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Use of Eco-Friendly Materials in the Stabilization of Expansive Soils

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Abstract: Volume change of expansive soils is a challenging issue, which affects various engineering structures all over the world. Consequently, we need environmentally-friendly and cost-effective soil stabilizers to address the challenges related to expansive soils. The utilization of natural fibers allows for the reduction in environmental impact since they are renewable and biodegradable raw materials. Moreover, the current article presents an experimental approach to study the effect of natural fibers on the mechanical behavior of expansive soils. Various experimental tests—such as Atterberg limits, standard compaction, direct shear, swelling potential, and swelling pressure—were conducted on control and treated soil samples using different percentages of fibers. The results of measurements of the physico-mechanical properties after reinforcement of the soil with 1%, 5%, and 10% of natural fibers indicate that the mechanical behavior of expansive soils is greatly influenced by the addition of natural fibers. To conclude, 86% reduction was observed in the swelling coefficient of treated soil. Future research can be done to check the durability of the current practice in detail.

Keywords: expansive soil; eco-friendly material; reinforcement; mechanical properties; diss fibers

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1. Introduction

The performance, economy, and safety of any building are significantly influenced by the behavior of the soils and rocks at the construction site and by the interactions of the earth materials both during and after construction. The main issue with expansive soils is the significant deformations of the soil in and around buildings brought on by the soil's swelling and shrinking during wetting and drying. These excessive movements can also damage public structures and services. The problems can be large or small and have a significant negative impact on the structure's performance in terms of time and cost [1]. Knowledge and understanding of the geology of earth materials are needed while dealing with expansive soils [2]. Much research has been conducted to investigate the influence of cyclic wetting and drying on the swelling behavior of expansive natural soils [3].

Thanks to innovative studies and techniques, it is now possible to build on all types of soils [4,5]. Current technological developments in soil reinforcement are moving towards more economical and more environmentally-friendly technical solutions [6,7].

Moreover, the possibility of using waste and ecological materials was studied. The use of bottom ash produced by municipal solid waste incineration in the construction field has been proposed. Improvements in the strengths and modulus of elasticity of the final product with the addition of this waste material has been found [8].

Various methods and equipment have been used to study the influence of the effectiveness of a solution or a product on the stabilization of clay soil. The use of building materials had been commonly applied to soil stabilization [9–11]. However, the use of polymeric materials as soil stabilizers has been among the best materials for these applications [12–14].

Reinforcing soils with plant fibers is a major step forward in the transition to the use of eco-materials in sustainable construction [15,16]. Previously, Diss fibers were used to cover the roofs of houses and in particular as reinforcements in mixtures during the manufacture of the walls of old earthen dwellings because of their good mechanical, hydrous, and hygrothermal qualities [17–19]. Recently, this material has been involved in the development of soil reinforcement materials in geotechnics [20]. The use of natural fibers, either to manufacture eco-geotextiles or mixed with the soil to form a composite material, has recently met with some success in the field of construction (stability of soils and embankments, control of erosion, infiltration, etc.) as a substitute for synthetic reinforcing fibers used in particular in geotextiles. Moreover, studies have been carried out to investigate the effect of plant fibers on the compaction properties, and found a reduction in the maximum dry density and an increase in the optimum moisture content with the addition of fibers for percentages of 0.5 and 2% in the soil matrix [21].

Moreover, the mechanical behavior of a very plastic clay can be reinforced with sisal fibers by varying their length (1.5–3 cm in length) and their percentage (0.25–1%). The results showed that optimum water content increases relative to untreated soil, and maximum dry density decreases with increasing length and fiber content [22]. Similarly, the effect of plant fibers on mechanical shear properties has been studied by [23]. They reinforced sandy soils with synthetic and plant fibers (reeds and palm leaves), varying several parameters such as the percentage and the orientation of the fibers. The results of their tests showed that there is improved strength and increased axial strain at break.

The physical and mechanical properties of plant fibers have been addressed by many researchers [24–26]. In their study on plant fibers, these researchers found that the tensile strength and modulus of elasticity of plant fibers are proportional to their cellulose content. Thus, they noticed that the resistance depends on the shape of the filament spirals. They find that the spiral wide-angle fibers have high deformability but a low resistance, while the low-angle spiral fibers have low deformability and a high resistance.

Prajisha et al. [25] Studied the strength and durability of Kuttanad soil stabilized with lime and reinforced with banana fibers. This study was conducted on fibers immersed in two different media, namely, (i) in clean and soft water (pH = 7.0) and (ii) a lime solution [Ca(OH)2]. The study intended to determine the changes in the chemical composition of the fiber after a specified period. They have found that the untreated fibers are more severely attacked by the alkaline medium and water when they are subjected to alternating exposure of the wetting and drying type. Khelifi et al. [26] studied the biodegradation in soil of *Stipa tenacissima* (Alfa) leaves. Nonlinear mechanical tests were performed at various stages of biodegradation. The results showed that tensile strength, loading and unloading, Young's moduli, and dissipation energy decreased with burial time, while plasticity increased. This loss of strength was correlated with rapid cellulose degradation.

According to a review oof the literature on the stabilization of expansive soils by natural materials, this study is carried out by mixing different ratios of natural fibers (1%, 5%, and 10% of the total weight of the sample) with expansive soil. The basis for selecting the dosages of various modifiers is based on previous studies, which added lower doses of additives directly to the base soil.

