VOL. 15, NO. 21, NOVEMBER 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EFFECT OF COMPACTION STATES IN COMPRESSIVE STRENGTH AND VOLUME CHANGE OF ELASTIC SILTS MODIFIED BY DISCONTINUOUS SYNTHETIC FIBER

Omar Al Hattamleh[1], Samer Rababah[2], Hussein Aldeeky[1,] and Hazim Dwairi[1]
[1]Department of Civil Engineering, College of Engineering, The Hashemite University,
Zarqa, Jordan
[2]Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan
E-Mail: srrababah@just.edu.jo

ABSTRACT

Fine soil improvement through the inclusion of randomly distributed discrete elements, such as fibers, has recently attracted more attention in the geotechnical engineering community. Consequently, the purpose of this study is to investigate the influence of soil compaction conditions on the shear strength and volume change of elastic silts reinforced with glass fiber experimentally. A series of unconfined compressive strength and free swell tests were conducted on unreinforced and reinforced elastic silts specimens. The fiber content in the tests varied between 0.25% and 1.0% by weight of dry soil. The test results revealed that the inclusion of fibers in soil significantly increases the unconfined compressive strength. Furthermore, little inclusions of the fibers were able to eradicate the undesired volume change occur during wetting of elastic silts and partially eliminate the dependent of soil strength on seasonal water variation which is extremely important for subgrade soil.

Keywords: discontinuous synthetic fiber, free swell, shear strength, elastic silts.

1. INTRODUCTION

Fiber-reinforced soil is one of the best choices when it comes to the application of soil veneer or localized repair of failed slopes. The fiber-reinforced soil not only has the ability to take an irregular shape, but it also eliminates the anchorage requirements for the repair of failed slope. Landfill covers closed to the atmosphere without sufficient protections are prone to damage from desiccation [1, 2]. Thus, fiber-reinforced soil introduced into the landfill covers will prevent such damage through tensile failure [3]. Furthermore, randomly distributed fiber inclusions, either synthetics or natural fibers, incorporated into soils mass improve their mechanical behavior (e.g., [4-11] There are many types of synthetic fiber currently in use, such as Polypropylene, Polyester, Polyethylene, Nylon, Steel, Polyvinyl alcohol, and Glass fibers. The inclusion of glass fibers in silty sand soils was effectively used to improve peak strength [12, 13]. Furthermore, the inclusion of glass fiber in cemented treated soil increased the deviatoric stresses and increasing stiffness of the soil samples [13]. The use of glass fiber was found to increase the unconfined compressive strength (UCS) of kaolinite/fiber soil composite. The addition of 1% to 4% of glass fiber to cement-treated sand resulted in an increase of (UCS) by 50% compared with non-reinforced samples [14]. Moreover, the addition of roving, fiberglass threads, between 0.10% to 0.2% by weight, to cohesionless soils increased the soil cohesion between 100 and 300 kN/m^2 [15]. Lastly, Lovisa *et al.* (2010) benefits of the addition of glass fibers to sandy soil. The results indicated that the addition of 0.25% was able to introduce an apparent cohesion intercept to dry sand and remain unchanged with increasing water content after that.

Numerous articles demonstrate the benefits of adding different fiber to soils, but very few authors have studied the effect of water content and to the best knowledge of the authors the effect of initial placement density [17]. Furthermore, with repair slope subjected, especially in the semiarid region, to intermittent or prolonged rains, the treated expansive soil may have exposed to volume increase; consequently, the soil density may reduce, which will affect the available shear strength. This reduction in shear strength may jeopardize the stability of the slope. Hence, in this paper, the inclusions of glass fibers in the fine soil of elastic silts and the impact of dry density and water content on selected properties of reinforced soil will be investigated experimentally. The study will include the effect of glass fibers addition at different compaction conditions on unconfined compression strength, soil suction, and the volume change through the free swell.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

The fine soil used in the present study was obtained from the Azraq Basin in Jordan. The sample was collected by manual excavation in a disturbed state condition. In order to characterize the Azraq soil, grain size distribution(ASTM D422 2007), specific gravity [20], and Atterberg limit [20] tests were performed. Table-1 shows the physical properties of the soil. Scanning Electron Microscopy (SEM) was conducted on soil sample to investigate the soil microstructure (Figure-1). As it can be seen from Table-1 Azraq soil is a fine-grained soil with a liquid limit of 86%, a plasticity index of 45%, a fine portion percentage of 95%. Therefore, Azraq soil is classified according to the Unified Soil Classification System [21] as an Elastic Silts (MH). Moreover, the standard compaction tests according to [22] were performed on the soil. As it can be seen in Figure-2, the maximum dry density is 1340 kg/m^3 and the optimum water content is 33%.

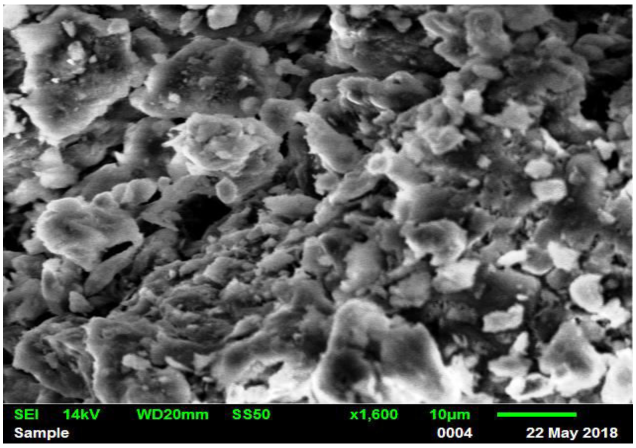


Figure-1. SEM for natural prepared soil.

