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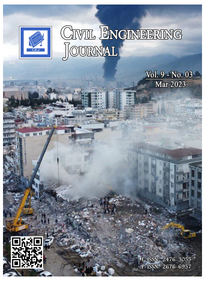

Effect of Polypropylene Fibers on Swelling Potential and Shear Strength of Clay

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Abstract

Expansive clays can cause major problems for urban development (roads, railways, infrastructure, etc.); therefore, reducing the swelling potential of clays has always been a concern in the geotechnical field. The presented paper investigates the effect of polypropylene reinforcement fibers on the swelling potential and shear strength of clay. The samples studied were taken from the clayey region of Mila, located in the northern east of Algeria. The experimental procedure adopted in this research consists first of the assessment of the physical, mechanical, and mineralogical characteristics of the soil samples without reinforcement. Then, swelling pressure, swelling rate, and swelling index are used to assess the swelling potential of these samples. After the reinforcement using a variety of polypropylene fiber concentrations (2 to 6% of the weight of the dry clay), the free swelling is clearly reduced. The optimum reinforcement rate in this case is 4%, in which the swelling was reduced by 90.7%. Finally, to offer more insights regarding the impact of clay reinforcement using polypropylene fibers, the effect of this later on the mechanical properties of the studied clay was also analyzed through the tangential shear strength. It was found that the polypropylene fibers increased the tangential shear resistance of Mila's clay.

Keywords: Clay; Swelling Potential; Shear Strength; Polypropylene Fiber; Reinforcement.

1. Introduction

Swelling in clay soils is very common. Intrinsic parameters (like the mineralogical composition, low dry density, etc.) and surrounding parameters (like the presence of water, external loading, etc.) can influence this phenomenon. Expansive clays are the root of numerous problems in urban development (roads, railways, infrastructures, etc.), which lead to substantial economic losses. Therefore, reducing the swelling potential of clays has always been a concern in the geotechnical field [1–4].

A number of techniques have been developed to solve the problem of expansive soils, which can be divided into two categories: (1) mechanical stabilization (compaction, substitution, pre-humidification, addition of sand, etc.) and (2) chemical stabilization (by adding materials such as fly ash, salts, cement, lime, etc.). Recently, the addition of synthetic fibers [5–13] and natural fibers [13–19] has been considered among effective soil improvement techniques. Many studies have shown that the use of fibers (of natural or synthetic origin) gives satisfying results regarding the expansive behavior of soils [1-4, 8, 9, 12-14].

Regarding the assumption behind the structural advantage, it is assumed that the presence of polypropylene fibers helps improve the cohesive behavior of clays throughout their entanglement within the clay's solid structure. The use of

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this technique has some constraints in the geotechnical field; the operation of mixing the fiber with soil is a major inconvenience due to the absence of specialized equipment that performs this task. On the other hand, this technique presents some key advantages: the cost of polypropylene fiber is low compared to other reinforcement techniques such as adding fly ash and cement. From an ecological perspective, polypropylene is chemically inert, which makes it an eco-friendly material.

In the pertinent literature, the aspect of using polypropylene fibers for soil stabilization has raised interest in the research field. In 2006, Cai et al. studied the effect of the mixture of lime and polypropylene fibers on the properties of clay [5]. Yilmaz (2009) [20] conducted an experimental study on the strength properties of a sand-clay mixture stabilized with polypropylene fiber. Three years later, Pradhan et al. (2012) studied the effect of incorporating polypropylene fibers on the strength properties of a cohesive soil [21]. Chen et al. (2015) investigated Shanghai soft clay through an experimental study that tackled the effect of polypropylene fibers on the mixture of cement and fiber-stabilized samples [22]. After two years, Pekrioglu (2017) studied the mechanical properties of a mixture of polypropylene fiber and marble dust on gypsum-stabilized soil [23]. Hussein and Ali (2019) discussed the effect of polypropylene fibers on expansive soil [8]. Tomar et al. (2020) studied a mixture of polypropylene fiber and nanosilica regarding its durability and strength [11]. On the other hand, Murthi et al. (2021) tackled the subject of the behavior of a mixture of silica fume and polypropylene [10].

Most recently in research, many researchers took interest in the field of soil reinforcement using polypropylene fiber. Reshma et al. (2022) examined the effect of polypropylene fibers and alccofine on soil stabilization [24], whereas the strength and deformation of soft soil by polypropylene fiber was studied by Al-Kaream et al. (2022) [25]. Yang et al. (2022) elaborated an experimental study on the strength of polypropylene fiber reinforced cemented silt soil [26]. The behavior of cohesive soil reinforced by polypropylene fiber was investigated by Al-Neami et al. (2022) [27]. In the same year, Wang et al. (2022) tackled the subject of lime-treated subgrade soil improved by polypropylene fiber and class F fly ash through an investigation of the mechanical characteristics [28]. In 2023, Rajabi et al. analyzed the influence of polypropylene and glass fibers on the strength and failure behavior of clayey sand soil [29].