The current study has been conducted to utilize the additives with higher amounts as compared to the previous studies related to the current practice. Additionally, the experimental work examines the effect of natural fibers on the geotechnical properties of expansive soils. Finally, environmental and economic aspects, which are more important for every engineering project, were also considered during the current practice.

2. Materials and Methods

2.1. Materials

2.1.1. Bentonite

Bentonite's swelling and adhesive properties are what make it an attractive material for a wide range of applications. It is made by extraction and, even with a moisture content of 30%, it remains solid. Once extracted, it is usually crushed and processed before being used [27,28].

The bentonite used in this study is from a quarry in the Maghnia region (Western Algeria). It is extracted from the Hammam Boughrara deposit (Tlemcen, Western Algeria). The properties of bentonite are shown in Table 1 [14].

Table 1. Physic-Mechanical and Chemical Properties of Bentonite used [14].

Property	Value
Humidity (%)	<12
Granulometry of fine elements (%)	95
Water content (%)	9
Swelling rate (mL/2 g)	25–27
Liquid limit (%)	181
Plastic limit (%)	30
Plasticity Index (%)	151
Impact Resistance (kg cm/cm^3)	40
MgO_3 (%)	1
Na_2O (%)	4
CaO (%)	2
Fe_2O_3 (%)	3
Al_2O_3 (%)	19
SiO_2 (%)	58
Other minerals (%)	13
pH	5

2.1.2. Natural Soil

The soil used in this research was collected from the municipality of Elhadeik, in Skikda region (North-Eastern Algeria). Ten samples were obtained at a depth of 2.5–3 m, and transported to the laboratory in plastic bags to maintain the moisture content.

The soil was initially characterized by the various geotechnical tests at the LHC (SKIKDA unit) housing and construction laboratory. In order to activate and increase the swelling of the study soil, we reconstituted a new material with a higher swelling potential, by mixing 80% natural soil with 20% bentonite, which is commercially available and supplied by the Algerian company BENTAL. According to standard ASTM D4318-17e1, initial water content was measured and valued between 10% and 20%. The liquid limit (LL) of the mixture (SB) was 68%, and the plasticity index (PI) was 34%. The various index properties of the (SB) considered in this study are shown in Table 2.

According to the GTR, 2000 (Guide to Road Groundwork, Embankment and Layering, LCPC, SETRA, Boxborough, MA, USA, 2000) [14], and from the results found, it can be said that the studied mixture is a very plastic clay (class A3).

Table 2. Engineering properties of the soil–bentonite mixture.

Property	Value	Standard
Liquid limit (%) Plastic limit (%) Plasticity index (%) Consistency index	68 34 34 1	(ASTM D4318-17e1) [29]
Methylene Blue value	7.33	(ASTM C837-09) [30]
Maximum dry density (t/m^3) Optimal water content (%)	1.6 19.95	(ASTM D1557-12e1) [31]
Swelling index (%) Compressibility index (%) Compressibility pressure (bars)	12.11 24.65 1.02	(ASTM-D2435) [32]
Immediate Bearing Index (%)	3.3	(ASTM D1883-16) [33]
Friction angle (°) Cohesion (bars)	10.61 0.99	(ASTM D3080-98) [34]
Grain size distribution Clay (%) Silt (%) Sand (%)	 70 23 7	(ASTM D7928-16e1) [35]

2.1.3. Natural Fibers

The Diss (Ampelodesmos mauritanicus, Poaceae) of the Gramineae family is an herbaceous plant with a height not exceeding one meter (Figure 1). These fibers are extremely robust and rough. It is widespread in the wild in the Mediterranean basin. The Diss is abundantly available throughout the year, which makes it an important biomass [17–19].

Figure 1. Plant of Diss in Skikda (North-East Algeria).

Plant fibers have cellulose fibrils dispersed in a matrix of lignin and hemicelluloses. They also contain small amounts of free carbohydrates, proteins, extracts, and inorganic substances. For plant fibers, cellulose is the basic structural component and the most abundant natural polymer on earth. Hemicelluloses are polysaccharide polymers made up of polymer chains shorter than cellulose. Lignin is an amorphous polymer of phenol-propane units. It can be a trusted agent that gives rigidity to plant cell walls.

In this study, the Diss fibers used were picked from the Skikda region, whose characteristics are detailed in Table 3.

Table 3. Characteristics of Diss fibers.

Characteristics	Details	Diss Fiber
Physical	Absolute density (kg/m^3) (ASTM D5444-15) [36]	950
	Diameter (mm)	0.85
	Cross-sectional area (mm^2)	0.57
Chemicals (% by mass) [37]	Cellulose	45.2
	Lignin	15.6
	Hemicelluloses/pectin	26
	Extraction & others	13.2
Mechanical^2(ASTM D3822-07) [38]	Elastic modulus (MPa)	5477.42
	Standard deviation	1734.87
	Tensile strength (MPa)	78
	Standard deviation	8
	Fracture strain (%)	2
	Standard deviation	0.22
	Fracture elongation (mm)	1.12
	Standard deviation	0.11
Water absorption (%)	5 min	72
	24 h	155

The cross-section of the fiber was measured using a CCD camera mounted on a LEICA MZ16 trinocular loupe. This device makes it possible to take enlarged photos and allows length measurement with an accuracy of 1 µm (Figure 2). Microscopic observations were carried out using a scanning electron microscope (SEM) type JEOL JSM-6460LV to characterize the constitution and the shape of the cell walls within the fibers of the Diss (Figure 3). A confocal observation of the roughness of Diss fiber surfaces was carried out. The confocal images were obtained with a Leica DCM 3D device, in order to determine the roughness of the surface of the plant fibers used (Figure 4).