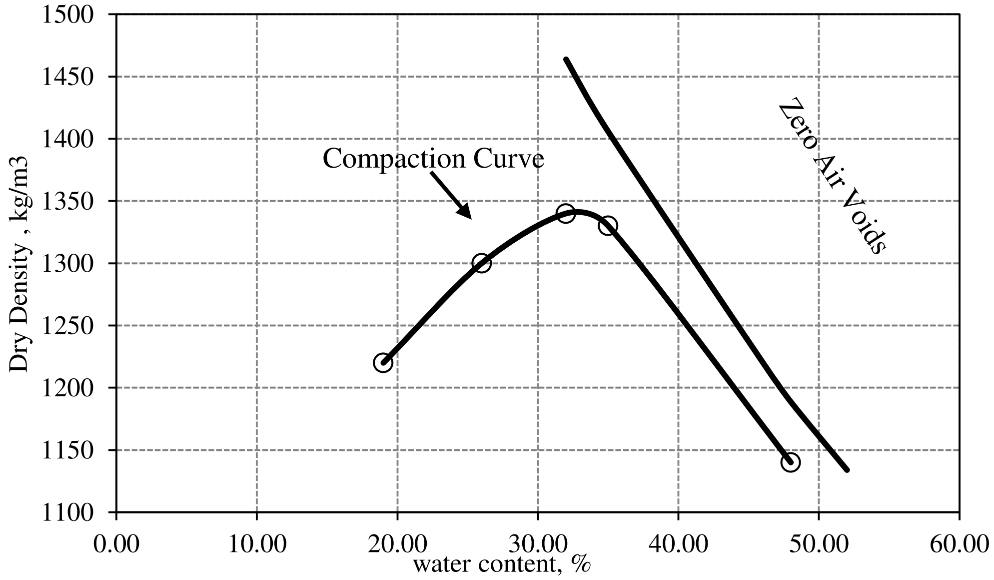


Figure-2. Soil density moisture content relationship curve for Azraq clay.

The used Discontinuous Synthetic Fiber was the glass fibers of the following physical and mechanical properties as provided by the manufacturer: Density: 2500 kg/ m3, Tensile strength: 300 MPa, Elongation at break: 3%, specific gravity: 2.7, no water absorption <<1% and length of single yarn is 30 mm and an aspect ratio of 300. Figure-1b shows the used fiber as received from the supplier. Lastly, distilled water was used for molding specimens for all tests carried out during this study.

Table-1. Soil physical properties.

Soil Properties	Standard	Value
Grain size analysis	**ASTM D422 and ASTM D1633**	
Gravel (%)		0.0
Sand (%)		5.0
Silt (%)		31
Clay (%)		64
Liquid limit (%)	ASTM D4318(2010)	86
Liquid limit, oven dry (%)	ASTM D4318(2010)	81
Plastic limit (%)	ASTM D4318 (2010)	41
Plasticity index (%)		45
Specific Gravity	ASTM D854 (2014)	2.76
PH	ASTM D4972 (2013)	6.4
Standard compaction test	ASTM D698 (2012)	
Maximum dry density (kg/m^3)		1340
Optimum water content (%)		33

2.2 Methods

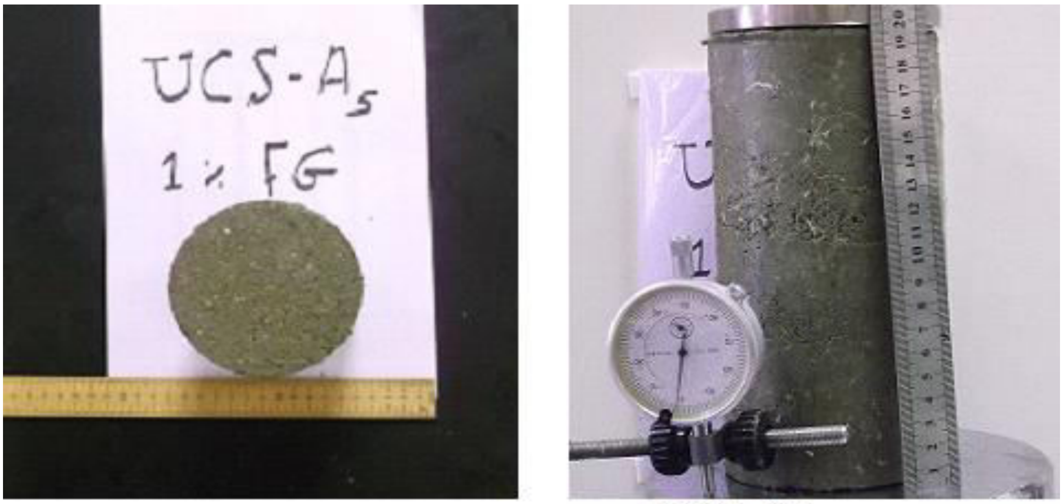
To study the effect of both the dry density and water content on the UCS, five soil compaction points were chosen, as shown in Table-2. The chosen points were determined after a series of compaction tests were conducted to examine the effect of fiber content in maximum dry density and optimum water content. The results indicate, for this type of fiber, that its inclusion has a negligible effect on the maximum dry density and optimum water content.

Table-2. Experimental test conducted at chosen soil compaction points.

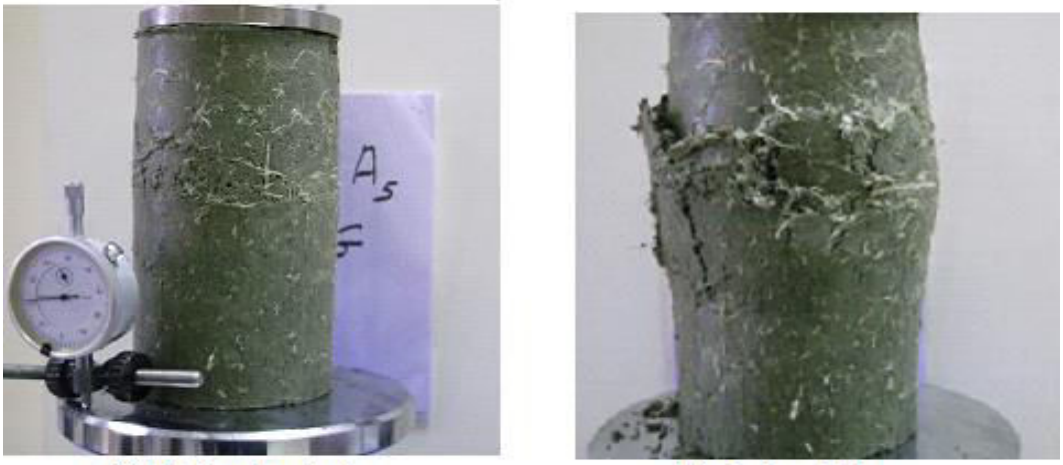
Soil Compaction Points	Dry Density (kg/m^3)	wc*	FC§, %	UCS⁑	FS⸸	S‡
A1	1250	22%	0.0	√	√	√
A2	1250	33%	0.0	√	√	√
A3	1250	40%	0.0	√	√	√
A4	1400	33%	0.0	√	√	√
A5	1340	33%	0.0	√	√	√
A1	1250	22%	0.25	√	√	√
A2	1250	33%	0.25	√	√	√
A3	1250	40%	0.25	√	√	√
A4	1400	33%	0.25	√	√	√
A5	1340	33%	0.25	√	√	√
A1	1250	22%	0.50	√	√	√
A2	1250	33%	0.50	√	√	√
A3	1250	40%	0.50	√	√	√
A4	1400	33%	0.50	√	√	√
A5	1340	33%	0.50	√	√	√
A1	1250	22%	0.75	√	√	√
A2	1250	33%	0.75	√	√	√
A3	1250	40%	0.75	√	√	√
A4	1400	33%	0.75	√	√	√
A5	1340	33%	0.75	√	√	√
A1	1250	22%	1.00	√	√	√
A2	1250	33%	1.00	√	√	√
A3	1250	40%	1.00	√	√	√
A4	1400	33%	1.00	√	√	√
A5	1340	33%	1.00	√	√	√