The influence of polypropylene fiber (or the mixture of this later with other components) on the mechanical properties of soils has been treated in literature worldwide; however, the state of the art regarding the impact of polypropylene fiber to stabilize expansive soils is still poor. For Algerian clay, the impact of polypropylene fibers on the swelling potential of these soils has never been studied. Thus, the present paper represents the first attempt to understand the effect of polypropylene fibers on the swelling potential and shear strength of an Algerian clay.

The region of Mila, located in the northern east of Algeria (Figure 1), is known for its clayey soils, which exhibit in some cases an expansive behavior [30–32]. The presented paper tackles the effect of polypropylene reinforcement fibers (a synthetic fiber) on the swelling potential of Mila region clay. An experimental study was carried out in order to better understand the impact of the aforementioned fiber on Mila's clay. Furthermore, the effect of polypropylene reinforcement on the mechanical properties of the studied clay was also analyzed through its tangential shear strength.

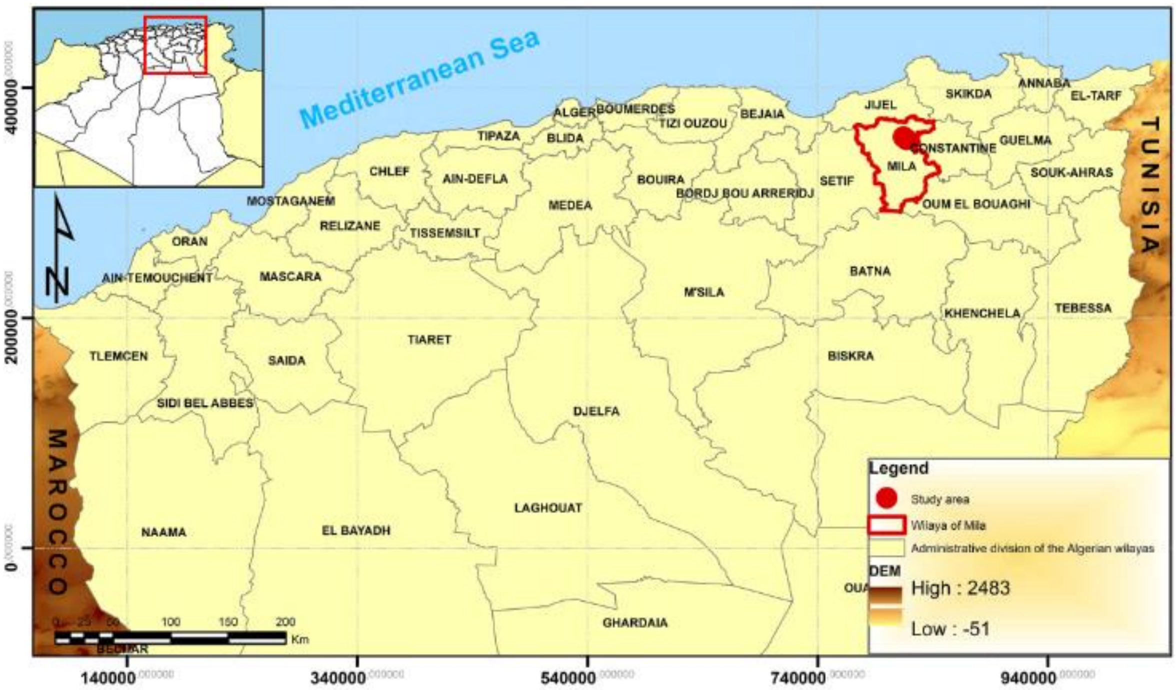

Figure 1. Location of the sample area

2. Experimental Study

The studied samples were taken from the region of Mila (marly clay, plastic, multi-chrome color). Clay samples were collected by digging a pit into the study area using a power shovel. The soil is sampled at a depth of two (02) meters in order to avoid the layer of topsoil or backfill that may affect the obtained results.

Initially, the physical identification tests were performed on the clay samples as shown in Figure 2, and then, regarding the mechanical tests, the samples were dried and sieved through a 5 mm sieve in order to perform the Proctor test. The experimental study consists of characterizing the behavior of soils with and without reinforcement with polypropylene fiber in order to understand its effect on improving the mechanical performance of soils. To this end, a series of tests were carried out at the laboratory level.

