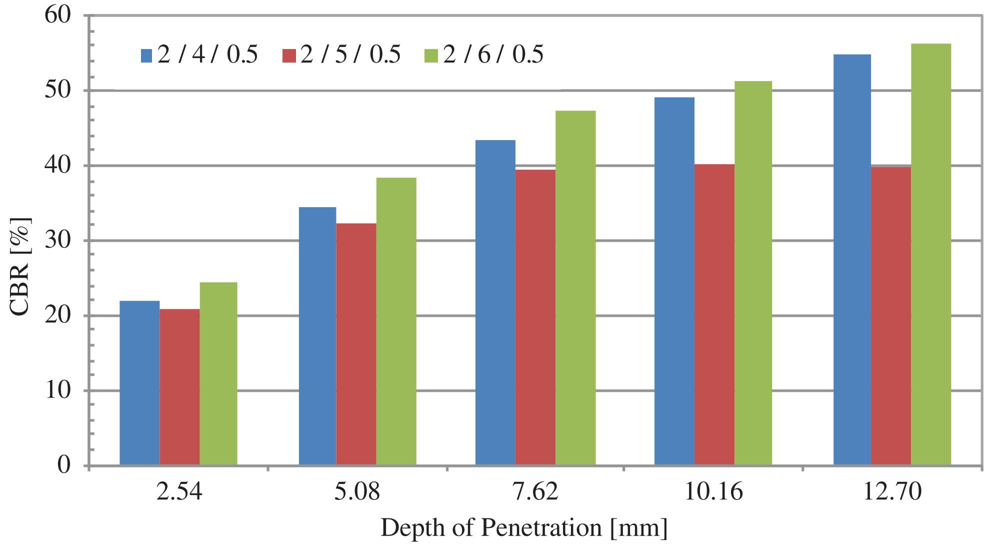
CBR values, with increasing depth of penetration. The change in soil behavior with the inclusion of geofiber is attributed to the tensile strength developed with increasing depth of penetration (Hazirbaba, 2017).

The data in Figure 7 shows the best CBR performance occurring at 0.5% geofiber content. This dosage can be specified as optimum geofiber content for the sand investigated. Lower and higher dosages (i.e., 0.25% and 0.75%) did not provide as good CBR performance. The CBR value of unreinforced soil was obtained at 5.08 mm penetration as 27. At the same depth of penetration, the CBR value of reinforced soil with 0.5% geofiber content is 54; this indicates 100% improvement over the performance of unreinforced soil.

3.4. CBR performance with the combined use of synthetic fluid and geofiber

In this category, the combined use of synthetic fluid and geofiber was tested. Samples of soil were prepared at gravimetric dosage rates of 2% synthetic fluid and 0.5% geofiber with a varying water content of 4%, 5%, and 6%. Thus, three groups of soil composition were subjected to CBR tests. The results of these tests are presented in Figure 8. Significant improvement over the performance of soil without additives was obtained. For example, at 5.08 mm penetration depth (this depth of penetration is referenced because in practice the design CBR is typically the greater value obtained at 2.54 mm and 5.08 mm penetrations) the CBR of sand subjected to synthetic fluid and geofiber treatment varied between 32 and 39. This indicates an improvement range of 19% to 95% when compared to the performance of sand without additives.

Figure 8. CBR performance of aeolian sand treated with synthetic fluid and geofiber.



Earlier studies noted time-dependent strength gain with the use of a synthetic fluid (Hazirbaba & Gullu, 2010). This was investigated on the three groups of soil compositions (i.e., 2/4/0.5; 2/5/0.5; 2/6/0.5). Samples of each group were prepared and left in the laboratory for 28 days in room temperature without any other special treatment. Once the curing period was completed, CBR tests were performed on these samples. The results, as presented in Figure 9, were promising in that substantial increase in CBR value was found to occur for all compositions tested. As a reference of comparison, the CBR value at 5.08 mm penetration improved in each composition group as follows: 35 to 59 (69% increase) in case of 2/4/0.5; 32 to 68 (125% increase) in case of 2/5/0.5; and 39 to 43 (10% increase) in case of 2/6/0.5. The presence of water within the soil appears to have influenced the curing process; the best performance was obtained at 5% water content. Thus, the optimum composition of treatment may be specified as 2% synthetic fluid, 5% water, and 0.5% geofiber for the sand investigated.

3.5. Shear strength of treated aeolian sand

Shear strength measurements of the large-scale direct shear box were conducted for three separate categories of soil. These are: (1) aeolian sand with varying geofiber content; (2) aeolian sand treated with synthetic fluid and geofiber; and (3) aeolian sand with synthetic fluid and geofiber subjected to curing. The first series of testing were performed on the sand with 7% water content and geofiber contents of 0% (no additive), 0.25%, 0.5%, and 0,75%. Peak and post-peak (residual) shear strength were determined for each of the soil composition tested, as listed in Table 5. In practice, whether to use peak or post-peak shear strength is a decision typically needs to be made in the context of a specific design situation (Hazirbaba, 2018). In the current study, the residual strength is defined as the strength corresponding to 15% shear strain. Peak strength envelopes obtained from this group of testing are shown in Figure 10 with best-fit R-square trend for each geofiber content. Inclusion of geofiber appears to improve the peak friction angle (ϕ_{peak}); the best performance is obtained from the sand reinforced with 0.5% geofiber content. At this geofiber content, a strength improvement of about 23% is achieved over unreinforced sand (i.e., ϕ_{peak} increased from 29° to 35.8°). As for the other geofiber contents, the strength improvement achieved at geofiber content of 0.25% is about 16% while almost no gain in strength is obtained with the inclusion of 0.75% geofiber content. Similar trends of residual strength are observed in terms of post-peak friction angle ($\phi_{residual}$), as shown in Figure 11.