*water content; § Fiber Content; ⁑ Unconfined Compressive Strength; ⸸ Free Swell; ‡ Soil Suction

The sample preparations used in this study started with hand mixing the dry soil and water; after that, the GF was added. The specimens were compacted in three layers into a 100 mm diameter by 200 mm high mold to achieve the desired density, as indicated in Table-2. The UCS tests were carried out according to [23] in a strain rate control test with an axial strain rate of 1.0 mm/ minute. A tested specimen at different stages of testing until failure is shown in Figure-3.



(a) Top View (b) Side View



(c) At the beginning of failure (d) At the failure (end of test)

Figure-3. UCS specimen from preparation to failure for compaction point A5.

For the Free swell tests (FS), five soil compaction points were chosen, as indicated in Table-2. The specimen was molded directly into an oedometer ring and was statically pressed to achieve the required initial density. The specimen was then mounted into an oedometer device and inundated with distilled water and allowed to swell freely without any surcharge load, which is slightly modified from ASTM D4546 (2014).

There are many methods that can be used to measure the matric suction; however, it was found that the most suitable technique is the contact filter paper method because of the laboratory conditions and the nature of the soil-fiber mixture. The ASTM D5298 (2010) - Standard Test Method for Measurement of Soil Potential (Suction) using Filter Paper was followed to measure the matric suction for different percentages of the mixture at different water contents.

For soil suction tests (SS), five soil states were chosen as shown in Table-2. The samples were prepared according to ASTM D5298 (2010). In which a pair of soil disks specimen were molded in the required state. Three stacked of filter papers were laid between the two soil disks while the other two filter papers were placed on a screen above the top disk. The filter paper used was Whatman No. 42. The samples then placed in an airtight container for seven days "to allow sufficient time for the vapor pressure of pore-water in the specimen, vapor pressure of pore water in the filter paper, and partial vapor pressure of water in the air inside the container to reach equilibrium" [25].

3. RESULTS

The maximum dry density and the matching optimum moisture content for the elastic silts samples modified with different percentages of glass fiber inclusions are shown in Figure-4. As the figure shows, the increase in glass fiber content has no significant impact on both maximum dry density and optimum moisture content.

This is occurred because of the little amount added of fiber by weight and the higher specific gravity of the soil materials, G_s=2.76, compared to the Glass fiber, G_s=2.7. However, these results of this fiber in contrary to the finding of other fibers such as sisal or propylene fiber where the aspect ratio of the fiber is higher, where both maximum dry density and optimum water content altered notably by their additives [17].

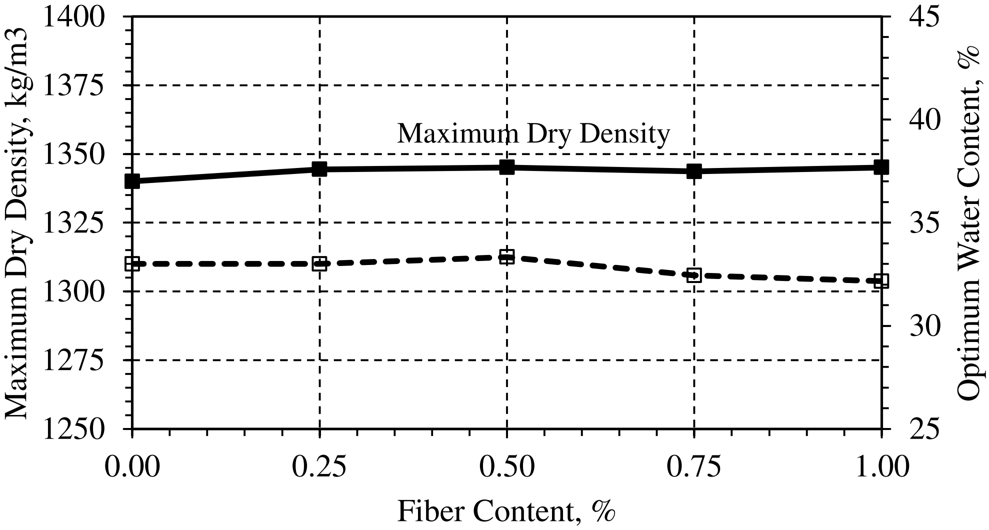


Figure-4. Effect of fiber content on maximum dry density and optimum water content.

A series of UCS was conducted on modified and non-modified soil specimens. Figure-5 shows a typical resulted from UCS for a modified specimen with different inclusion of FG at a compaction point A4. It can be observed that the FC content has a great effect on the strength and axial strain at failure of the specimens. The UCS increased substantially across all amounts of fiber content added. The presence of GF in soil resulted in an encapsulated soil cluster between the yarn that, in turn, increases the internal confining pressure within the soil specimen and therefore increases the overall strength of the treated soil. The maximum increase in UCS was at 1%, while the highest axial strain at failure achieved was obtained at 0.50% fiber content.