- The first part concerns the identification of the samples and the assessment of its swelling potential.
- The second part of the experiment deals with the mechanical performance of the clay/polypropylene mixture samples with different fiber dosages.

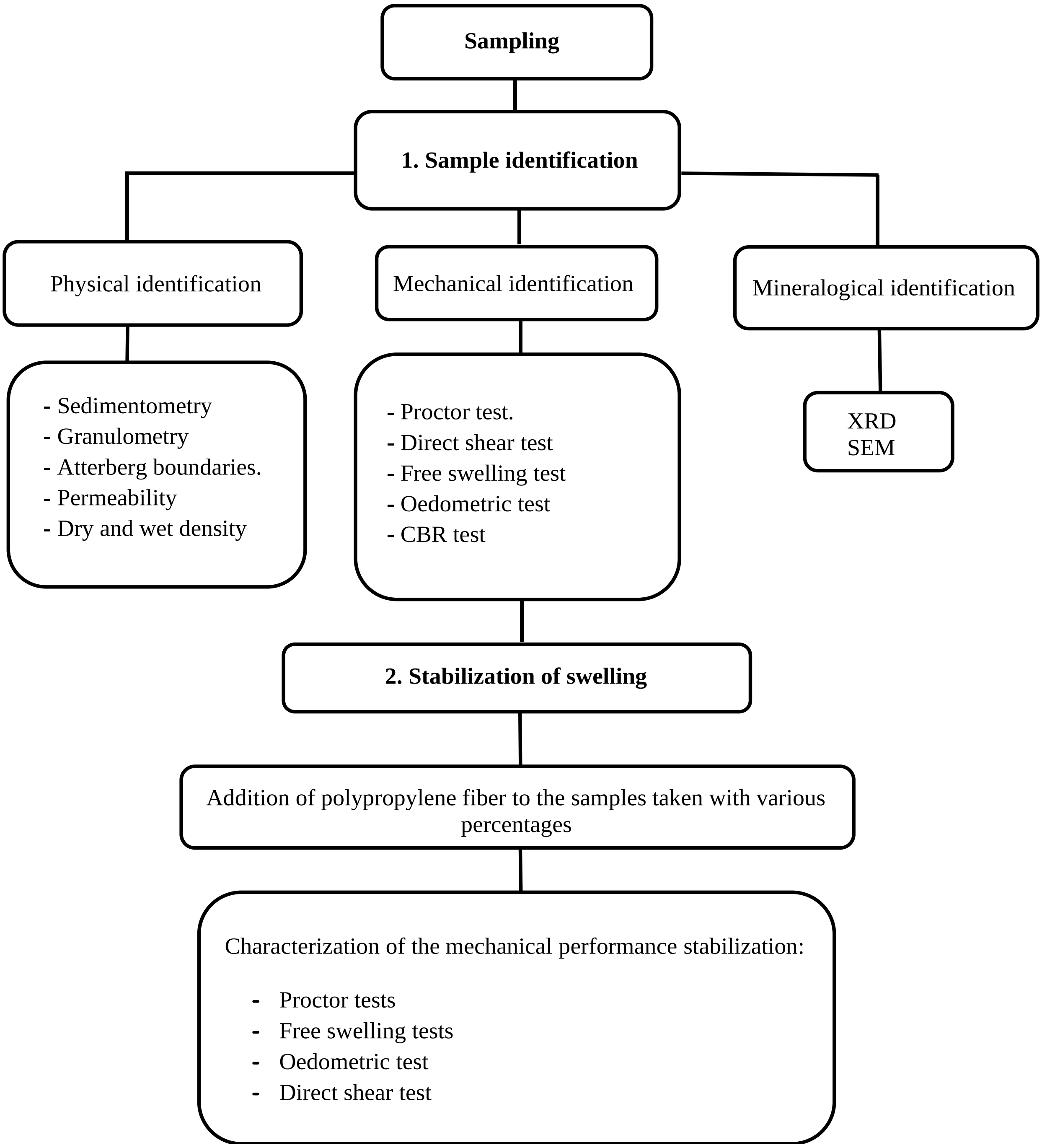

Figure 2. Flowchart of identification methodology and sample processing

The principle of this approach is to achieve compaction using the standard Proctor test, which consists of compacting the clay/polypropylene mixture (Figure 3). The displacement pressure and the deformation were registered in order to assess the intrinsic parameters of the samples. In addition, the characterization of the change in the oedometric mechanical parameters is analyzed. Table 1 summarizes the tests performed in this study with respect to the standards. Finally, the direct shear tests were performed with the different percentages of fibers.