In the second group of direct shear testing, the optimum combination of synthetic fluid and geofiber, determined from CBR testing (2% synthetic fluid and 0.5% geofiber), was evaluated at various water content. These tests are listed in Table 6. Peak and post-peak strength envelopes for the combined use of synthetic fluid and geofiber are shown in Figures 12 and 13, respectively. The

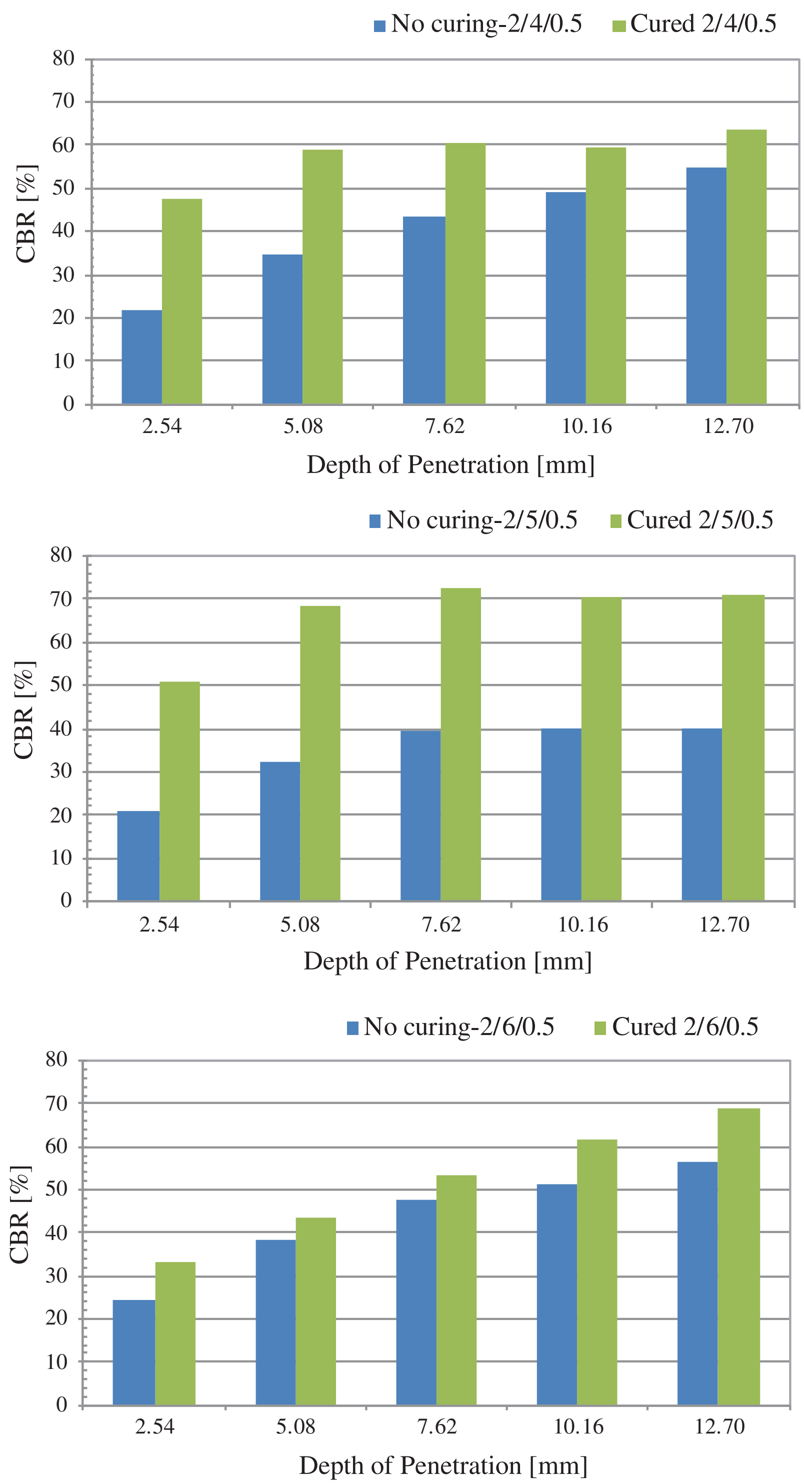


Figure 9. Effect of curing on the CBR performance.

results are interestingly showing very similar strength with a slight variation between the combinations tested. Strength envelopes representing all three combinations tested show a peak friction angle of about 32°. This indicates 10% improvement over unreinforced/untreated sand. As for the post-peak strength, the residual friction angle of this group is approximately 29°.

Table 5. Large-scale direct shear box testing data of geofiber reinforced aeolian sand