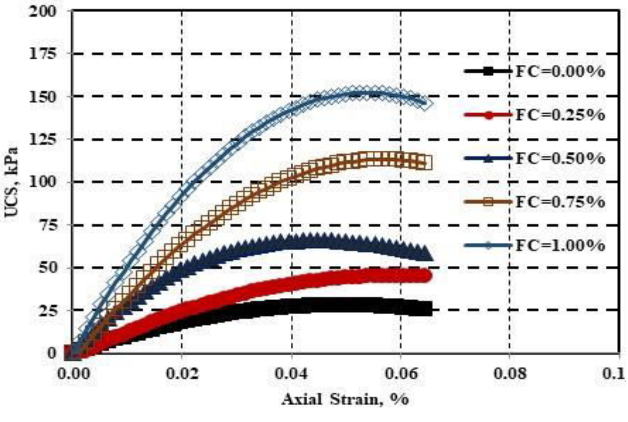
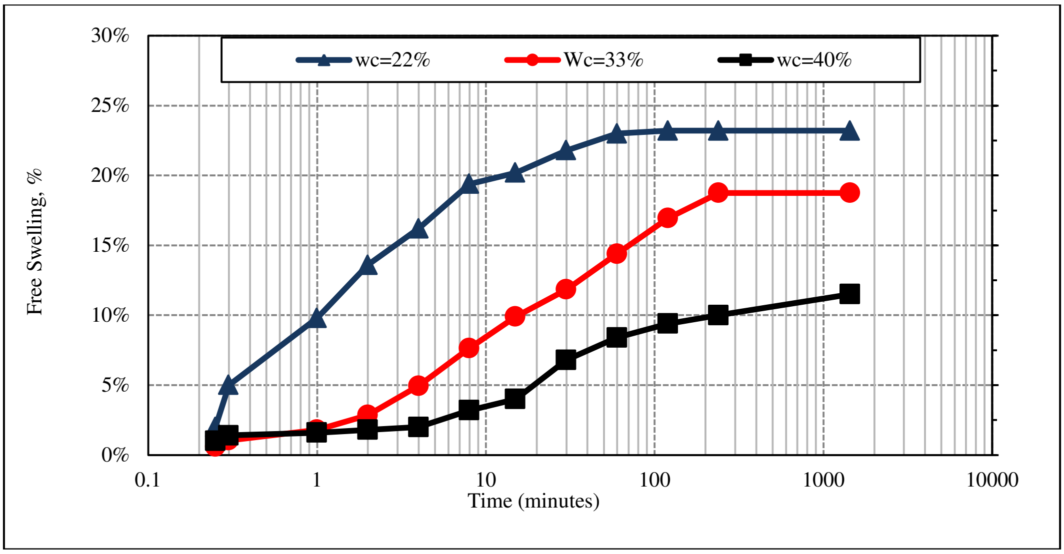


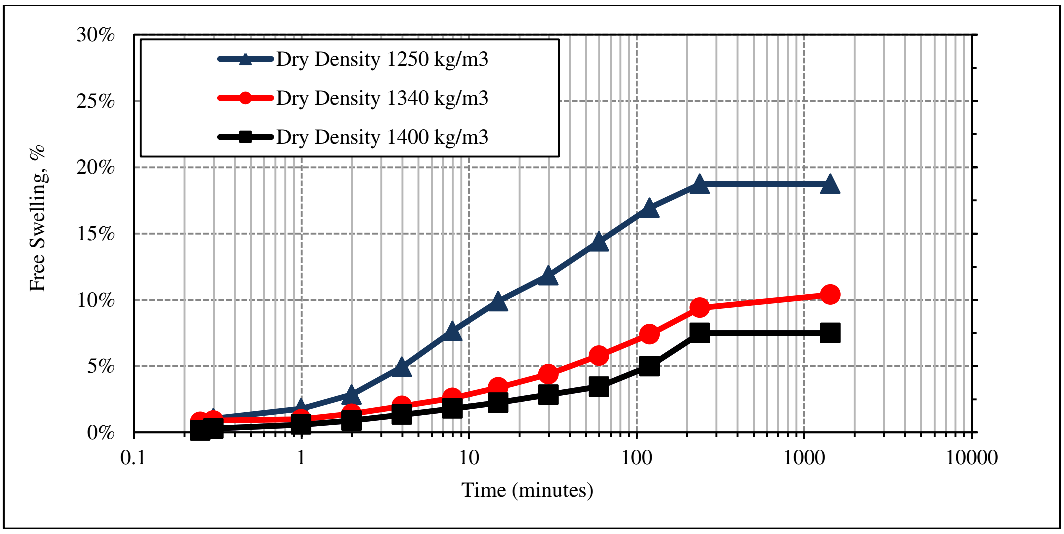
Figure-5. UCS test results for different FC at state A4.

One-dimensional swell tests were performed in an oedometer apparatus on remolded elastic silt specimens for both unreinforced and glass fiber reinforced conditions to study the effect of fiber inclusions on the free swell. The effect of the fiber content in free swell at different soil states was studied. The free swell method conducted allows the sample to absorb water freely until the heave is seized. This method employed previously in the analysis the effect of Nylon fiber, by Phanikumar and Singla (2016), and Palmyra fiber, by Al-Akhras et al. (2008), on the volume change of high expansive soils.

Even though the current fine soil considers low activity (A=0.7) according to Skempton (1984) designation, it undergoes large swell potential according to Seed and Lundgren (1962) and as it can be seen from Figure-6. It is clear from Figure-6(a) that the soil sample compacted at the dry side of the optimum produced higher swelling potential compare with the samples compacted at the wet side of the optimum (23.2% cf. 11.5%). This behavior matches well with the behavior of fine-grained soil of high activity, since they have a greater deficiency of moisture, and therefore have a greater propensity to suck and adsorb moisture. Furthermore, for the samples of fixed moisture content, Figure-6(b), as density increases free swelling decreases; since all samples are in flocculated fabric condition, the less density sample has the ability to swell more due to fewer obstacles in the direction of volume change.



(a)



(b)

Figure-6. Free swelling (A) at initial dry density of 1250 kg/m3 (B) at molded moisture content wc=33%.

