DOI:10.1515/sspjce-2021-0007

Behaviour of cemented and compacted clayey sand reinforced with two types of fibers

Adjabi Souhila[*1a], Nouaouria Mohamed Salah[1b]

(1) University of 8 May 1945, Guelma, Algeria
(1) Civil Engineering and Hydraulic Laboratory
e-mail: ([*a]) adjabi.souhila@univ-guelma.dz,([b])nouaouria.mohamed@univ-guelma.dz

Abstract

Considering Soil reinforcement techniques have been rapidly developed because of its efficiency in geotechnical engineering. The goal of this experimental work is to improve the characteristics of a collapsible soil with polyethylene fibers in the aim of reducing the number of plastic bottles thrown in nature and with natural materials such as sisal fibers. Polyethylene fibers contents in mass were used in this investigation, namely: 5%, 10% and 15%; Sisal fibers contents: 0.5% and 1% respectively. Oedometer apparatus is used to study the reinforcing fibers effect on the Collapse Potential, and direct shear box is used to determine the intrinsic characteristics of this treated soil. Results show that when the fiber reinforcement is combined with other processing procedures such as compaction and the addition of APC cement decrease the collapse potential until a non-collapsible soil is obtained.

Key words: Collapse potential, Polyethylene fiber, sisal fiber, collapsible soil, compaction energy, shear strength, cohesion

1 Introduction

Buildings a civil engineering structures on collapsible soils is not safe because such soils can settle suddenly when are loaded and wetted.

It is quite common to find soils that do not meet the basic necessities of an engineering project technically, economically or in terms of timing. Economic issues have raised interest in the development of alternative materials that fulfill design specifica¬tions. The well-established technics of soil stabilization and soil reinforcement are generally used to obtain improved geotechnical materials, either through the addition of cementitious agents or through the inclusion of randomly distributed discrete elements such as fibers. Stabilized and reinforced soils are composite materials that result from the combination and optimization of the properties of individual constituent materials.
Many investigators have studied stress-strain characteristics of reinforced soil by using

triaxle, direct shear, and plane strain tests since the early 1970's. From 1977, extensive experimental work has been performed on geotextile-reinforced sand. Incorporating reinforcement inclusions within soil is also an effective and reliable technique that can be used to improve the engineering properties of soil. Many investigators have used various types of fibers under different test conditions. A state of art of some investigations is cited as follow:

Maher and Ho [1] evaluated the effect of randomly distributed fiber reinforcement on the response of cemented sand to load. The results of the test indicated that fiber reinforcement have significantly increased the compressive and shear strength of cemented sand.

Consoli N.C. [2] assessed the effect of randomly distributed fiber reinforcement and cement inclusion on the response of a sandy soil to load. The results showed that the addition of cement to the soil results in the increase of stiffness, brittleness and peak strength. The addition of fibers increases both the peak and residual triaxial strength, and decreases stiffness and changes the cemented soil's brittle behaviour to a more ductile material.

Ayadat and Dahili [3] improved the properties of a collapsible soil. They examined the bituminous treatment of collapsible soil at a depth of less than 4m ha, the results indicated that for obtaining no collapsible soil, a minimum water content of 4%, a bitumen content between 10 and 12 % and a high compacting energy (more than 80 blows by layer for a total of two layers in oedometer ring) have been applied.

Yetimoglu T. and Salbas O. [4] studied the effect of the fiber reinforcement content on the shear strength. The results of the tests indicated that the peak shear strength and the initial stiffness of the sand were not affected significantly. However, the fiber reinforcement could reduce soil brittleness providing smaller loss of post-peak strength, and increase the residual shear strength angle of the sand.

Chauhan M.S and Mittal S. [5] investigated the effect of reinforcement with coir fiber and synthetic fiber in subgrade soil on the strength; they reported that the permanent and resilient strains in all materials decrease with confining pressure but increase with the number of load cycles and deviator stress in reinforced and unreinforced conditions.

Ahmed F. and Batni F.[6] evaluated the response of randomly distributed oil palm empty fruit bunch (OPEFB) fiber on the strength of reinforced silty sand. The results indicated that the shear strength parameters of the soil- fiber mixture (Ø' and c') can be improved significantly, but (OPEFB) fibers are biodegradable and must be protected from any circumferential agents to ensure long-term performance.

Al Adili A. and Azzam R. [7] studied the effect of soil reinforced with randomly included papyrus fiber on the strength behaviour. The results of these tests have shown a significant improvement in the failure deviator stress and shear strength parameters of the soil with 10% of papyrus fiber. This addition also reduced the deformation of the soil under loading.

Chegenizadeh A. and Nikraz H. [8] investigated the effect of paper inclusion on the modulus of elasticity of subgrade material; the results indicated that the increase of paper percentage in mass slightly increases the modulus of elasticity

Cristelo. N, Glendinning S [9], investigate the role of calcium content in fly ash used to stabilize soft soils through alkaline activation with sodium-based alkaline activators, the results that low calcium fly ash is a better source for long term soft soil stabilization with alkaline activation than high calcium fly ash.

Zhang M., and al [10], studied, stabilization of lean clay with metakaolin based geopolymer at different concentration (ranging from 3 to 15 wt. % of unstabilized soil at its optimum water content) to examine the feasibility of geopolymer in stabilizing soils. Geopolymer stabilized soil specimens were characterized with compressive strength testing, volume measurements during curing .The results indicated that with geopolymer concentrations, compressive strength, failure strain and Young's modulus of the stabilized soil specimens increased, and shrinkage strains during curing decreased.

Botero E. and Ossa A.[11] investigated the mechanical behaviour of a silty soil that was reinforced with randomly distributed PET fibers. The results indicated that the reinforced specimens presented increase of shear strength that was associated with the increasing quantities of the PET fiber.

In comparison with conventional geosynthetics (strips, geotextiles, geogrids, etc.), there are some advantages in using randomly distributed fibers as reinforcement. Firstly, the discrete fibers are simply added and mixed randomly with soil, in the same way as cement, lime, or other additives. Secondly, randomly distributed fibers limit potential planes of weakness that can develop parallel to oriented reinforcement.

The objective of this paper is to determine the effect of randomly distributed short polyethylene-fiber, glass fibers and sisal fibers, respectively, on the collapse behaviour of a clayey sand material. A series of compression tests were carried out in the Oedometer apparatus, on soil samples made of sand, fibers and Kaolinite. Three lengths of fibers were respectively used, such as: 5mm, 10mm and 25 mm.

This paper describes a study of the collapse behaviour of Kaolinite-sand mixed samples reinforced with randomly distributed polyethylene fibers, sisal fibers and glass fibers respectively, under Oedometer loading conditions. The specific objectives of the present work are to evaluate the effect of fiber insertion on the collapse potential of sand samples mixed with Kaolinite in different proportions such as: 0 %, 5%, 10%, 15%, 20%, 25% and 30% respectively, to determine the optimum content of Kaolinite giving the maximum potential collapse.