SFC(%)	W(%)	GFC (%)	Target σ (kPa)	σ Measured (kPa)	Side Friction (kPa)	Adjusted σ (kPa)	Peak Shear Strength				Residual Shear Strength			
							Peak τ (kPa)	c (kPa)	ϕ	R^2	Residual τ (kPa)	c (kPa)	ϕ	R^2
-	7	-	25	26.35	9.82	16.53	14.46	8.1	29.0	0.9892	12.67	5.7	27.7	0.988
-	7	-	50	51.67	17.75	33.92	32.44				28.34			
-	7	-	100	102.4	16.72	85.68	52.65				47.98			
-	7	-	150	155.65	30.54	125.11	75.54				67.82			
-	7	-	200	205.41	34.44	170.97	104.78				98.64			
-	7	0.25	25	28.23	9.45	18.78	17.62	8.7	33.6	0.9743	14.9	4.2	31.6	0.998
-	7	0.25	50	52.45	10.22	42.23	35.43				30.07			
-	7	0.25	100	103.43	15.54	87.89	76.16				58.94			
-	7	0.25	150	154.32	40.17	114.15	86.34				76.32			
-	7	0.25	200	205.16	55.34	149.82	102.65				94.43			
-	7	0.5	25	27.21	7.87	19.34	16.65	5.3	35.8	0.9952	13.44	0.3	32.6	0.990
-	7	0.5	50	54.12	8.12	46.00	41.31				33.89			
-	7	0.5	100	106.34	21.78	84.56	68.87				48.65			
-	7	0.5	150	151.23	24.37	126.86	92.54				79.38			
-	7	0.5	200	204.76	24.76	180.00	136.34				118.65			
-	7	0.75	25	28.22	9.59	18.63	15.21	7.0	29.4	0.9913	14.71	0.5	26.5	0.990
-	7	0.75	50	53.38	11.84	41.54	32.11				28.75			
-	7	0.75	100	105.47	14.61	90.86	57.23				45.43			
-	7	0.75	150	154.23	24.67	129.56	84.92				68.4			
-	7	0.75	200	206.86	33.76	173.10	101.24				93.87			

SFC: synthetic fluid content
W: water (moisture) content
GFC: geofiber content

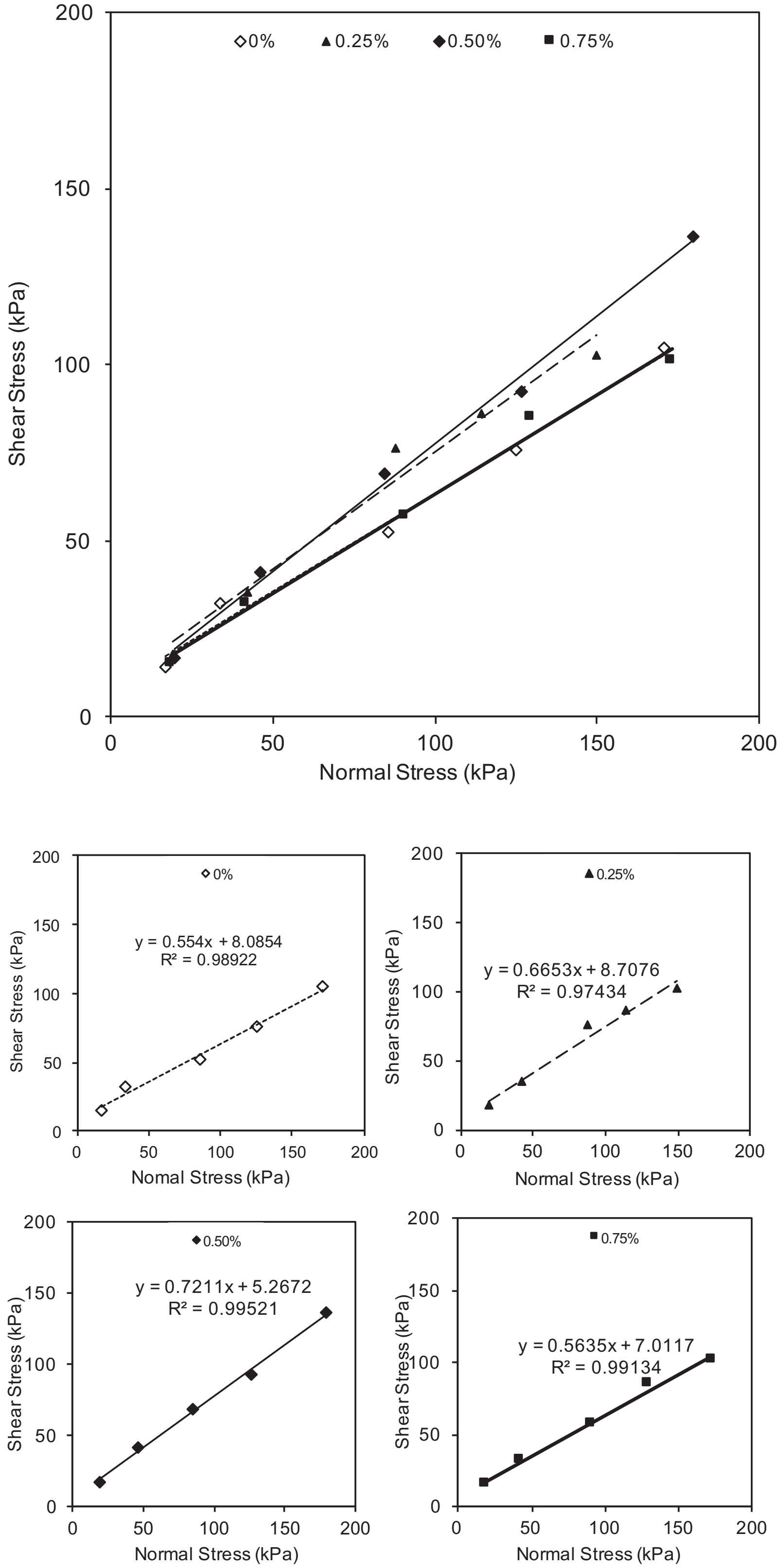


Figure 10. Peak shear strength of aeolian sand with geofiber.

Figure 11. Residual shear strength of aeolian sand with geofiber.