4. DISCUSSIONS

4.1 Effect of the Fiber Content and Compaction on UCS

The effect of molded water content in UCS of fiber treated soil at a given density of 1250 Kg/m^3 is shown in Figure-7. It is a well-known fact that an increase of molding water content at a given density will reduce the UCS. For a given dry density of 1250 kg/m^3, the inclusion of fiber at a water content of 22% was able to increase the UCS 76.2%, 117.3%, 174.4% and 224.7% for fiber content of 0.25%, 0.50%, 0.75% and 1.0% respectively. While for the same density, 1250 kg/m^3 and water content of 33% was able to increase the UCS 32.6%, 65.1%, 147.7%and 332.2% for fiber content of 0.25%, 0.50%, 0.75% and 1.0% respectively. Comparing samples tested in the same density but with different water percentages (22% and 33%), fiber was able to enhance the UCS regardless of its percentage, and the maximum decrease of UCS with respect to the variation of water content was at 0.75% of fiber content. Similar trends were also found by Patel and Singh (2017) in their study of adding GF to low plastic clay (CL). Moreover, the effect of FC on the strain at maximum UCS for the soil molded at different water content and density of 1250 kg/m3. It is clearly shown that the fiber content of 0.5% gave the highest strain at failure for the water content of 33%, which in return will provide the best axial strain at failure for soil modified at this water content. While for the water content of 22%, the strain at maximum UCS has its maximum at 0.25% fiber content with little variation up to 0.75% fiber content, then decreases. Therefore, a little dose of this fiber, 0.25%, will able to increase the ductility of this soil, which is required in case of patch repairing of slopes.

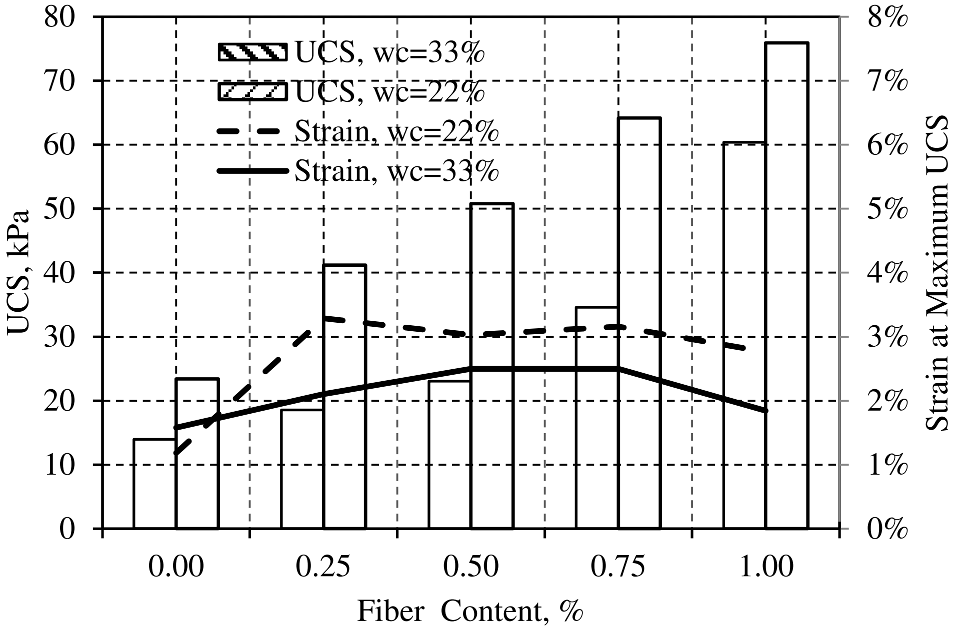


Figure-7. Effect of molded water content in the UCS of fiberglass- improved soil, at ρ_d=1250 kg/m^3.

The effect of density at a fixed molded water content of 33% is shown in Figure-8. As it is expected, as dry density increases, the UCS increases at the given water content regardless of the amount of GF in the sample, either it is zero content or any percentile of fiber inclusions. This result conforms with the rate process theorem [31], which demonstrated that the number of interparticle contacts per unit area of soil cross-section, in other words, the density, is the most important single factor influencing unconfined compressive strength. Furthermore, as the amount of fiber content added, more contacts/ obstacles are anticipated and needed to be overcome in the same shearing plane; thus, the UCS in return will increase. Moreover, the increase of GF content increases the UCS in a significant amount. It increases the UCS from 13.96 kPa, at zero fiber content, up to 60.35 kPa, at the fiber content of 1% of the molded density of 1250 kg/m3 (i.e., 332.3% increased). Furthermore, the UCS increase from 27.59 kPa at zero fiber content up to 153.40 kPa at the fiber content of 1% of the molded density of 1400 kg/m3 (i.e., 456.0% increased).

Moreover, Figure-8 also shows the effect of initial dry density at a fixed molded water content of 33%. From this figure, it is apparent that adding GF will increase the axial strain at failure of almost equal amount in low at until 0.5% fiber content. Moreover, at an initial dry density of 1250 kg/m^3 and a molding water content of 40%, the specimens were hard to remove from the preparation molds, and if any specimen removed it was highly deformed, and thus at this low density and a high amount of water contents, a chemical treatment is preferred over the addition of fibers for fine soil.

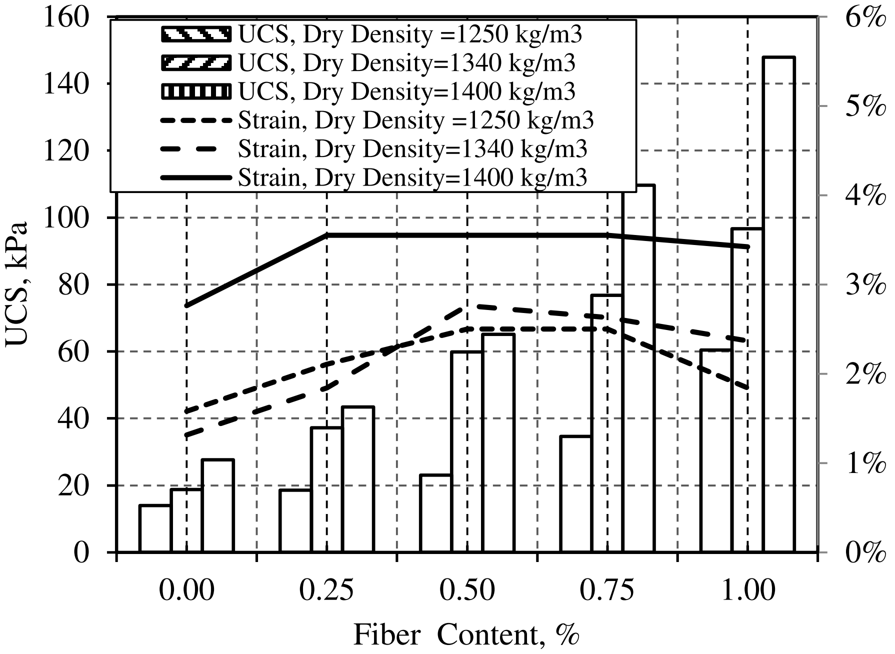


Figure-8. Effect of dry density in the UCS of fiberglass - improved soil at Water content = 33% and dry densities as shown in the legend.