In order to get healthier drinking water, millions of people use bottled water. The annual global consumption of bottled water has reached billions of liters. This requires the production of innumerable quantities of large and small bottles which are generally thrown in the nature. This act is harmful to the environment. Only about 20% of plastic bottles are recycled; 80% end up in landfills, or in nature. Plastic bottles begin to decompose in nature only after hundreds of years. In order to reduce the quantity of used plastic bottles, we undertake this study based on the use of these bottles to treat the collapsible soil.

This is in order to protect the environment and to address this type of soil problems by finding economic solutions; soil was reinforced with polyethylene fibers contents of 5%, 10% and 15% respectively. For each content three different lengths were used (5 mm, 10mm and 25 mm respectively), and 0.5%, 1% (5mm, 10mm and 25mm long) for sisal and glass fibers.

2 Materials, Equipment and Experimental Program

2.1 Materials

2.1.1 Soil

The reconstituted soil in the laboratory used in this experimental work is composed of sand with the grain size distribution curve is unlisted in Fig.1.

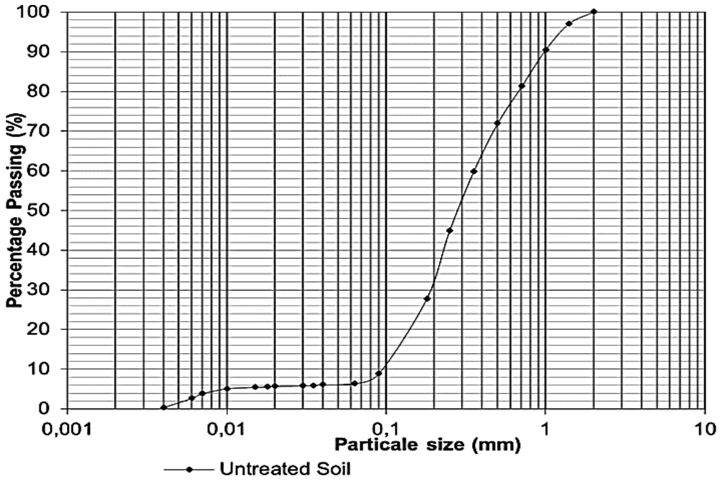


Figure1. Particle size distribution curve of kaolinite and sand

It is mixed with kaolinite or china clay, its chemical formula is $Al_2O_3.2SiO_2.2H_2O$, in proportions of 25% which is the optimum content of Kaolinite giving the maximum potential collapse [12&13]. The properties of this material are indicated in table 1.

Table 1. Properties of Kaolinite used in the study

Properties	value
Liquide limit WL [%]	60
Plastic limit W_P [%]	45
Plasticity Index IP [%]	15
Specific gravity G_s	2.60
SPECIFICATION: SiO_2 Al_2O_3 H_2O Density:	 53% 43% 0.5% max 2.5 g / cm^3

2.5.1 Treatment Materials

The materials used for the treatment in this study are:

a. Cement

Artificial Portland Cement (APC) type CEM I with strength class 42.5 complying with Algerian Standard NA433-2002 was used. The absolute density and specific surface area of the cement were 3.15 and 3200 cm2/g respectively.

b. Polyethylene Fibers

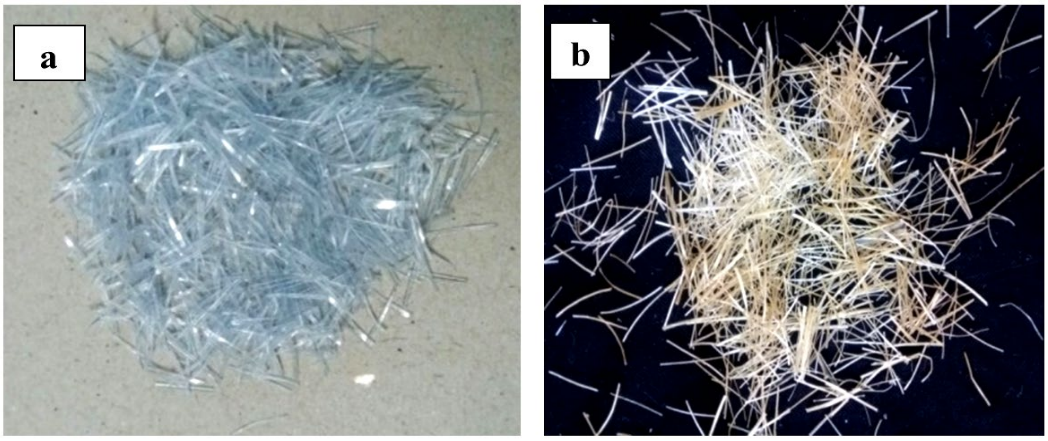


Figure2. Fibers used for reinforcement: (a) Polyethylene fibers, (b) Sisal fibers

Another processing material is Polyethylene fibers (abbreviated PE); it is a recycled material from the plastic bottle. This plastic decomposes completely in nature after hundreds of years (see Fig. 2(a)). Fibers of 5 mm long were used because they gave the minimum collapse potential against fibers of 10 mm and 25mm long.
Sisal Fibers
Sisal, shown in Fig. 2(b), is a natural fiber; the botanical name is sisalan, which produces rigid fibers used in the manufacture of various products. Sisal is biodegradable, so it is environmental friendly fiber based on the results of the previous paper [12], in this study the sisal fiber content used is 0.5% with 5 mm length.

2.2 Equipment

2.2.1 Compacting Device.

The compaction apparatus first designed by Ayadat. (1998) [3], consists of a vertical stem of 150 mm long and 12.2 mm in diameter. It is attached to a horizontal disk of 50.25 mm in diameter and 5 mm thick. A movable disc slides along the vertical stem of 136g, 16.4mm thick and a diameter of 39.2 mm.

2.3 Sample Preparation

Collapse potential increases as the initial water content decreases. In this investigation, the collapse behaviour is assessed with an initial water of 4%.
According to the tests results that investigate the impact of the Kaolinite content on the collapse potential, it was noted that the Kaolinite content of 25% has clearly given maximum collapse potential, as presented in Fig. 3. These findings confirm the observations made by Lawton [13], who stated that the maximum collapse is found with clay content between 10 % and 40 % and are in concordance with results of the investigation undertaken by Nouaouria et al [14] who have indicated that the maximum collapse potential was obtained with an optimal content of about 25% of Kaolinite.
Who have indicated that the maximum collapse potential was obtained with an optimal content of about 25% of Kaolinite.