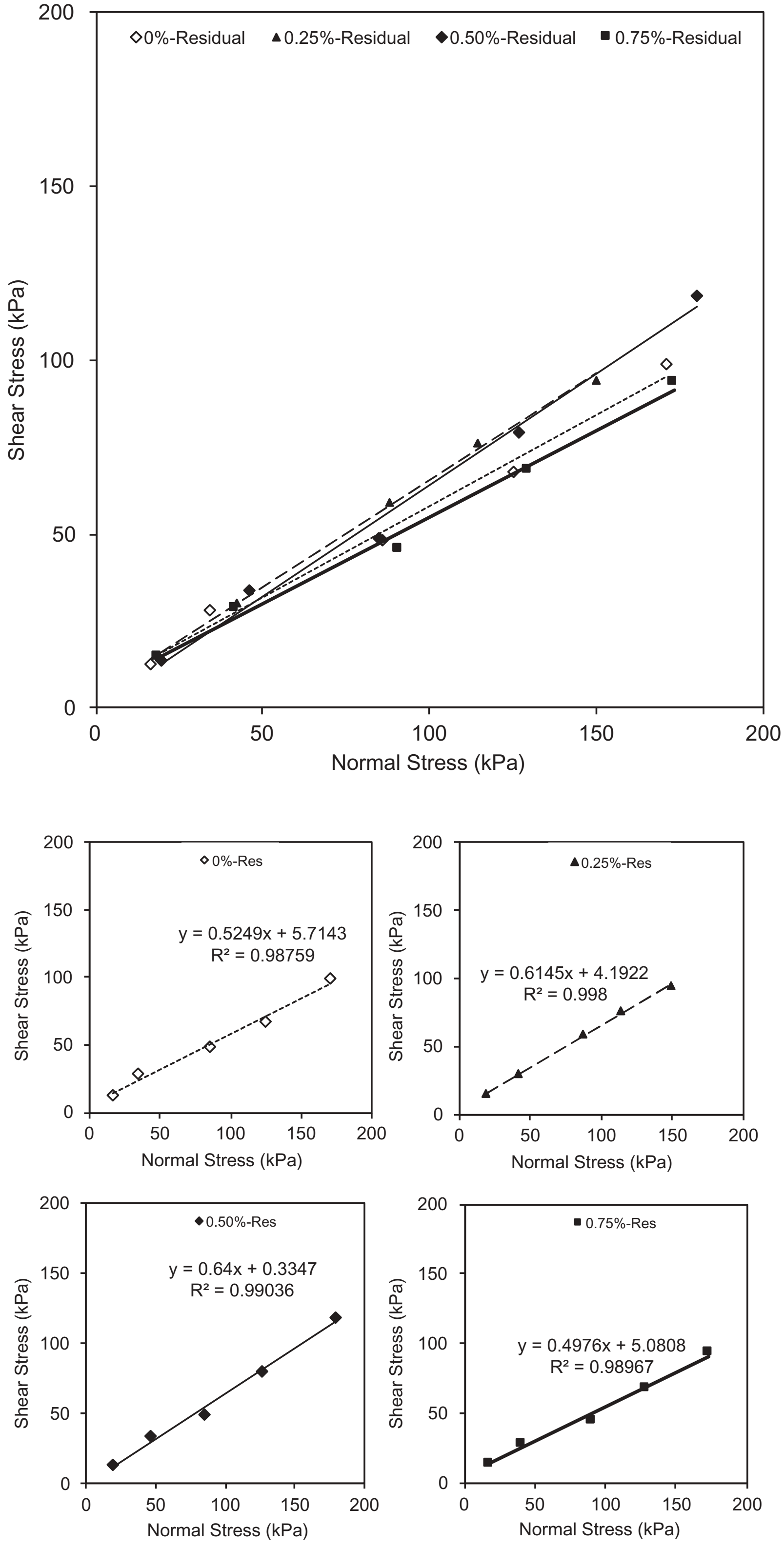


Figure 12. Peak shear strength of aeolian sand treated with synthetic fluid and geofiber.