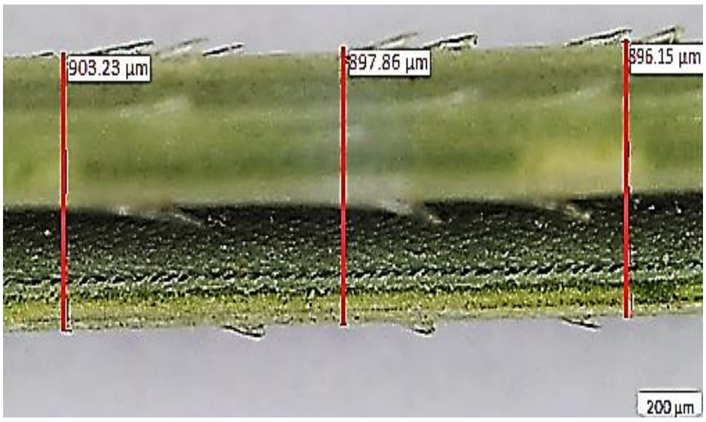
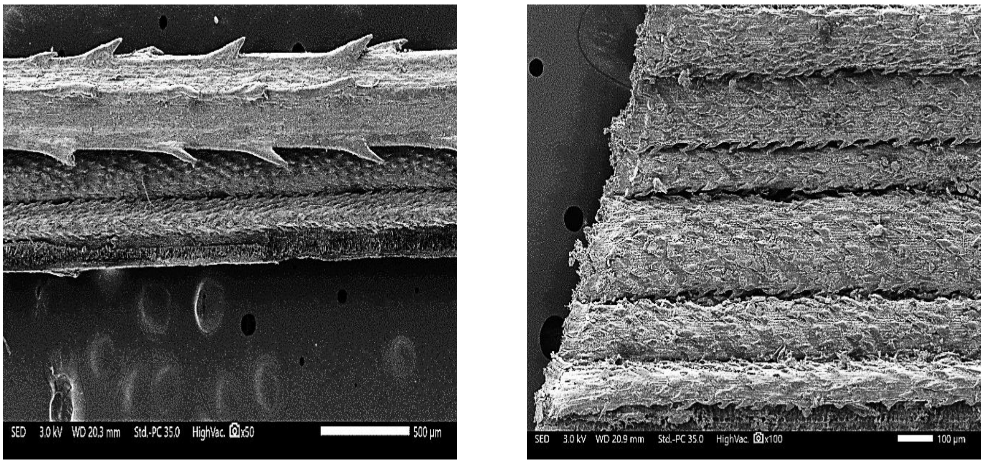


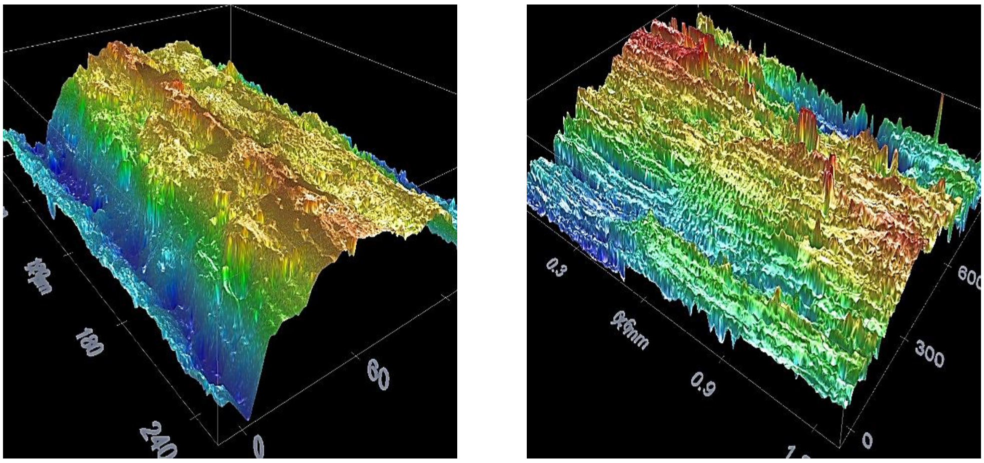
Figure 2. Observation by optical microscope: diameter measurement of the Diss fibers.

As shown in Figures 2 and 3, the sections of the fibers do not have a regular geometric shape. Diss leaves come in a coiled form and take on a shape that approximates an ellipse with a spiked surface. The outer surface of the Diss fiber is spiny. In addition, the inner surface is covered with spines, which are evenly distributed and have visible ridges covered with fine tangled needles. Figure 5 demonstrates that the Diss fibers have rough surfaces showing the different reliefs observed to clearly appear in the spins, which allows them to have a better anchoring in a soil matrix.



(**a**) (**b**)

Figure 3. Observation by scanning electron microscope: longitudinal section, (**a**) exterior and (**b**) interior of the Diss fiber.