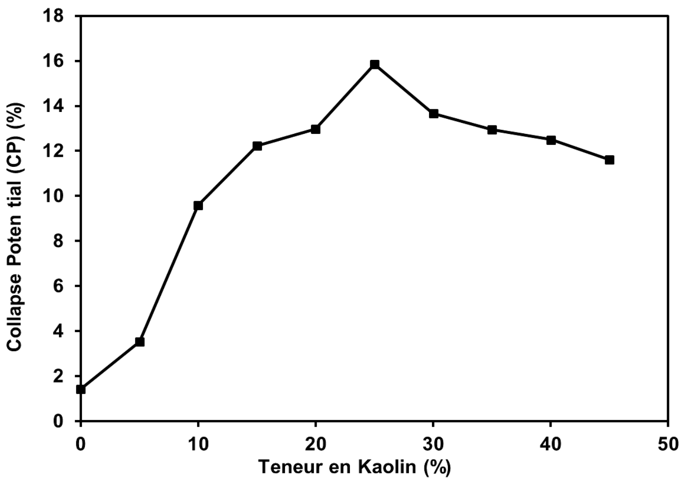


Figure 3. Effect of the kaolinite content on the collapse potential

The reconstituted soil is well mixed with 15% of polyethylene fibers or with 0.5% of sisal fibers of 5mm long both. In the first series of tests, the mixture is placed into Oedometer ring and compacted with different values of compaction energy as illustrated in table 2 in order to examine the effect of compaction. In the second set of specimens, the cement is added into three different contents, namely 1, 2 and 5% to examine the effect of cement on the collapse potential. Finally, a combination is made of cement and compaction energy to assess the influence of these two parameters on the collapse potential.
The hydro-collapse tests were carried out based on the procedure of Jennings and Knight [15]. According to Ayadat [3], the compaction is undertaken using dropping, hollow disk from a constant height of H = 150 mm. This disk slides freely along the vertical rod until it hits the circular base of the device that transmits the shock to the sample.

Direct shear tests were performed for the treated samples. The samples are subjected to different normal pressures (σ= 100, 200, 300 kPa) respectively to obtain the cohesion c and the internal friction angle φ. Two types of samples were tested unsaturated samples and saturated samples in order to investigate their behaviour before and after collapse.

3 Results and Discussions

3.1 Effect of Energy of Compaction on Collapse Potential (CP)

The effect of compaction energy on the collapse potential, of soil treated with polyethylene fibers is shown in Table 2. It is clearly seen that the CP decreases with increasing the number of blows/layer.

$$CP = [\Delta e/1+e_o] * 100 \% \quad (1)$$

Where:
Δe : Change in void ratio resulting from saturation
e_o: initial void ratio

Table 2. Compaction effect on the collapse potential of reinforced soil with fibers

Number of blows/ layer	5	10	15	20	25
Compaction Energy [KJ/dm^3]	0,065	0,13	0,195	0,261	0,326
CP (%) (Polyethylene Fibers)	9,41	8,67	7,51	6,64	5,34
CP (%)(Sisal Fibers)	12,39	11,73	10,31	9,07	/

The collapse potential is then considered to cause trouble according to Jennings and Knight Classification [15]. The decrease of collapse potential is within the limits of 70% (see Fig. 4). As far as the compaction effect on the collapse potential of sisal fibers reinforced soil is concerned, the results are shown in Fig. 4 and table 2.

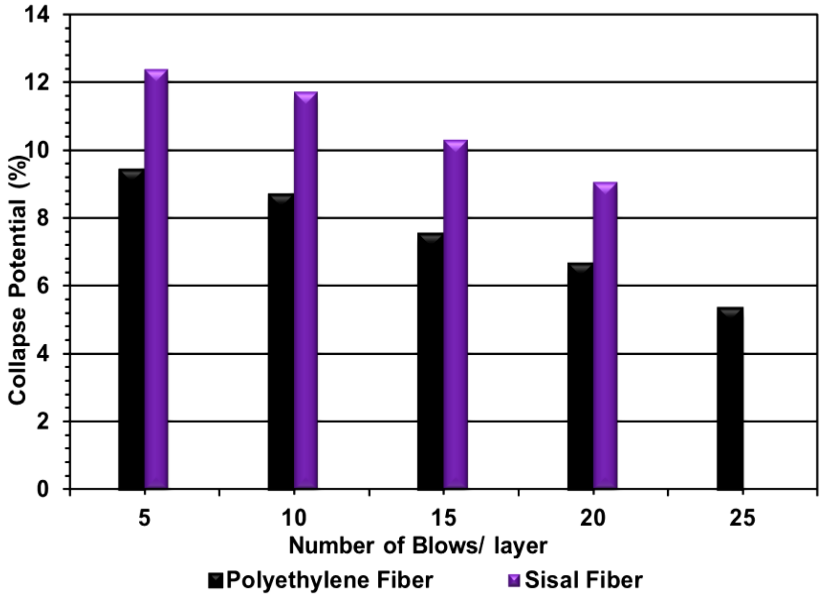


Figure 4. Compaction effect on the collapse potential of polyethylene and sisal fibers reinforced soil

The collapse potential is approximately ranging between 12.39 % and 9.07 %, it can be pointed out that the treatment of soil with sisal fibers content of 0.5% and 5mm long has decreased the collapse potential to 9.07% with a compaction energy corresponding to 20 blows/ layer. Compacted soil at energy of 5 blows/ layer still have an open structure with a relatively high void ratio, facilitating the migration of fine particles from a level to another in the soil sample. Now, compaction with 20 blows/layer makes it dense, and the destruction of intergranular bonds and movement of fine particles become relatively difficult, but the potential collapse is still high (9.07%), according to the Jennings and Knight classification [15], the collapse potential is considered to cause “disorders” to "severe troubles".

3.2 Effect of Cement Content on the Collapse Potential (CP)

To decrease the collapse potential, addition of another agent of treatment is considered, which the Artificial Portland Cement (APC).
To improve the characteristics of the reinforced soil with polyethylene fibers and sisal fibers, an amount of Artificial Portland Cement is added in three different proportions such as: 1, 2 and 5% respectively. The results are illustrated in Fig. 5 and table 3.

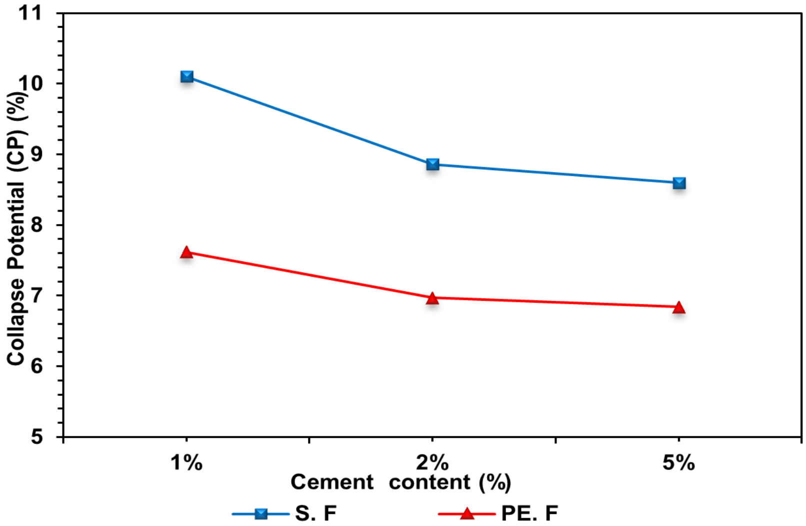


Figure5. Effect of cement content on the collapse potential

Table3. Effect of cement (APC) content on the collapse potential of reinforced soil with fiber

APC (%), 3 B/L	1	2	5
CP [%] (PE. Fiber)	7,62	6.97	6.84
CP [%] (Sisal. Fiber)	10.4	9.52	8.20

In this study, polyethylene fiber content of 15% of 5 mm long, and sisal fiber content of 0.5% of 5 mm long were used. Samples were simply compacted under 3 blows/layer, in two layers. It can be noted that the collapse potential is clearly affected by the added cement content, as illustrate in Fig. 5.