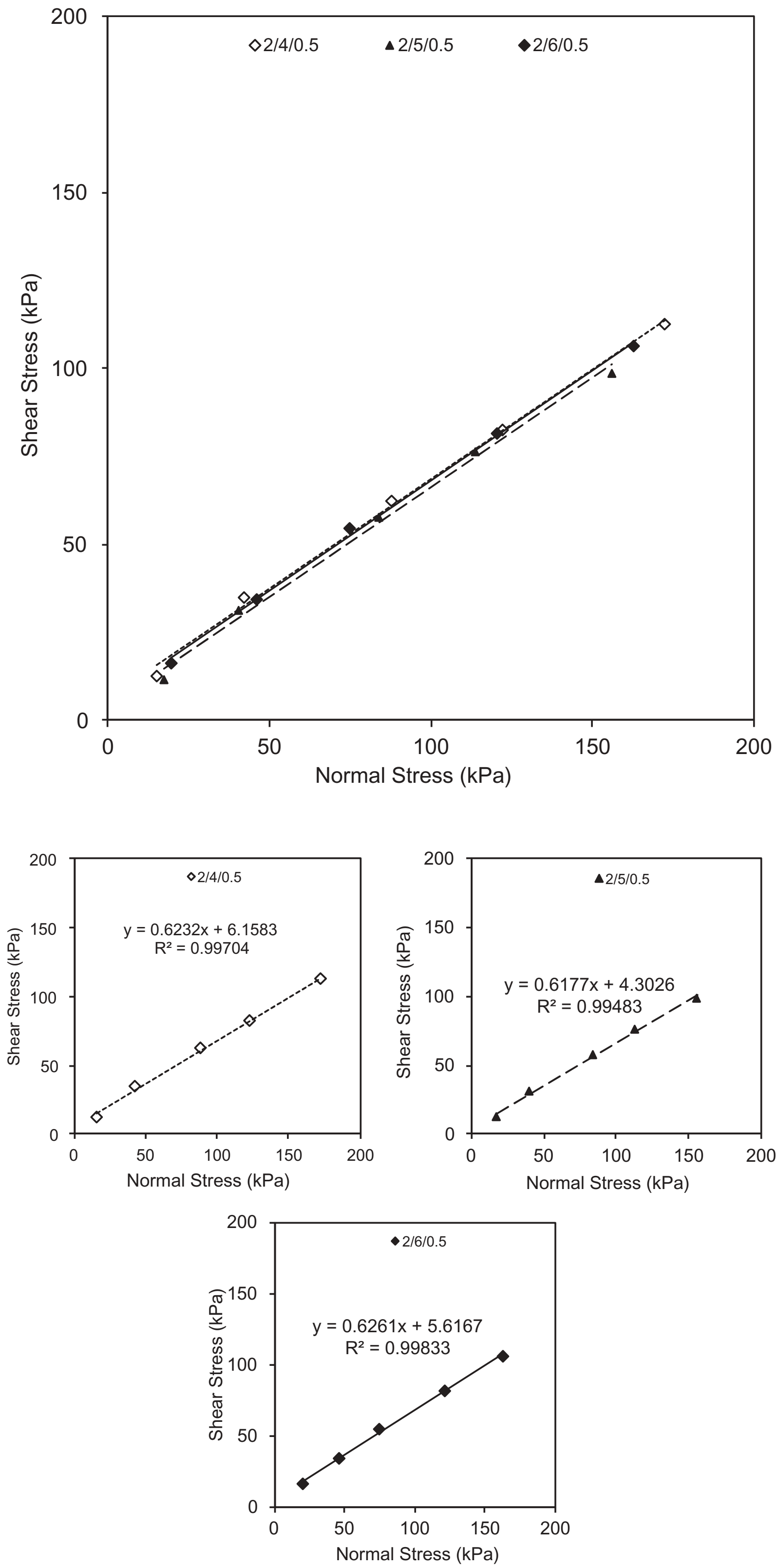


Figure 13. Residual shear strength of aeolian sand treated with synthetic fluid and geofiber.

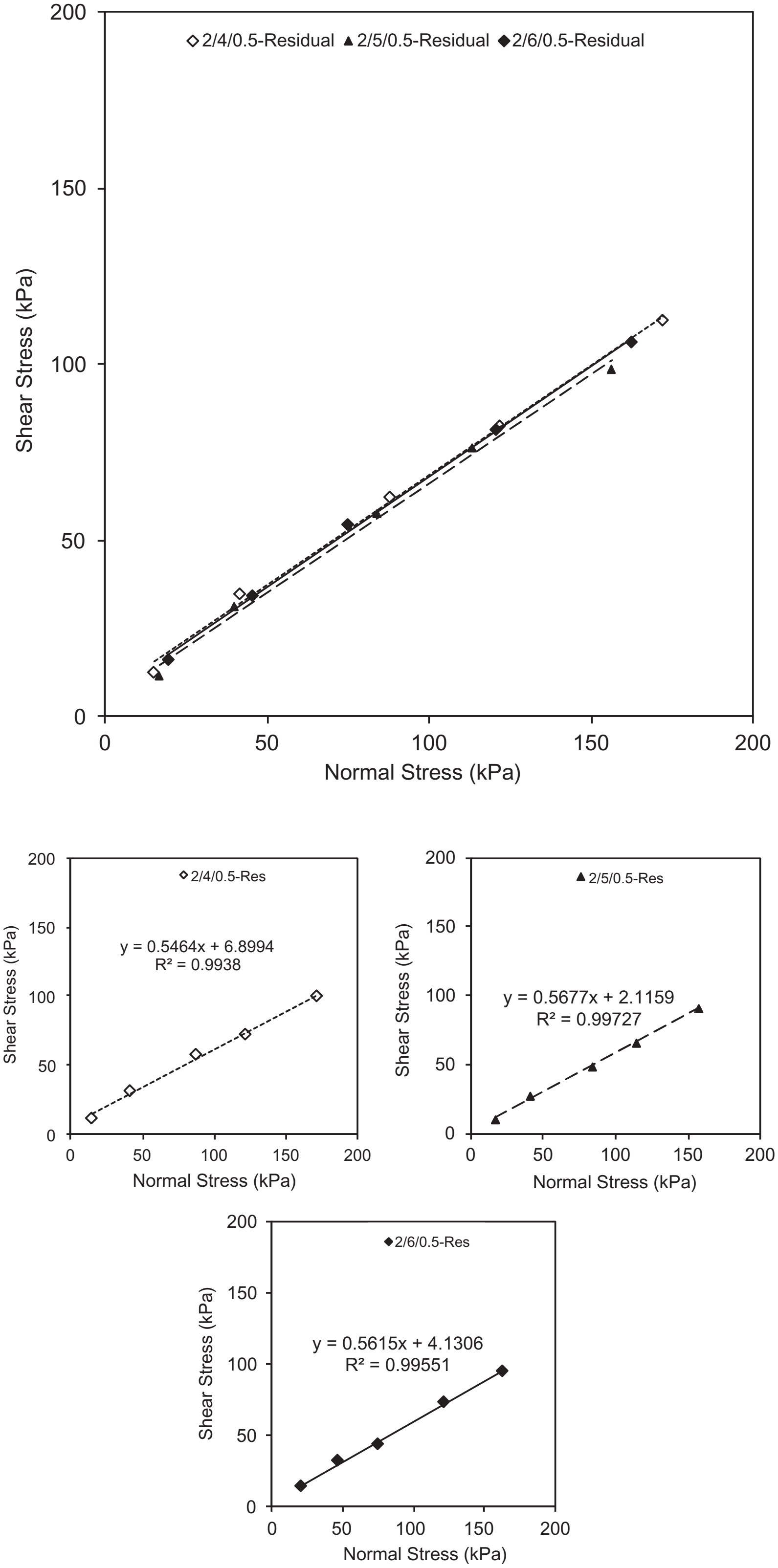
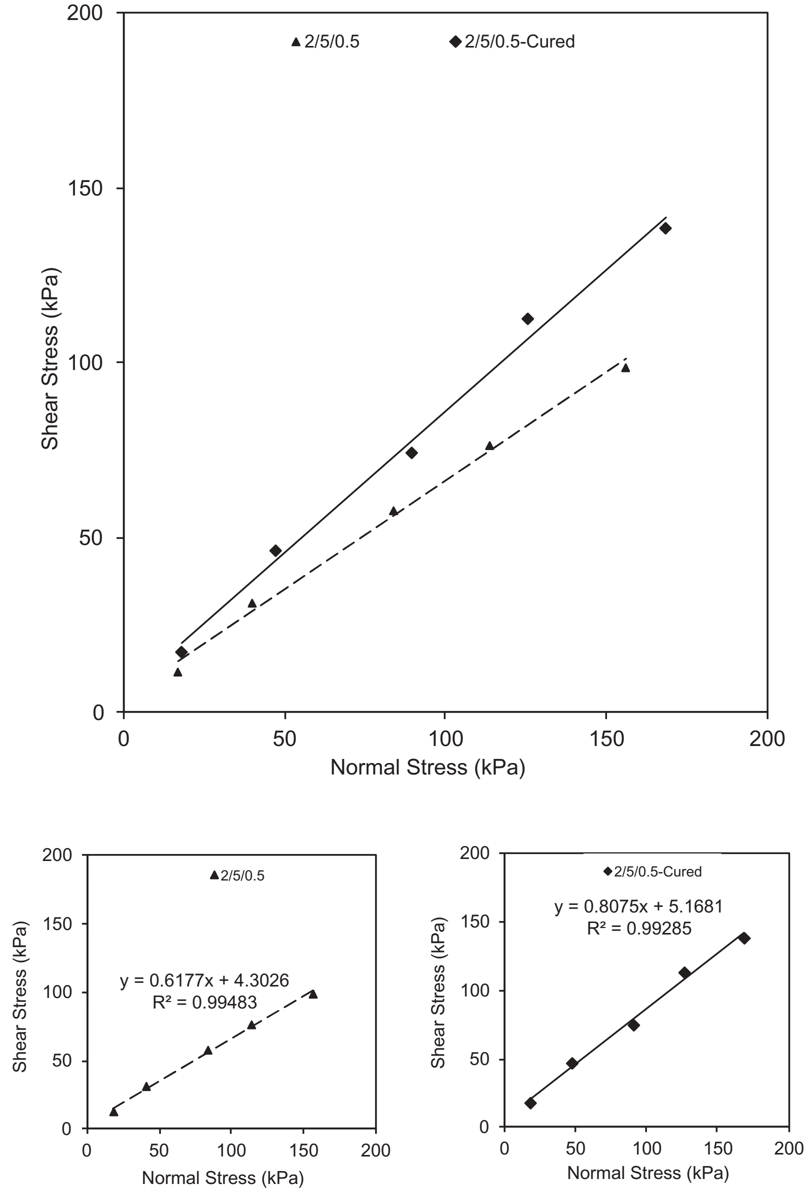