(**a**) (**b**)

Figure 4. Confocal observation: longitudinal section, (**a**) exterior and (**b**) interior of the Diss fiber.

(**a**) (**b**)

Figure 5. Preparation of soil–bentonite mixture: (**a**) soil–bentonite, (**b**) bentonite.

2.2. Methods

The following method was adopted for the mixing and sample preparation. Soil was dried in an oven at 105 °C for 24 h, followed by manual grinding of the soil to eliminate large grains. Sieving was done with a sieve to get a mesh diameter equal to 1 mm. Moreover, to obtain a fine, dry, and homogeneous soil, soil was mixed with 20% bentonite as shown in Figure 5 (dosage was in grams of dry soil mass). After that, the Diss sheets were washed with plenty of tap water to remove dust and dried in open air simultaneously. A Retsch-type parallel-cut knife mill was used for grinding purposes as shown in Figures 6 and 7. Subsequently, the dry soil was mix with the different rates of natural fibers with various percentages of 1%, 5%, and 10%.

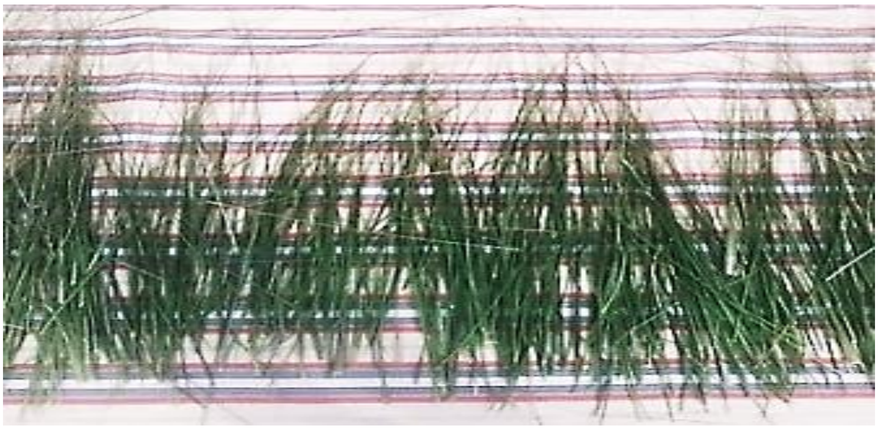


Figure 6. Diss fibers before grinding.

(**a**)

(**b**)

Figure 7. Preparation and visualization of Diss fibers used: (**a**) Diss fibers after grinding and (**b**) grinder.

In order to determine the mechanical behavior of the soil in interaction with the Diss fibers, various physical and mechanical tests are carried out (Table 4).

Table 4. Geotechnical Tests and Standards.

Test	Standard	Purpose of the Test
Atterberg limits	ASTM D4318 [29]	Determine Atterberg limits of soil: liquid limit, plastic limit, plasticity index and consistency index.
Proctor standard compaction test	ASTM D1557 [31]	Determine the maximum dry density and the optimum moisture content.
Direct shear strength	ASTM D 3080 [34]	Determine the resistance parameters using the Casagrande box.
Compressibility test	ASTM D 3080 [32]	Determines the compressibility parameters of fine soils.

3. Results and Discussion

3.1. Effect of Diss Fibers on Atterberg Limits

Atterberg limits, plasticity limits, or consistency limits are used to characterize the behavior of fine soils, although their behavior varies over time. The Atterberg limits and the plasticity index of soil vary not only with the importance of its clay fraction but also with the nature of the clay minerals and the adsorbed cations. The results of the Diss fiber effect on the Atterberg limits are shown in Figure 8.

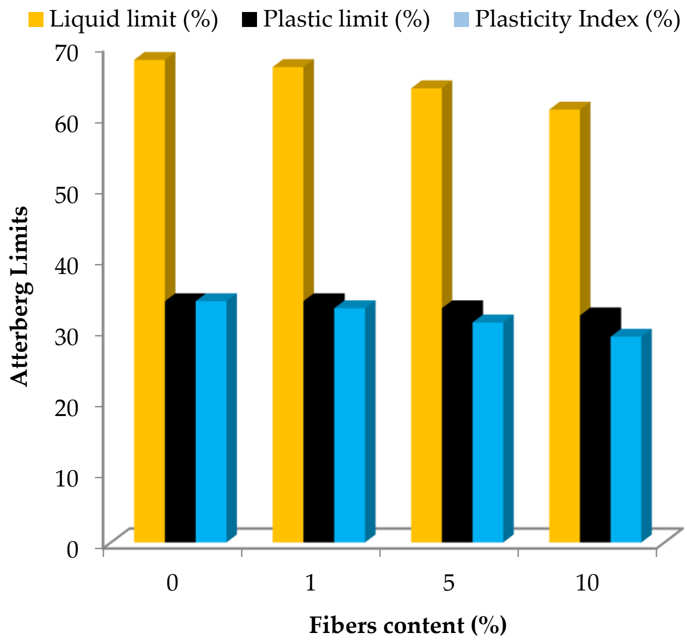


Figure 8. Variation of the Atterberg limits according to the Diss fibers' content.