Taking into account table 3 and Fig 5, it is clearly observed that the collapse potential was decreased up to about 60%, but the goal of our study has not been reached yet.
For the soil reinforced with sisal fibers, as illustrate in Fig. 5 and Tables 3, the effect of the cement content on the collapse potential is insignificant; the decrease is about 52%. This reduction did not achieve the goal of getting a non-collapsible soil.
For sisal fibers reinforced soil, the adding of APC content of 5%, has reduced the collapse potential from 17.28% for non-treated soil to 8.20% (Table 3), the reduction is in order of about 53%. It can be seen that the difference between the 2% and 5% cement additions is small, but the study will depend on the value that gave the smallest collapse potential because this difference will be increased when the addition of cement combined with compaction.
This reduction is caused by the effect of cement which prevents destroying intergranular bonds at the time of wetting.

3.3 Effect of Combination of Three Methods of Treatment on the Collapse Potential

Table 4. Effect of blows on the collapse potential of treated soil with polyethylene fibers and APC

Number of blows/ layer	5	10	15	20	25	30	40	50	60
Compacter Energy [KJ/dm3]	0.065	0.13	0.195	0.261	0.326	0.391	0.522	0.652	0.783
CP [%]	6.42	4.37	4.04	3.65	2.88	2.73	2.14	1.96	0,9

Now, the objective of this study is to obtain a CP less than 1%. The soil treated with PE fibers and compacted under 60 blows /layer, has a reduction in CP value of about 94% (CP= 0,9%) (See table 4 and Fig. 6). For sisal fibers content of 0.5% of 5 mm long, and APC content of 5%, the number of blows is increased upto 40 blows/ layer. The obtained collapse potential of 0, 9 % and 0.69% is now considered to cause no problem according to Jennings and Knight classification[15].

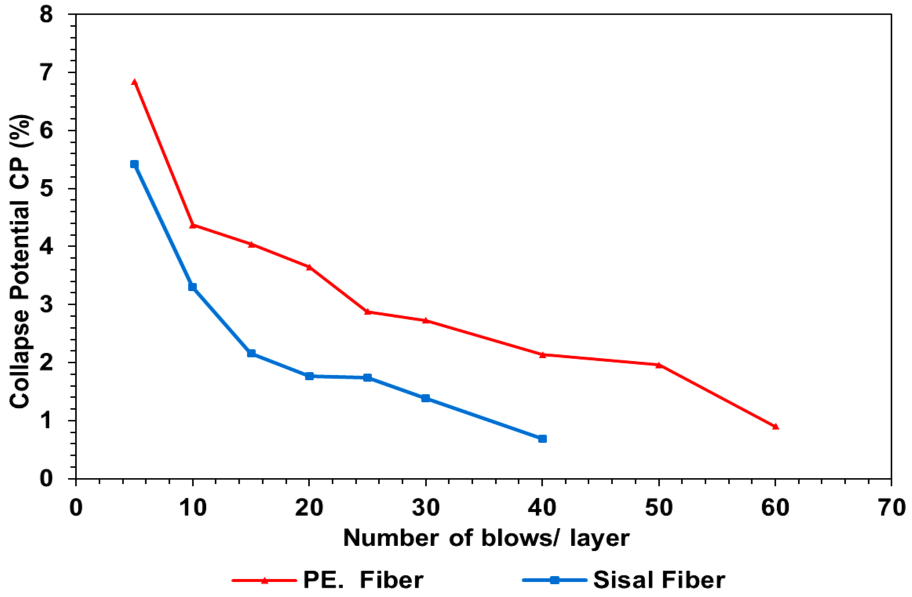


Figure 6. Effect of cement content and compaction energy on the collapse potential of soil reinforced with Polyethylene fibers and sisal fibers

Table 5. Effect of compaction energy on the collapse potential of treated soil with sisal fibers and APC

Number of blows/ layer	5	10	15	20	25	30	40
Compacter Energy[KJ/dm3]	0.065	0.13	0.195	0.261	0.326	0.391	0.522
CP [%]	5,42	3,3	2,16	1.76	1.74	1.39	0.69

The results are indicated in Table 5 and Fig. 6. This reduction is due to the effect of compaction which renders the soil dense and the cement which prevents the destruction of intergranular bonds upon wetting.

Scanning electron microscope is used to determine the morphology characteristics of the mixture of fibers reinforced clayey sand soil and Artificial Portland Cement.
The microstructure examination shows that the sample in both magnifications shows an open structure (see Fig 7).