4.2 Effect of the Fiber Content and Compaction on the Free Swell

Figure-9 shows the effect of adding different percentages of fiberglass to fine-grained soil at different moisture states. Figure-9 a, b, c, d, and e clearly show that even with a small percentage of fibers, the free swelling decreased significantly.

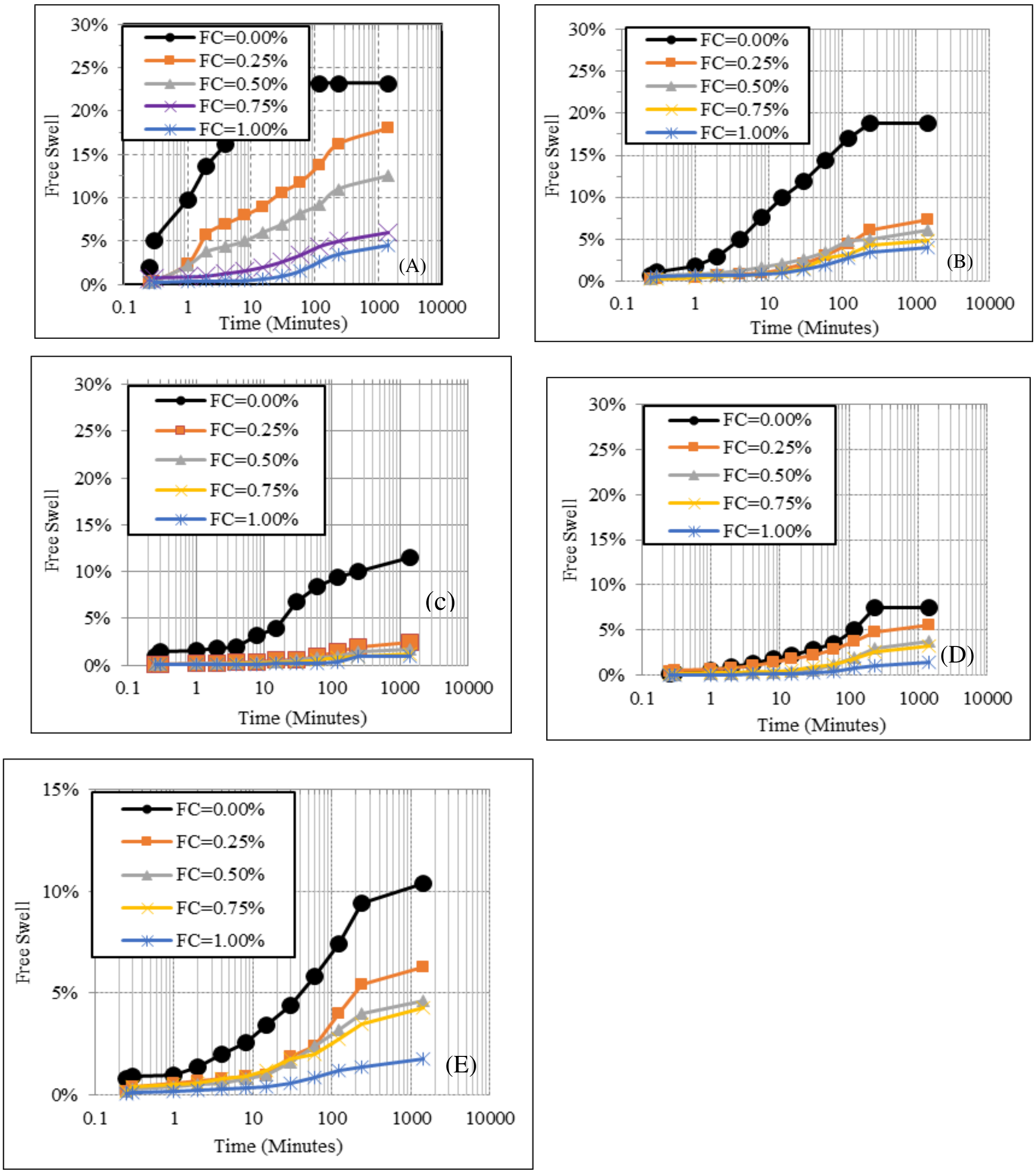


Figure-9. Free swelling results (a) compaction point A1 (b) compaction point A2 (c) compaction point A3 (d) compaction point A5 and (e) compaction point A4.

This could be attributed to the effect of knitting of fiber yarns [26, 27, 32], confinement, and to interfacial friction [27, 32, 33] generated by introducing (glass) fiber within the soil matrix. In addition to the increase of the amount of non-expansive matter (glass fiber, which is hydrophobic in nature) in a soil matrix subjected to imbibing water. Moreover, contrary to wide fiber such as polypropylene fiber, glass fiber has an aspect ratio of 300, which helps the fibers not subjected to bending and folding, which could potentially reduce the effective soil-fiber contact area and therefore reduce the ability to restrain the swelling activity. To give a clear picture of the effect of molding content, swelling potential, as well as soil suction in the range of tested water content for different fiberglass content, is depicted in Figure-10. In Figure-10, It is clearly shown that for lower molding water content (wc=22%) higher amount of fiber is needed to seize the higher swell, while for higher molded water content (wc=33% and 40%) less amount of fiber (FC=0.25%) was enough to reduce the swelling by 70% and 80%, respectively. Furthermore, for higher molding water content, the addition of fiber more than 0.25% resulted in little or no effect in impeding the swelling. In addition, as adding a fiberglass increase in the soil sample, the suction tends to decrease in all reported water content. Since as the soil suction decrease, the ability to imbibe water is decreased; therefore, the free swell will be decreased. Moreover, according to Low surface hydration theory (Low, 1992), the more the water content, the larger the water layer thickness surrounding the clayey particles, the lower is the swelling. And since any addition of fibers content will overall reduce the total surface area of the composites, the lower is the surface subjected to hydration, thus, the lower is the swelling.