The study of the effect of Diss fibers on the plasticity properties of clay soils shows that the quantity of the additions plays an important role in the characterization of the final product—in our case, where the fibers are crushed and cut in a crusher whose fiber length is between 0.5–2 cm. The results show that with the increase in the percentage of fibers, the plasticity characteristics are reduced. A drop in the plasticity index of 34% for the soil without fibers is observed at the value of 29% at 10% Diss fibers. This may be explained by the effect of absorption, fiber surface effect, and particle rearrangements with fibers [39]. These results have been confirmed in the specialized literature [7,13,14]; in these studies, the authors used several types of polymers with several concentrations, indicating that there is a reduction in the properties of plasticity. This is explained by the fact that with the addition of polymer to the soil, the particles agglomerate and become larger, and they therefore offer less surface and take up weaker layers of water, resulting in the reduction in the soil plasticity.

3.2. Effect of Diss Fibers on Compaction Properties

In order to see the influence of the different percentages of Diss fibers' additions on the soil compaction parameters, a series of normal Proctor compaction tests were carried out. The results obtained are shown in Figure 9.

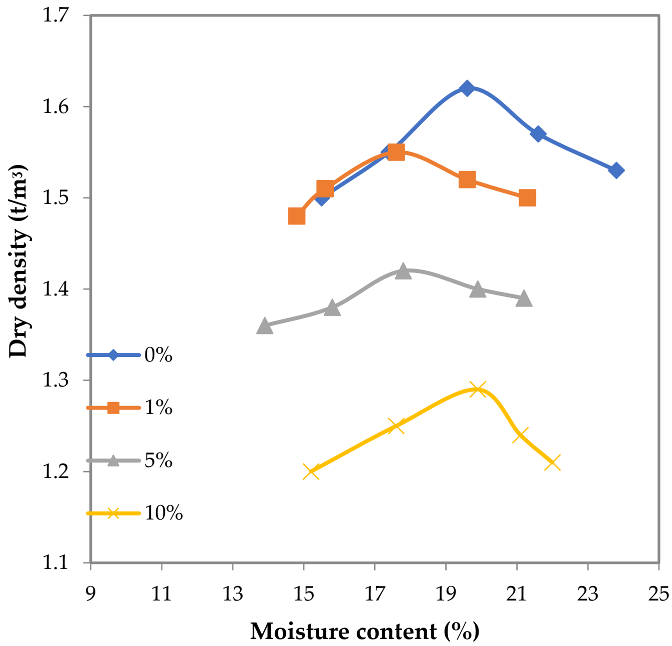


Figure 9. Effect of different Diss fibers' content on compaction characteristics.

Adding Diss fibers to the soil decreases the maximum dry density value. It is noted that these values go from 1.60 g/cm^3 for the soil alone to the value of 1.28 g/cm^3 for the soil mixed with 10% of Diss fibers. Thus, for the optimum water content, initially at 1% fiber, a decrease is observed, and then it increases according to the percentage of fiber added (Figure 10). Authors in [20,21] noticed the same result, which is most likely due to the higher water absorption capacity of fibers (fiber hydrophilicity) compared to soil. In addition, the decrease in the dry density noticed is explained by the low specific weight of the fibers compared to the grains of the soil, as the fibers prevent the particles of soil from approaching each other.

3.3. Effect of Diss Fibers on Mechanical Shear Characteristics

The study of the shear strength of soil is necessary to know the mechanical behavior of soils. The shear strength depends on the type of soil encountered, whether it is cohesive or not, and whether the material is coarse or fine. In solving stability problems in geotechnics, it is necessary to know the shear strength parameters of the soil. Thus, the angle of internal friction and cohesion are involved in the stability calculations of dams, embankments, and dykes. Indeed, small variations in the shear characteristics can induce significantly different sizing of geotechnical structures. The most widely used experimental apparatus in soil mechanics to assess shear strength properties is the rectilinear shear test. Additionally, in geotechnical studies and designs, two of the most important and fundamental factors are cohesion (C) and internal friction angle. These parameters are usually determined using the direct shear test. The variation of shear strength with the Diss fibers is shown in Figure 11.

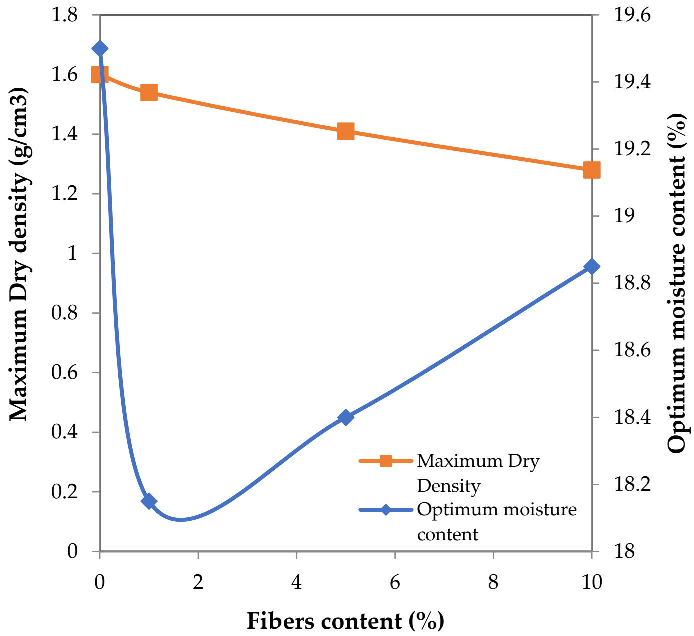


Figure 10. Variation of compaction characteristics as a function of the Diss fibers percentage.