Table 6. Large-scale direct shear box testing data of aeolian sand treated with synthetic fluid and geofiber

SFC(%)	W(%)	GFC(%)	Target σ (kPa)	σ Measured (kPa)	Side Friction (kPa)	Adjusted σ (kPa)	Peak Shear Strength				Residual Shear Strength			
							Peak τ (kPa)	c (kPa)	ϕ	R^2	Residual τ (kPa)	c (kPa)	ϕ	R^2
2	4	0.5	25	25.34	10.12	15.22	12.76	6.2	31.9	0.997	11.88	6.9	28.7	0.994
2	4	0.5	50	54.38	12.34	42.04	34.85				32.37			
2	4	0.5	100	103.49	15.49	88.00	62.49				58.04			
2	4	0.5	150	152.38	30.22	122.16	82.36				72.45			
2	4	0.5	200	206.12	33.78	172.34	112.41				100.03			
2	5	0.5	25	26.49	9.39	17.10	11.87	4.3	31.7	0.995	10.28	2.1	29.6	0.997
2	5	0.5	50	51.62	11.38	40.24	31.08				27.64			
2	5	0.5	100	102.24	18.38	83.86	57.61				48.62			
2	5	0.5	150	156.92	43.24	113.68	76.52				66.28			
2	5	0.5	200	203.42	47.04	156.38	98.48				91.24			
2	6	0.5	25	29.19	9.37	19.82	16.53	5.6	32.1	0.998	14.27	4.1	29.3	0.995
2	6	0.5	50	56.17	10.16	46.01	34.44				32.38			
2	6	0.5	100	102.49	27.52	74.97	54.83				43.62			
2	6	0.5	150	155.22	34.68	120.54	81.36				73.89			
2	6	0.5	200	206.18	43.37	162.81	106.47				94.64			
2*	5*	0.50*	25	27.49	9.48	18.01	17.34	5.2	38.9	0.993	13.76	4.1	31.3	0.997
2*	5*	0.50*	50	57.41	10.33	47.08	46.32				35.11			
2*	5*	0.50*	100	106.38	16.48	89.90	74.38				56.4			
2*	5*	0.50*	150	158.22	32.39	125.83	112.43				82.34			
2*	5*	0.50*	200	205.16	36.43	168.73	138.38				105.82			