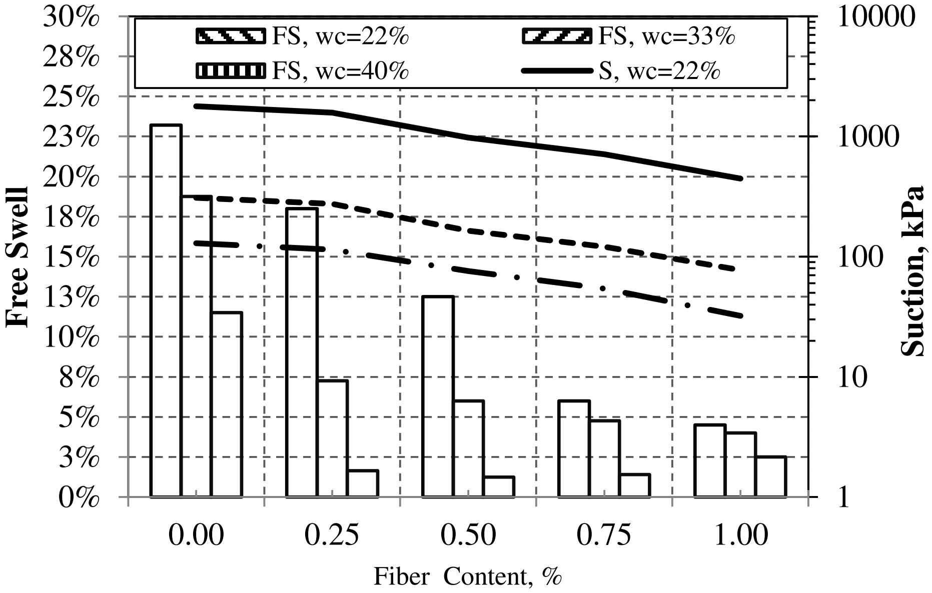


Figure-10. Effect of molding water content on free swell and soil suction as a function of Fiber content, ρd=1340 kg/m^3.

The effect of initial dry density at constant molded water content on free swell at 24 hours' inundation and on soil suction with the addition of fiberglass content is shown in Figure-11. It is clearly shown that the free swell is reduced with the increase in the molding density. Hence the addition of fiberglass reduced the soil suction and sequentially substantially the free swell. The reduction of free swell after 0.5% of fiber content is of an order of ≤ 1% therefore, no need for further addition of fiber above 0.5%. The above finding is similar to reported test results in high expansive clay such (CH) modified by polypropylene fibers were the primary swell is reported to end after 24Hours [32].

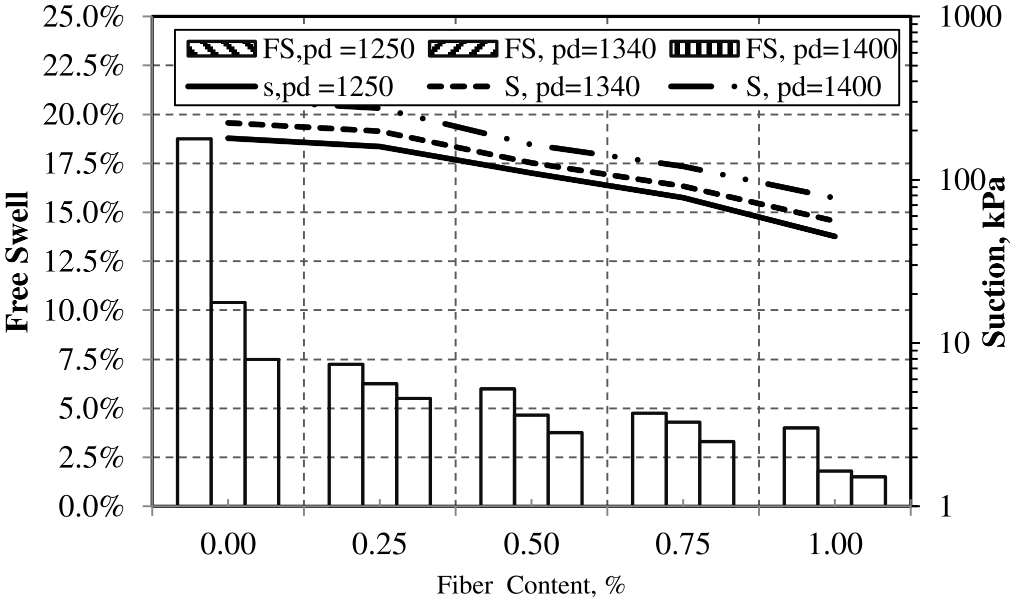


Figure-11. Effect of initial dry density at constant moisture content, wc=33%, on free swell and soil suction as a function of fiber content.

CONCLUSIONS

The effect of the inclusion of glass fiber in elastic silts in unconfined compression strength and free swell,as well as the soil, suctions at different compaction state was evaluated experimentally. The results obtained from the current research work show that the addition of GF to elastic silts has a considerable effect on their unconfined compressive strength and free swell. Particularly, the following conclusions can be drawn:

- The unconfined compressive strength of the elastic silts increases with the inclusion of fibers regardless of the initial soil compaction state.
- The strain atmaximum UCS was increased substantially by adding fiber content. Small inclusion of this fiber, 0.25%, was able to increase the ductility of this soil,which is required in case of patch repairing of slopes.
- Free swell decreases by increasing the fiber content in small doses regardless of the initial molding water content or initial dry density, and little enhancement occurs with a further increase in the doses.

In closure, the additive of this discrete randomly fiber was able to reduce the soil suctions which not sustain wetting coming from the rain with posting both the shear strength and restain the soil from heaving.

REFERENCES

[1] B. A. Albrecht, C. H. Benson. 2007. Effect of Desiccation on Compacted Natural Clays, J. Geotech. Geo environmental Eng. 127: 67-75. doi:10.1061/(asce)1090-0241(2001)127: 1(67).

[2] D. E. Daniel, Y. Wu. 1993. Compacted Clay Liners and Covers for Arid Sites, J. Geotech. Eng. 119: 223-237. doi: 10.1061/(asce)0733-9410(1993)119: 2(223).

[3] J. Li, C. Tang, D. Wang, X. Pei, B. Shi. 2014. Effect of discrete fibre reinforcement on soil tensile strength, J. Rock Mech. Geotech. Eng. 6: 133-137. doi:10.1016/j.jrmge.2014.01.003.