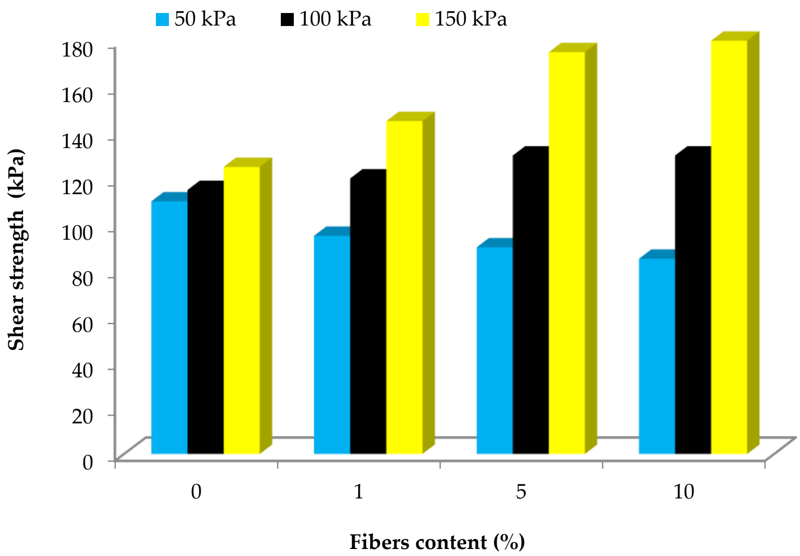


Figure 11. Stress-strain plot of soil treated at different Diss fiber rates.

Figure 11 presents the effect of Diss fibers on the strength characteristics of the soil studied. Shear stresses are improved depending on the addition of Diss fibers and depending on the normal stress; this is justified by the favorable effect of the introduction of fibers into the soil, which plays the role of reinforcement.

From Figure 12, it can be seen that there is a net change in the cohesion and the angle of friction of the reinforced soil as a function of the percentage of fibers. We note a remarkable reduction in the cohesion which drops by more than 60% compared to the soil without additions, and we can also note that the angle of friction has had a significant increase in the value of 10.61° for the soil not reinforced to the value of 44.48° for the floor with 10% Diss. This is due to the low density of the Diss fibers, the rearrangement and new texture resulting from the introduction of the Diss fibers into the soil matrix.

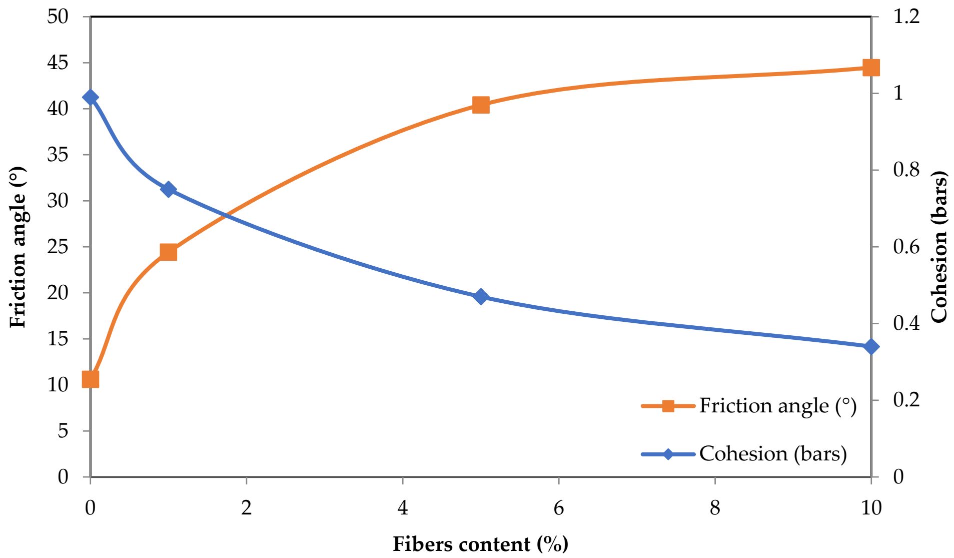


Figure 12. Variation of the mechanical shear characteristics according to the Diss fibers' content.

The mechanism of stabilization of the swelling and improvement of the geotechnical properties of the soil studied is at the same time physical and mechanical. Adding the fibers of Diss, the structure of the soil will be changed. In addition, the application of forces and loads in the various tests contributes to the tightening of the grains and reduction in the voids, which improves the behavior of the soil in general. These results are confirmed by other studies [23,25].

3.4. Effect of Diss Fibers on Compressibility Properties

The purpose of this test is to study the consolidation of intact or reworked soil samples, subjected to a constant vertical load in stages, drained vertically, and laterally surrounded by a rigid enclosure. Table 5 shows the effect of Diss fibers' content on the compressibility characteristics of soil reinforced with different percentages of natural fibers.

Table 5. Variation of compressibility parameters as a function of the percentage of Diss fibers.