SFC: synthetic fluid content
W: water (moisture) content
GFC: geofiber content
*Subjected to curing

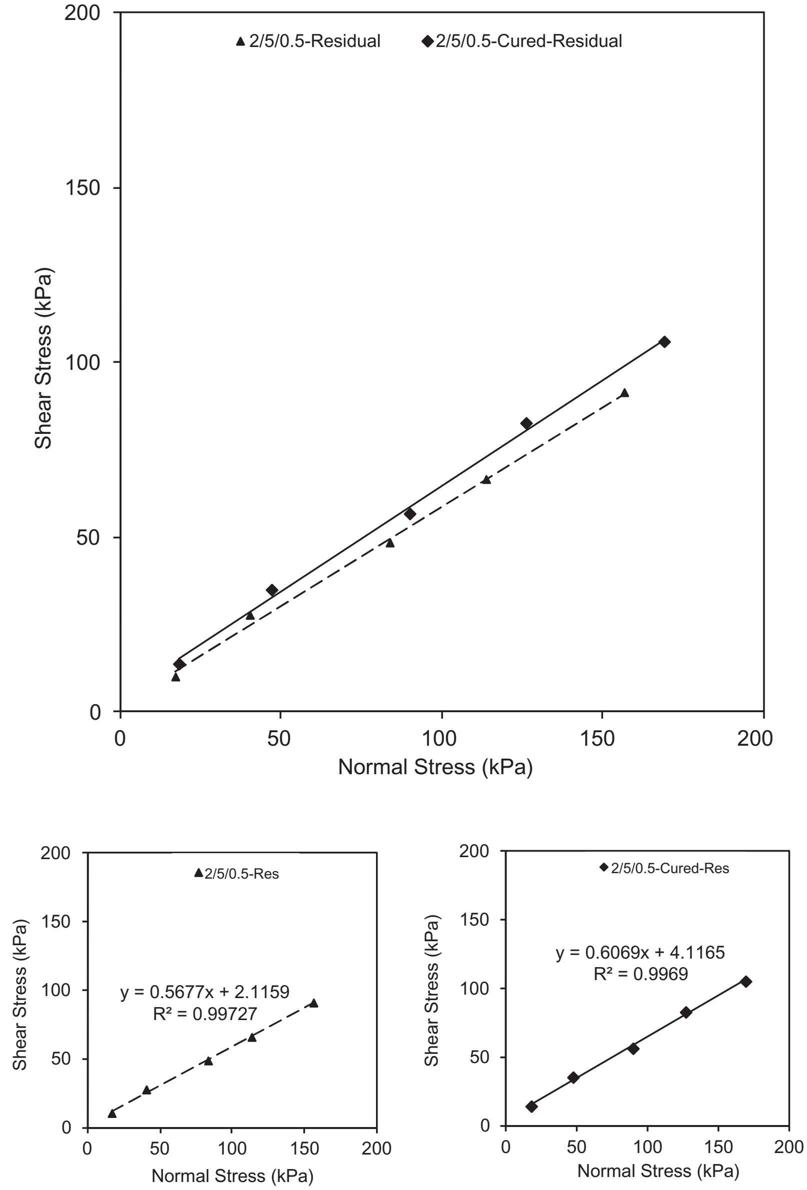
Figure 14. (a) Effect of curing on the peak shear strength of aeolian sand treated with synthetic fluid and geofiber. (b) Effect of curing on the residual shear strength of aeolian sand treated with synthetic fluid and geofiber.



The effect of curing and time-dependent strength gain was evaluated with the combination of 2*/5*/0.5*. The series of tests run under this category are shown at the bottom of Table 6. The samples of this group were prepared following the same procedure. Curing, as in the case of CBR testing, was accomplished by leaving the soil samples in the laboratory for 28 days before subjected to direct shear testing. Cured samples did exhibit significant gain (about 23%) in terms of peak shear strength when compared to uncured samples, as shown in Figure 14a. However, post-peak strength of cured samples, as depicted in Figure 14b, did not show a noteworthy improvement. This finding suggests that the bonding developed by curing deteriorates with excessive deformation, thus the residual strength of cured and uncured soil appear to be about the same.

A relationship between peak and residual strength to quantify the strength loss was suggested by Hazirbaba (2018) for geofiber-reinforced sand as follows:

Figure 14. (Continued).



$$L_S = [\phi_{peak}/\phi_{residual}] - 1 \tag{1}$$

where ϕ_{peak} and $\phi_{residual}$ are the peak and residual friction angles, respectively. Smaller values of L_S refer to the higher potential of preserving the peak strength even at excessive deformation. The strength-loss ratio (L_S) for all compositions of soil subjected to direct shear testing is presented in Figure 15. Unreinforced/untreated soil (0/7/0) shows the smallest drop in strength (greatest potential of maintaining its peak strength) at excessive deformation. Cured sand composition (2*/5*/0.5*), however, appears to experience substantial loss of strength at large deformation. This suggests that the curing process does not improve the residual strength.

Correlation between strength parameters and the CBR value allows some flexibility for the designer in pavement design practices. To analyze whether a reasonable correlation exists between the friction angle and the CBR values obtained in this research, each soil composition tested in direct shear test box was evaluated with the corresponding CBR value in Figure 16. The

Figure 15. Strength loss of various soil compositions (*subjected to curing).