[4] N. C. Consoli, M. Bellaver Corte, L. Festugato. 2012. Key parameter for tensile and compressive strength of fibre-reinforced soil–lime mixtures, Geosynth. Int. 19: 409-414. doi:10.1680/gein.12.00026.

[5] C. A. Anagnostopoulos, D. Tzetzis, K. Berketis. 2013. Shear strength behaviour of polypropylene fibre reinforced cohesive soils, Geomech. Geoengin. 9: 241-251. doi:10.1080/17486025.2013.804213.

[6] E. Botero, A. Ossa, G. Sherwell, E. Ovando-Shelley. 2015. Stress-strain behavior of a silty soil reinforced with polyethylene terephthalate (PET), Geotext. Geomembranes. 43: 363-369. doi:10.1016/j.geotexmem.2015.04.003.

[7] M. Chen, S.-L. Shen, A. Arulrajah, H.-N. Wu, D.-W. Hou, Y.-S. Xu. 2015. Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay, Geotext. Geomembranes. 43: 515-523. doi:10.1016/j.geotexmem.2015.05.004.

[8] A. Diambra, E. Ibraim. 2015. Fibre-reinforced sand: interaction at the fibre and grain scale, Géotechnique. 65: 296-308. doi:10.1680/geot.14.p.206.

[9] L. Festugato, E. Menger, F. Benezra, E. A. Kipper, N. C. Consoli. 2017. Fibre-reinforced cemented soils compressive and tensile strength assessment as a function of filament length, Geotext. Geomembranes. 45: 77-82. doi:10.1016/j.geotexmem.2016.09.001.

[10] A. Boz, A. Sezer. 2018. Influence of fiber type and content on freeze-thaw resistance of fiber reinforced lime stabilized clay, Cold Reg. Sci. Technol. 151: 359-366. doi:10.1016/j.coldregions.2018.03.026.

[11] Y. Wang, P. Guo, X. Li, H. Lin, Y. Liu, H. Yuan. 2019. Behavior of Fiber-Reinforced and Lime-Stabilized Clayey Soil in Triaxial Tests, Appl. Sci. 9: 900. doi:10.3390/app9050900.

[12] N. C. Consoli, P. D. M. Prietto, L. A. Ulbrich. 1998. Influence of Fiber and Cement Addition on Behavior of Sandy Soil, J. Geotech. Geoenvironmental Eng. 124: 1211-1214. doi: 10.1061/(asce)1090-0241(1998)124: 12(1211).

[13] N. C. Consoli, J. P. Montardo, M. Donato, P.D. Prietto. 2004. Effect of material properties on the behaviour of sand-cement-fibre composites, Proc. Inst. Civ. Eng. - Gr. Improv. 8: 77-90. doi:10.1680/grim.2004.8.2.77.

[14] M. H. Maher, Y. C. Ho. 1994. Mechanical Properties of Kaolinite/Fiber Soil Composite, J. Geotech. Eng. 120: 1381-1393. doi:10.1061/(asce)0733-9410(1994)120:8(1381).

[15] R. M. Al Wahab, G. B. Hecke. 1995. Static and Dynamic Strength Properties of a Fiber-Reinforced. Compacted Cohesive Soil, in: Third Int. Conf. Recent Adv. Geotech. Earthq. Eng. Soil Dyn., American

Society of Civil Engineers, St. Louis, Missouri. doi:10.1061/9780784413128.031.

[16] J. Lovisa, S. K. Shukla, N. Sivakugan. 2010. Shear strength of randomly distributed moist fibre-reinforced sand, Geosynth. Int. 17: 100-106. doi:10.1680/gein.2010.17.2.100.

[17] A. Abou Diab, S. S. Najjar, S. Sadek, H. Taha, H. Jaffal, M. Alahmad. 2018. Effect of compaction method on the undrained strength of fiber-reinforced clay, Soils Found. 58: 462-480. doi:10.1016/j.sandf.2018.02.013.

[18] ASTM D422. 2007. Standard Test Method for Particle-Size Analysis of Soils, ASTM Int. doi: West Conshohocken, PA.

[19] ASTM D4318. 2017. Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils, ASTM Int. doi: 10.1520/D4318-17E01.

[20] ASTM D854, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, ASTM D 854. (2014) Conshohocken, PA.

[21] ASTM D2487. 2017. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM Int.

[22] ASTM D698. 2012. Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft3 (600 kN-m/m3)), ASTM Int. doi: 10.1520/d0698.

[23] ASTM D2166. 2016. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM Int.

[24] ASTM D4546. 2014. Standard Test Methods for One-Dimensional Swell or Collapse of Soils, ASTM Int.

[25] ASTM D5298. 2010. Test Method for Measurement of Soil Potential (Suction) Using Filter Paper. doi:10.1520/d5298-94.

[26] B. R. Phanikumar, R. Singla. 2016. Swell-consolidation characteristics of fibre-reinforced expansive soils, Soils Found. 56: 138-143. doi:10.1016/j.sandf.2016.01.011.

[27] N. M. Al-Akhras, M. F. Attom, K. M. Al-Akhras, A. I. H. Malkawi. 2008. Influence of fibers on swelling properties of clayey soil, Geosynth. Int. 15: 304-309. doi:10.1680/gein.2008.15.4.304.

[28] A. W. Skempton. 1984. The Colloidal "Activity" of Clays, Sel. Pap. SOIL Mech. 60-64. doi:10.1680/sposm.02050.0009.

[29] H. B. Seed, R. Lundgren. 1962. Prediction of swelling potential for compacted clays, J. Soil Mech. Found. Div. 88: 53-87.

[30] S. K. Patel, B. Singh. 2017. Shear strength response of glass fibre-reinforced sand with varying compacted relative density, Int. J. Geotech. Eng. 13: 339-351. doi:10.1080/19386362.2017.1352157.

[31] J. K. Mitchell. 1964. Shearing resistance of soils as a rate process, J. Soil Mech. Found. Div. 90.

[32] A. Soltani, A. Deng. 2018. A. Taheri, Swell-compression characteristics of a fiber–reinforced expansive soil, Geotext. Geomembranes. 46: 183-189. doi:10.1016/j.geotexmem.2017.11.009.

[33] B. V. S. Viswanadham, B. R. Phanikumar, R. V. Mukherjee. 2009. Effect of polypropylene tape fibre reinforcement on swelling behaviour of an expansive soil, Geosynth. Int. 16: 393-401. doi:10.1680/gein.2009.16.5.393.