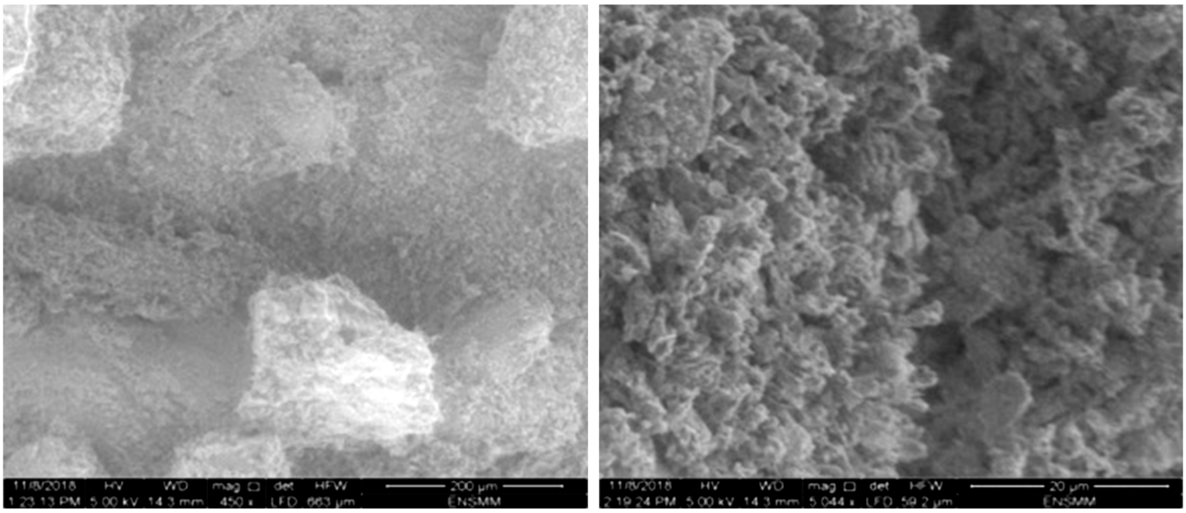
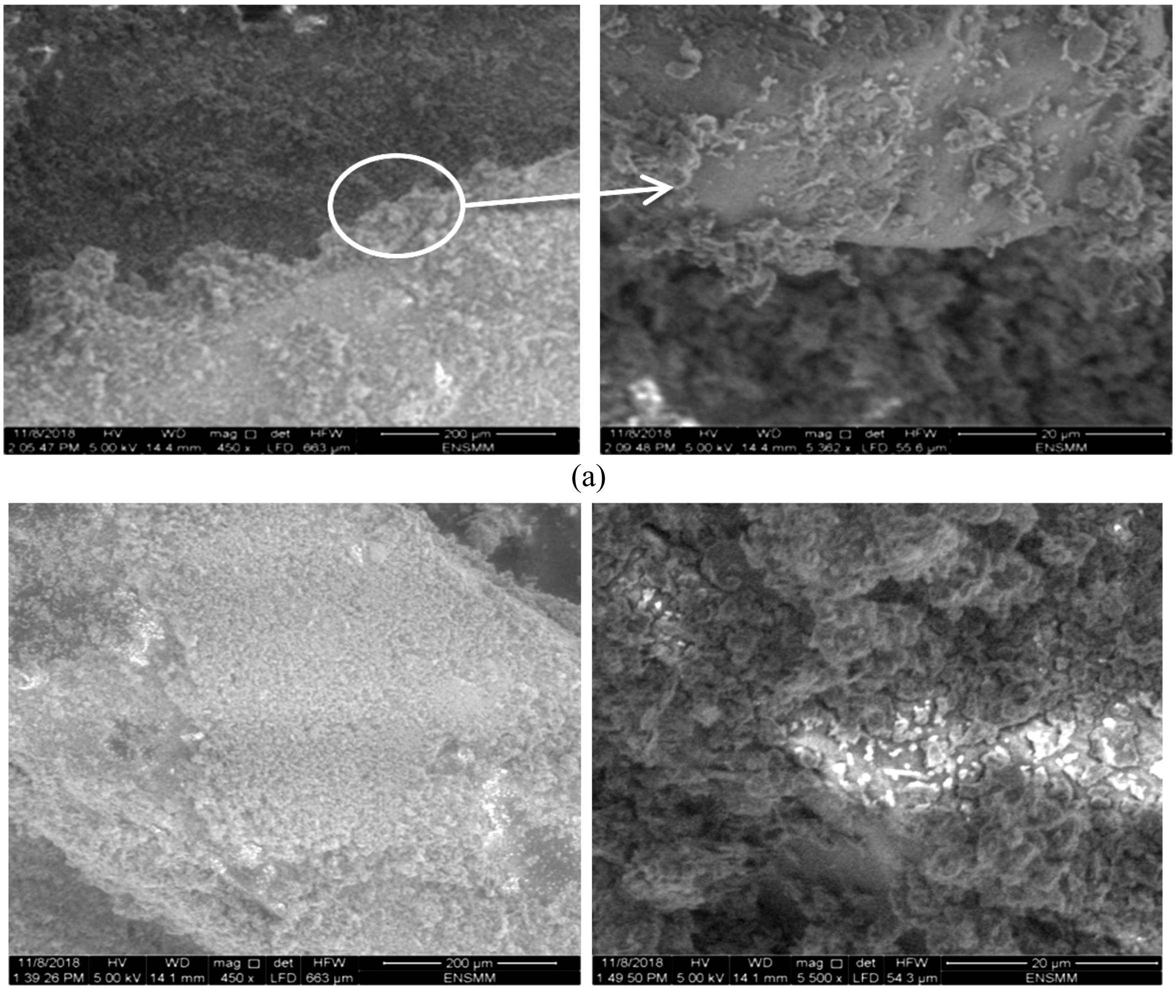


Figure7. Scanning electron micrograph of clayey sand sample showing an open structure of soil particles.

Microstructure of the clayey sand samples and Artificial Portland Cement mixture (5 %) is shown in Fig 8(b) and Fig 9(b). It is indicated that the voids of the mixtures were progressively reduced as a result of reactions between soil particles and cement aggregates.

Comparing Fig. 8(a) with Fig. 8 (b) for polyethylene fiber treatment and comparing also Fig. 9 (a) and Fig. 9(b) for sisal fiber treatment, it can be also seen that the formation of agglomeration where fine particles are bonded to larger ones, as a result of reactions between the cement and the clayey sand material. This is probably caused by a new formation of cementitious material that fills the porous areas within the mixture, leading to an increase in the density of the treated soil and a decrease in the collapse potential [16].



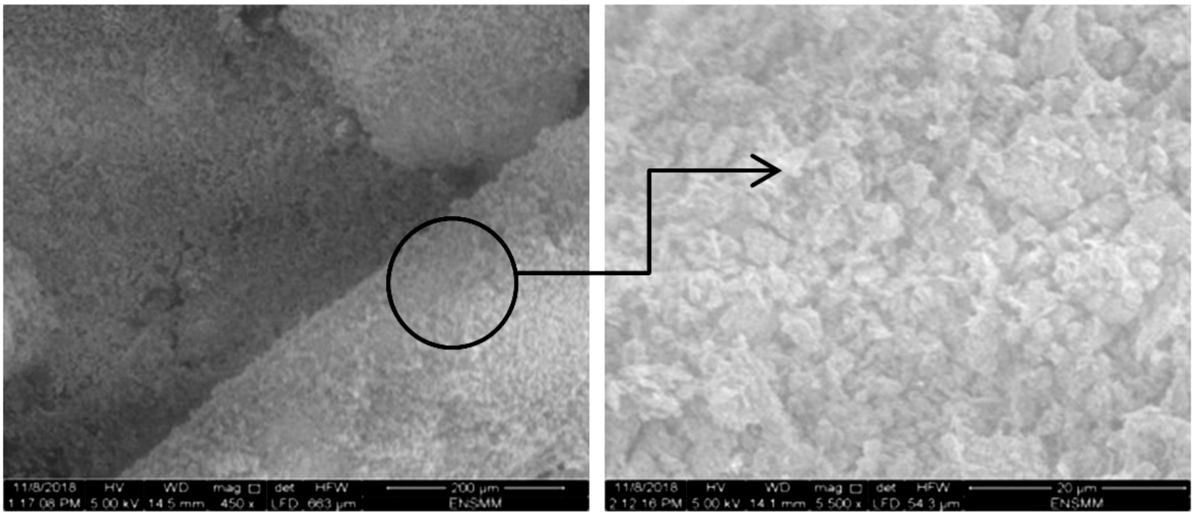
(a)

(b)