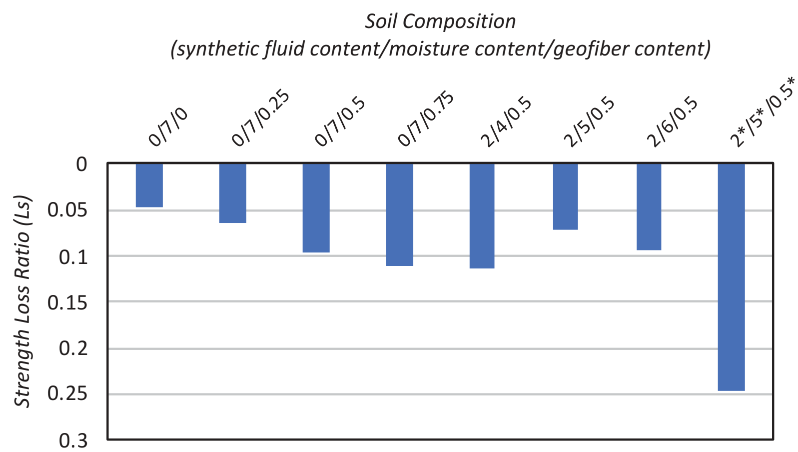
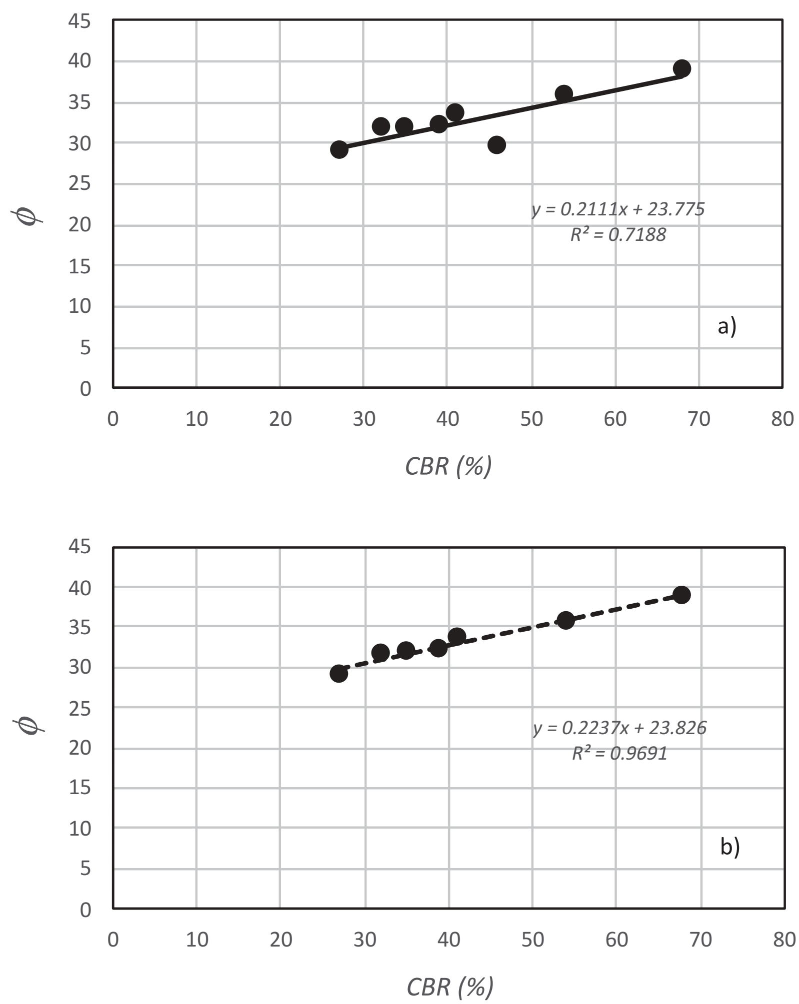


Figure 16. Correlation between CBR and friction angle (a): based on all data; (b): after outlier discarded.



trend suggests a relatively reasonable correlation with an R-square value of about 0.72 for predicting the peak friction angle using CBR results (Figure 16a). The correlation could be improved even further if the outlier performance of the 0/7/0.75 composition is to be discarded (Figure 16b). In this case, the best fit R-square value becomes 0.97, which indicates a much stronger correlation.

4. Conclusion

Bearing capacity and strength improvement of aeolian sand with geofiber and synthetic fluid additives were investigated through a systematic and comprehensive experimental program. A series of CBR tests were performed on various compositions of the soil and additives to evaluate the bearing capacity improvement. Additionally, a number of large-scale direct shear box tests were conducted for the assessment of the strength. The following conclusions may be drawn from the results of this study:

(1) Synthetic fluid is an effective additive for stabilization of aeolian sand, and especially in hot climatic conditions. It lowers the demand for water during compaction and improves the CBR performance.

(2) The best CBR performance of the aeolian sand investigated with synthetic fluid was found to occur at 2% synthetic fluid content and 5% water content. Lower and higher water contents reduced the effectiveness of the additive.

(3) Addition of geofiber enhanced the CBR performance of the sand substantially. The optimum geofiber content for aeolian sand was found to be 0.5%. An increase of 100% in the CBR value was attained at this dosage rate.

(4) Treatment of aeolian sand with combined use of synthetic fluid and geofiber improved the CBR performance by 19% to 95%.

(5) Further improvement of the CBR performance by as much as 125% was obtained by subjecting the treated soil to curing for 28 days under laboratory conditions.

(6) The best strength performance through large-scale direct shear box testing was obtained from the sand reinforced with 0.5% gravimetric geofiber content.

(7) Combined use of synthetic fluid and geofiber resulted in about 10% strength gain in terms of the peak friction angle.

(8) Curing of the treated sand containing 2% synthetic fluid and 0.5% geofiber showed around 23% increase of the peak shear strength.

(9) A strong correlation was found to exist between the CBR value and the shear strength obtained from large-scale direct shear box testing.

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