Compressibility Parameters	0% Diss Fiber	1% Diss Fiber	5% Diss Fiber	10% Diss Fiber
Swelling index (%)	12.11	11.79	7.29	1.69
Compressibility index (%)	27.65	27.09	27.01	19.99
Preconsolidation pressure (bars)	1.29	1.02	0.81	0.73

Figure 13, shows the effect of Diss fibers on the compressibility characteristics of the soil studied. The final value of the swelling, after stabilization, makes it possible to calculate the relative variation in the volume of the sample expressed as a percentage. The same procedure is used to study the swelling of the samples in the presence of different fiber content. The results of the oedometric tests show a decrease in the swelling index, the compressibility index and the preconsolidation pressure with the increase in the rate of Diss fibers. It is observed that the soil loses its sensitivity to swelling from 1% of fibers. The effect of adding Diss fibers is clearly visible. These curves show that the swelling potential decreases significantly from the addition of 1%. The swelling is linked to plasticity, and it affects the fine particles [3,39]. The randomly distributed Diss fibers are capable of altering the structure and texture of the soil in various aspects, namely resistive tension forces generated due to soil–fiber contact [40–42]. These changes can be attributed to the replacement of more of the swelling soil with non-swelling fibers. In addition, the presence of fibers in the mass of the ground creates voids, which involve the reduction in the surface of effective contact between the fiber and the expansive particles of the ground.

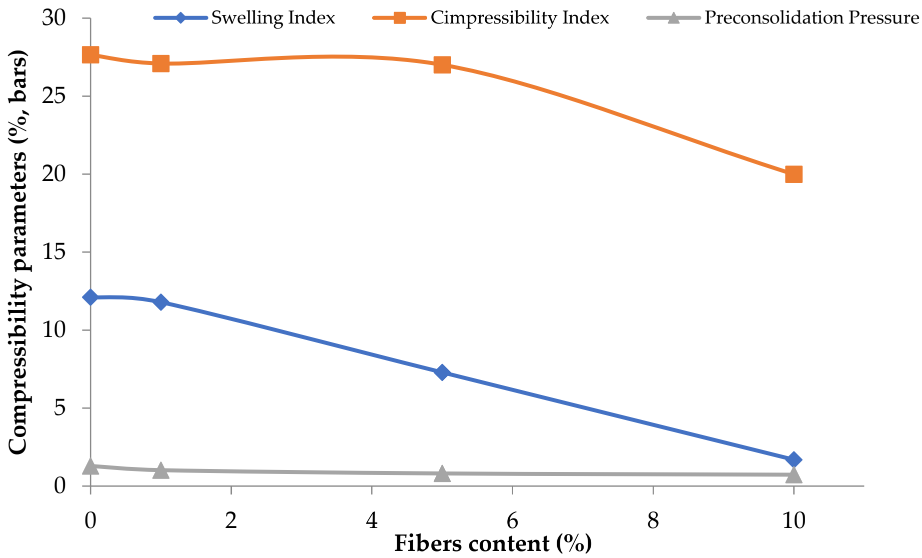
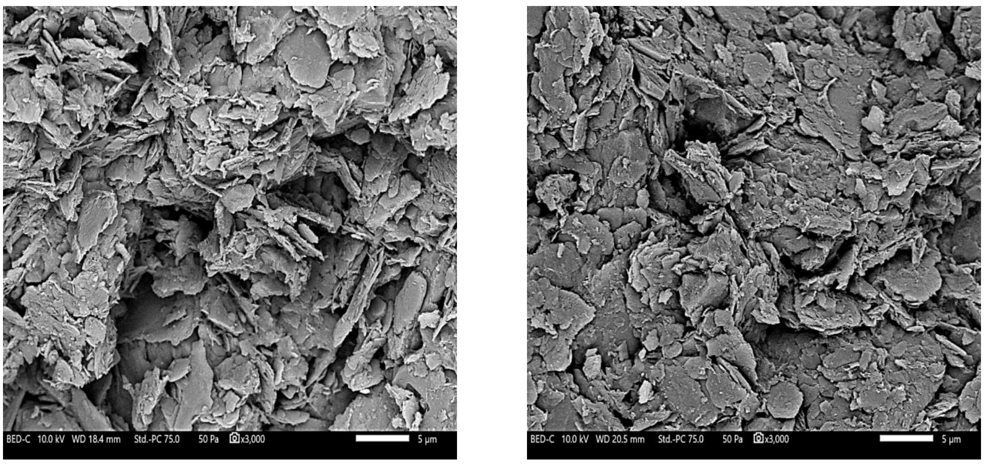


Figure 13. Variation of compressibility parameters as a function of the percentage of Diss fibers.

3.5. Effect of Diss Fibers on Microstructural Analysis

The scanning electron microscopy test consists of observing the texture of the sample and the characterization of its mineralogy. The morphologies of the untreated natural soil samples were observed by the SEM. Figure 14a shows the presence of voids, porosity, and cracks. There are many small particles of different shapes. At higher magnification, a number of large and small pores of different shapes can be seen without the appearance of aggregations. The image shows the surface of the natural ground allowing visualization of the structure in scales. This aspect of scales is due to the presence of montmorillonite proportion. Figure 14b shows the SEM image of the reference soil grains at 5 μm magnification. The SEM image of the untreated SB soil allows visualization of the weak and laminated structure with a certain arrangement between them. This laminated aspect is due to the presence of montmorillonite.



(**a**) (**b**)

Figure 14. SEM images with 5 μm magnification of (**a**) soil and (**b**) SB soil.