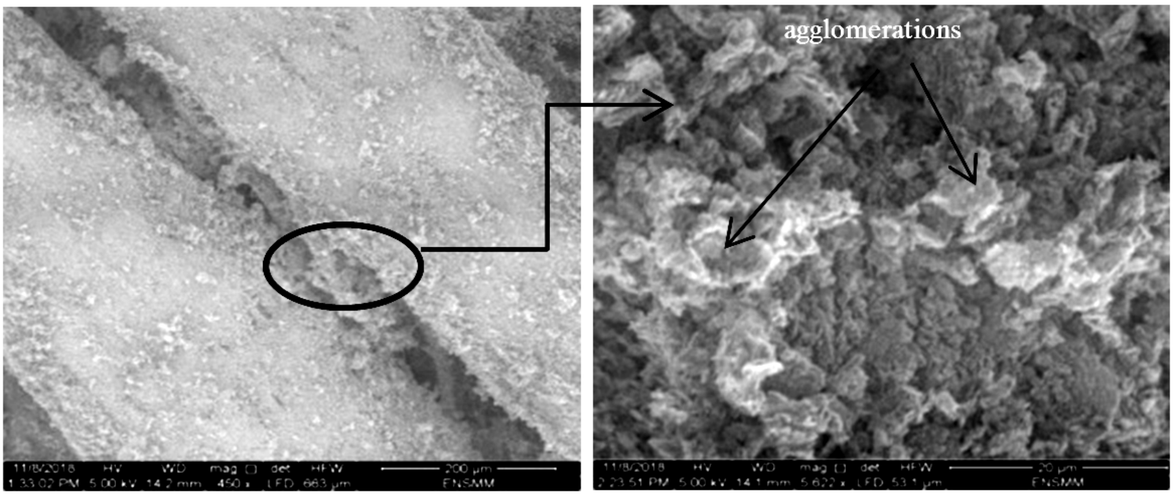
Figure8. SEM micrographs of: (a): polyethylene fibers in the matrix of soil, (b): clayey sand and Artificial Portland Cement mixture (5 %) reinforced with polyethylene fibers.

This is found to be in concordance with what has been outlined by Rashid et al. (2014) [17], who have reported that reactions of calcium ions with silica from sand and alumina from clay, resulted in the formation of pozzolanic products and produced a new soil matrix that is more dense and stable.

According to Fig. 9(a) and Fig. 9(b), some of the small particles adhere to fiber. This phenomenon may be responsible for increasing the stiffness and strength of the mixture samples. Therefore, the 5% cement content is able to effectively establish the stable cementation and the bonds between the different clay particles in comparison with the low cement contents used, where they may be responsible for the lack of bonds. Then, it can be mentioned to propose 5% as an optimal value for the decrease of collapse potential (CP).



(a)



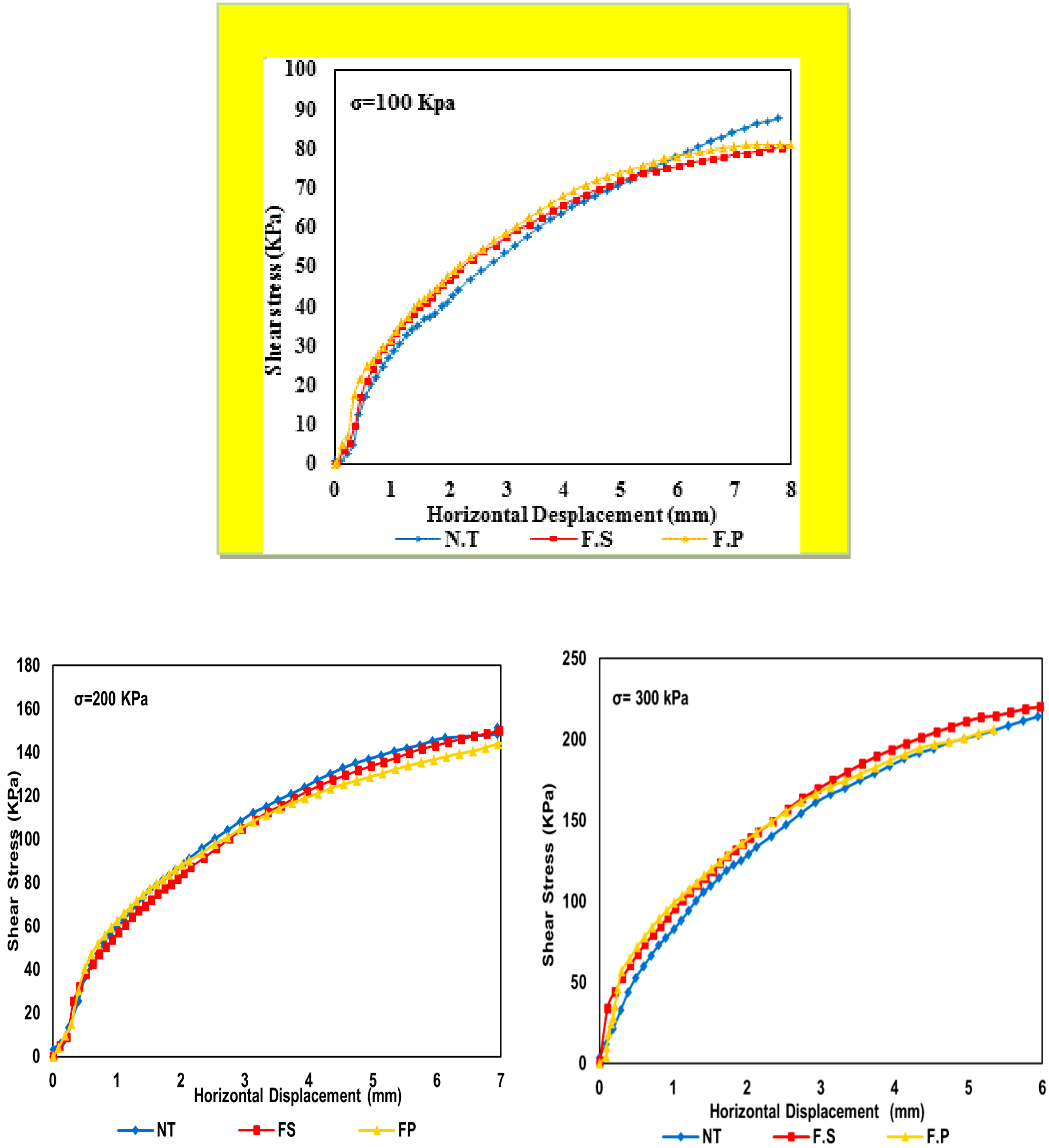
(b)

Figure9. SEM micrographs of: (a) Sisal fibers in the matrix of soil, (b) Clayey sand and Artificial Portland Cement mixture (5 %) reinforced with sisal fibers.

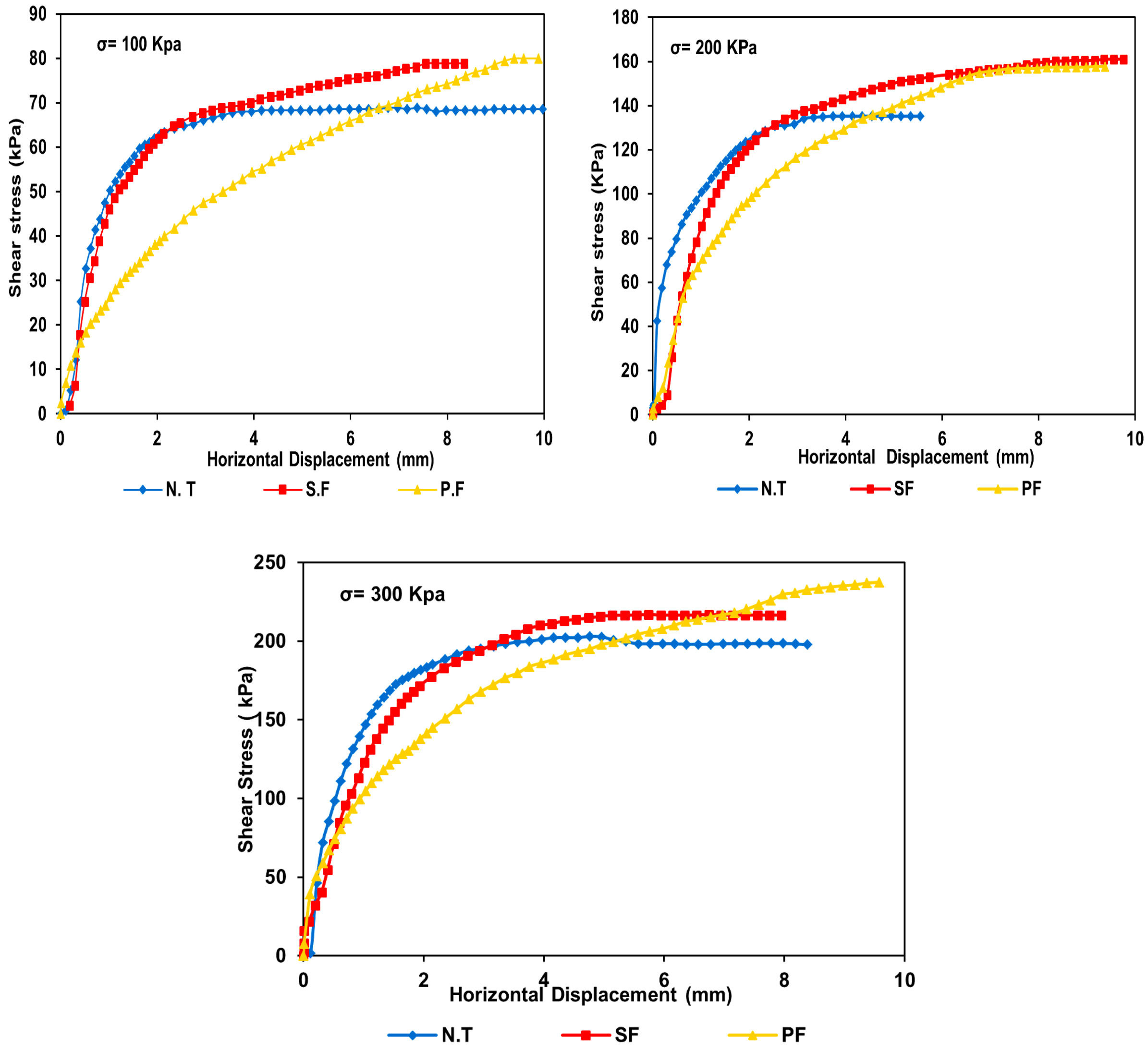
3.4 Shear Strength test

From the direct shear test it was found that there was not a large change in shear stress for untreated soil and treated soil with sisal fibers and polyethylene ones; for unsaturated soil, as shown in Fig. 10(a). After saturation, there was a decrease in shear stress for soil treated with polyethylene fibers and sisal fibers. It is noticed that the decrease of shear stress for soil treated with polyethylene fibers is larger than that in soil treated by sisal fibers (Fig.10 (b)).
The results of the direct shear tests are regroups in Fig.10. It can be seen that all the samples in the unsaturated case have almost the same behaviour with regard to the shear stress, but this stress is slightly higher in treated soils than in untreated soils. Tests on wetted samples show that water reduces shear stress, but this decrease is higher in cement-treated soils and polyethylene fibers. Treated soil with cement and sisal fiber produces the greatest

shear stress, so sisal fibers and cement increase the shear strength of the samples. The soil treated with polyethylene fibers and the cement gives the lowest value of shear strength, this is due to the flexibility of the fibers and their placement parallel to the shear plane.



10(a). Before wetting



10(b). After wetting

Figure10. Shear strength of cemented soil treated with polyethylene and sisal fibers, (a). Before wetting, (b). After wetting

Table 6. Cohesion C and internal friction angle φ values for all shear testes.

	Non treated soil	Polyethylene Fibers	Sisal Fibers
C[KPa] Before wetting	16,76	3,23	16,76
φ [°]Before wetting	34,67	31,94	37, 87
C [KPa] After wetting	4,72	0,92	11,48
φ [°] After wetting	32,86	38,22	35,41

From Table 6 and Fig. 11, it is noted that the compacted soil and treated with cement and polyethylene fibers has the same behavior as the untreated soil in the unsaturated case and after wetting there is a reduction in cohesion of about 94% and a small increase of 20% for the internal friction angle. In case of the compacted soil treated with, cement and sisal fiber, after wetting, there is an increase of about 72% in cohesion and a reduction of 6% in the internal friction angle. One of the most important factors affecting the strength of soil is the Bonding between particles [18], it can be said, that in wetting case of samples, the aggregates are more attached to the sisal fibers, which increase the value of the cohesion. In the case of polyethylene fibers, after wetting, there is a reduction of bond between the particles and fibers because of the smooth surface of this type of fiber, but this latter does not allow the movement of fine grains from one level to another. This explains the effectiveness of this type of fiber on the collapse and no influence on the cohesion.

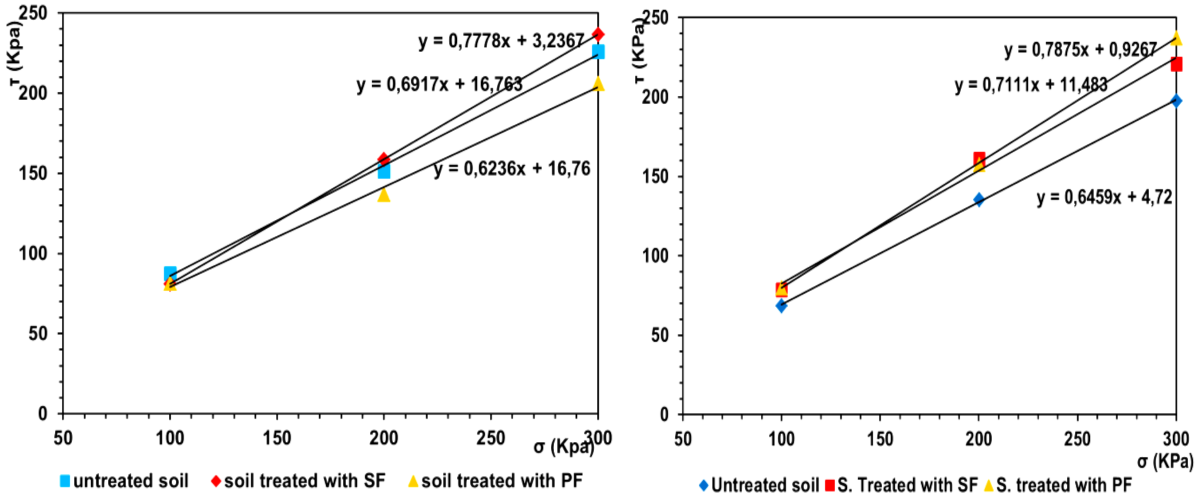


Figure11. Coulomb lines for treated samples

4 Conclusions

To preserve the environment from pollution resulted in the use of water plastic bottles thrown in nature, the polyethylene fibers are in general used rather than sisal fibers because these latter does not harm the environment. Reinforcing a collapsible soil with polyethylene fibers reduced the collapse potential up to 44%. The goal of this investigation is to improve the behaviour of a collapsible soil with the inclusion of sisal fibers and polyethylene fibers and treating this reinforced soil with the addition of cement and compaction technique. The next conclusions can be drawn:

- The combination of the fiber reinforcement of the collapsible soil, and the compaction technique gives interesting results. The collapse potential was decreased up to about 70% for PE fibers and 47.5 % for sisal fibers, but our objective has not yet attained because the collapse potential was still relatively high as indicated in Table2.
- To reduce collapse potential, the given cement content and PE fibers or sisal fibers were mixed with soil. Adding Artificial Portland Cement (APC) mixed with PE fibers reduced CP up to about 60%, and decreased the CP up to about 52% for sisal fibers.

- To have a non-collapsible soil, it is necessary to reduce the CP to a reasonable value. For this instance, the cement and the technique of compaction are combined with the reinforcement by PE fibers. Adding Artificial Portland Cement (APC) with compaction energy of 60 blows /layer decreased the CP to about 95% for PE fibers (CP=0,9%).
- In order to further reduce the collapse potential, the compaction energy applied to the samples is increased, which are prepared by the mixture of clayey sand with sisal fibers and cement. In this case, the value of CP decreased to 0, 69%. As a result, it can be concluded that there is no collapse problem according to the Jennings and Knight classification [15].
- These findings confirm the effectiveness of the compaction, cement, and fibers of sisal or polyethylene on the intrinsic parameters. Furthermore, the cohesion of collapsible soil is much more sensitive to wetting than its friction angle and it is thought to be responsible for the shear strength increase or decrease of the collapsible soil after wetting.

Acknowledgements

The authors wish to thank the LGCH laboratory of the University 8 May 1945 of Guelma where the experimental work was performed.

References

[1] M. Maher, Y. Ho, and H. Pincus, "Behavior of Fiber-Reinforced Cemented Sand Under Static and Cyclic Loads," *Geotech. Test. J.*, vol. 16, no. 3, p. 330, 1993, doi: 10.1520/gtj10054j.

[2] N. C. Consoli, P. D. M. Prietto, and L. A. Ulbrich, "Influence of fiber and cement addition on behavior of sandy soil," *J. Geotech. Geoenvironmental Eng.*, vol. 124, no. 12, pp. 1211–1214, 1998.

[3] T. Ayadat, M. Dahili, and K. M. H. Ahmed, "Traitement d'un sol effondrable par un liant hydrocarboné (bitume)," *Rev. française géotechnique*, no. 85, pp. 57–64, 1998.

[4] T. Yetimoglu and O. Salbas, "A study on shear strength of sands reinforced with randomly distributed discrete fibers," *Geotext. Geomembranes*, vol. 21, no. 2, pp. 103–110, 2003, doi: 10.1016/S0266-1144(03)00003-7.

[5] M. S. Chauhan, S. Mittal, and B. Mohanty, "Performance evaluation of silty sand subgrade reinforced with fly ash and fibre," *Geotext. Geomembranes*, vol. 26, no. 5, pp. 429–435, 2008, doi: 10.1016/j.geotexmem.2008.02.001.

[6] F. Ahmad, F. Bateni, and M. Azmi, "Performance evaluation of silty sand reinforced with fibres," *Geotext. Geomembranes*, vol. 28, no. 1, pp. 93–99, 2010.

[7] A. Al Adili, R. Azzam, G. Spagnoli, and J. Schrader, "Strength of soil reinforced with fiber materials (Papyrus)," *Soil Mech. Found. Eng.*, vol. 48, no. 6, pp. 241–247, 2012, doi: 10.1007/s11204-012-9154-z.

[8] A. Chegenizadeh and P. H. Nikraz, "Study on Sand and paper reinforcement," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 6, pp. 199–202, 2012.

[9] N. Cristelo, S. Glendinning, T. Miranda, D. Oliveira, and R. Silva, "Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction," *Constr. Build. Mater.*, vol. 36, pp. 727–735, 2012.

[10] M. Zhang, H. Guo, T. El-Korchi, G. Zhang, and M. Tao, "Experimental feasibility study of geopolymer as the next-generation soil stabilizer," *Constr. Build. Mater.*, vol. 47, pp. 1468–1478, 2013, doi: 10.1016/j.conbuildmat.2013.06.017.

[11] E. Botero, A. Ossa, G. Sherwell, and E. Ovando-Shelley, "Stress-strain behavior of a silty soil reinforced with polyethylene terephthalate (PET)," *Geotext. Geomembranes*, vol. 43, no. 4, pp. 363–369, 2015, doi: 10.1016/j.geotexmem.2015.04.003.

[12] S. Adjabi, M. S. Nouaouria, and C. Betehi, "Effect of reinforcement fibers on the collapse potential of clayey sands," in *MATEC Web of Conferences*, 2018, vol. 149, doi: 10.1051/matecconf/201714901034.

[13] E. C. Lawton, R. J. Fragaszy, and M. D. Hetherington, "Review of wetting-induced collapse in compacted soil," *J. Geotech. Eng.*, vol. 118, no. 9, pp. 1376–1394, 1992.

[14] M. S. NOVAOURIA, O. HARIRECHE, and A. ROUAIGUIA, "Comportement de l'affaissement de

loess," *Ann. du bâtiment des Trav. publics*, no. 3, pp. 37–41, 2002.
[15] J. E. Jennings, "A GUIDE TO CONSTRUCTION ON OR WITH MATERIALS EXHIBITING ADDITONAL SETTLEMENT DUE TO COLLAPSE" OF GRAIN STRUCTURE.," 1975.
[16] M. S. Ouf, "Effect of using pozzolanic materials on the properties of Egyptian soils," *Life Sci. J.*, vol. 9, no. 1, pp. 554–560, 2012.
[17] A. S. A. Rashid, R. Kalatehjari, N. M. Noor, H. Yaacob, H. Moayedi, and L. K. Sing, "Relationship between liquidity index and stabilized strength of local subgrade materials in a tropical area," *Measurement*, vol. 55, pp. 231–237, 2014.
[18] B. B. K. Huat, A. A. Aziz, F. H. Ali, and N. A. Azmi, "Effect of wetting on collapsibility and shear strength of tropical residual soils," *Electron. J. Geotech. Eng.*, vol. 13, pp. 1–44, 2008.