The result obtained from the SEM analysis for the Diss fiber-reinforced soil is shown in Figure 15. It illustrates the spatial relationship between the Diss fibers and the soil matrix. It can be observed that very few spaces are created between the fiber and the soil matrix.

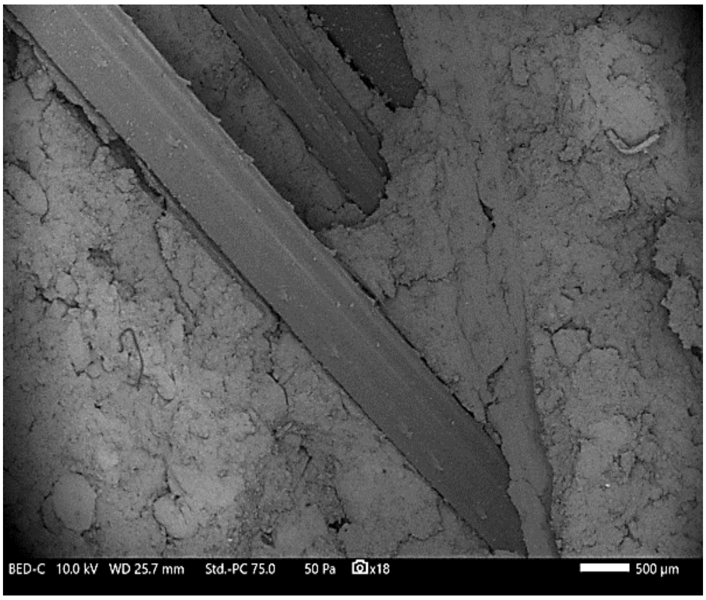


Figure 15. Inking of Diss fiber spines in soil matrix.

4. Conclusions

Algeria is a country very rich in vegetable plants. They are scattered throughout the national territory, and they are found in the coastal regions much more than in the interior regions of the country. The current context, which is particularly concerned about the environmental impact, leads to the use of natural plant fibers to replace synthetic fibers and even certain materials in the field of construction (slabs, the production of tiles and car park paving, as well as the reinforcement of fragile soils).

The use of Diss fibers shows significant improvements in the plasticity and engineering properties of expansive soils. The results show a significant modification of the parameters of shear, cohesion (reduction of 60% to 10% of fibers) and angle of friction (an increase of 35% to 10% of fibers) of the treated soil. The oedometer compressibility tests show a decrease in the swelling index (reduction of 86% to 10% of fibers), the compressibility index (reduction of 28% to 10% of fibers), and the preconsolidation pressure (reduction from 43% to 10% fiber) with increasing fiber content. Adding Diss fiber fundamentally changed the behavior of the soil. It depends on the amount of fiber added and those changes from 1% fiber dosage. It can be expected that with other laboratory tests such as triaxial tests, more soil parameters can be improved with soil–Diss fibers.

The use of Diss rods as a reinforcing element is an ancient technique, used by our ancestors for the reinforcement of natural clay walls, and these constructions still resist the vagaries of nature. However, its use at the research level is very recent. For this, efforts must be concentrated to develop its use as rods or fibers as reinforcement in clay matrices and/or construction materials. The fibers presented in this study are agricultural by-products generated at high volume; they can exist in different regions of Asia, Africa, and Europe, under different temperature and humidity conditions. This makes it possible to demonstrate the application capacity of organic fibers from different regions for the improvement of the mechanical properties of soils. In the same way, the results of these investigations open up the possibility of carrying out similar studies in other parts of the world, where natural fibers are available, which allows one to deepen the knowledge on this new technique of improvement of the technical properties of soils. This study has shown the complexity of the phenomena involved when using plant fibers as reinforcements in soils. It is necessary to follow these studies and study the biodegradation of natural leaves in a mineral-rich environment as a function of time to approximate common use cases for soil reinforcement such us embankments, road areas, etc., because their often low moisture resistance and incompatible nature of the fibers become the main disadvantages. Therefore, modifying the properties of these fibers with chemical treatments can improve the adhesion between the fibers and the matrix, as well as the mechanical properties of the reinforced soils. In the near future, natural fiber will become one of the sustainable and renewable fiber resources in the field of composites and geotechnics that can substitute for synthetic fibers in many applications.

5. Future Recommendation

The current research clearly demonstrates the use of natural fibers for expansive soil stabilization, which is an environmentally-friendly and economical alternative. In addition to that, the authors have some reservations that need to be addressed in the future. Primarily, the long term durability as well as its utilization in a wide range must need to be investigated. Secondly, the use of the natural fibers with some other pozzolanic materials is also recommend, and it needs to be examine in the future.

6. Suggestions Implement the Practice in a Real World Projects

- Diss fibers are obtained using a harvester (machine that cuts and collects the fibers). The preparation of the fibers is done in a shredder. The length of the fiber depends on the shredding time (adjustable).
- The mixing is carried out in the real world by the use of machines such as backhoe loaders, by mixing the materials according to the quantities defined by the formulation.
- Another procedure is to use a large motorized mixer specially designed to mix the materials used with the quantities already calculated.
- Alternative technology proposed for the preparation of composite involves the technology of large machinery such as the paver, which is used for the preparation of bituminous concretes where the aggregates can be replaced by soil, and bentonite and the bitumen tank can be replaced by Diss fibers. The mixing of the materials is carried out following the mixing of the bituminous concretes.

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