Figure 3. Photo of Clay - Polypropylene fiber mixture sample

Table 1. Tests standards adopted in the study

Standard	Designation
XP P94-041 [33]	Soil: investigation and testing. Granulometric description. Wet sieving method.
NF P94-057 [34]	Soils investigation and testing. Granulometric analysis. Hydrometer method.
NF P94-051 [35]	Soil: investigation and testing. Determination of Atterberg's limits. Liquid limit test using Casagrande apparatus. Plastic limit test on rolled thread.
XP P94-060-1 [36]	Soils: investigation and testing. Shrinkage test. Part 1: determination of shrinkage characteristic on remolded soil passing a 400 micrometers test sieve.
ISO 17892-11 :2019 [37]	Geotechnical investigation and testing — Laboratory testing of soil — Part 11: Permeability tests.
NF P18-592 [38]	Aggregates. Methylene blue test. Spot test.
NF P94-071-1 [39]	Soil investigation and testing. Direct shear test with shear box apparatus. Part 1: direct shear.
XP P94-090 [40]	Soil: investigation and testing. Oedometric test. Part 1: compressibility test on quasi-saturated fine-grained soil with loading in increments.
NF P94-078 [41]	Soils: investigation and tests. CBR after immersion. Immediate CBR. Immediate bearing ratio. Measurement on sample compacted in CBR mold.
NF P94-093 [42]	Soils: investigation and testing - Determination of the compaction reference values of a soil type - Standard proctor test - Modified proctor test
NF P94-091 [43]	Soil: investigation and testing. Swelling test with oedometer. Determination of deformations by loading several test pieces.

3. Identification of Soil Samples

3.1. Physical and Mechanical Identification

The analysis of the particle size was carried out by wet sieving. For particles size less than 80 µm in diameter, the analyses were performed by sedimentometry.

Soil plasticity has been identified using Atterberg limits. For more precision in understanding the plasticity of these samples, shrinkage characteristics on re-moulded soil passing a 400 micrometers test sieve were conducted. The permeability test was used to determine the permeability coefficient of clay. Finally, the methylene blue test was carried out to assess the degree of clay content in these samples. The angle of internal friction and the cohesion, the two main parameters, were determined using a direct shear test. The volume changes due to swelling were identified by oedometer for a cell with a capacity of 5 kN, as well as the swelling index of the materials by the CBR (California Bearing Ratio) test according to the standards, and the free swell oedometer test. Table 2 summarizes the characteristics of the studied soil.

Table 2. Characteristics of the studied soil

Tests	Results
Dry density (g/cm^3)	1.53
Wet density (g/cm^3)	1.96
Natural water content (%)	27.60
Liquidity limit (%)	67.09
Plasticity index (%)	37.76
Shrinkage limit (%)	17.20
Methylene Blue Value MVB (g/kg)	5.005
% Passing through a 0.2 mm sieve	98
% Passing through an 80 µm sieve	95
Proportion of clay % <2 µm	75
Permeability coefficient (m/s)	2.26×10^{-9}
Cohesion C UU (kPa)	56.98
Internal friction angle UU (°)	5.0
Pre-consolidation stress (KPa)	130.00
Compression index Cc	0.1534
Swelling index (Cg)	0.0982
Optimum water content %	17.85
Corrected density (t/m$^{3)}$	1.65
Corrected water content %	17.85
CBR (California Bearing Ratio) swelling %	2.05
CBR index %	3
Carbonate rate	34.58
Sulfate rate	387.84
PH	7.73
Electrical Conductivity (mmhos/cm)	1.065
Saturation %	74

3.2. The Mineralogical Composition and Petrographic Identification

The X-ray diffraction (XRD) on the fraction < 2µm was used to obtain the mineralogical composition. The diffractometer of configuration Bragg-Brentano was used in order to identify the mineral phases. The adopted diffractometer uses a copper anticathode with Kα = 1.54184 A. Microscope imaging was performed using scanning electron microscope (SEM). The spectrometry was executed using an elemental analysis technique allowing both to know the nature of the chemical elements present in a sample as well as their mass concentration.

To prepare the samples for chemical and mineralogical analyses (DRX, EDXS), the samples taken were first ground into pieces then dried for 24 hours at 105° C. After that, the samples are sieved through a 50 µm sieve. Table 3 and Figure 4 shows the results of the petrographic analysis, which reveals the predominance of silica, calcium and aluminium. The percentages of silica (SiO_2) and aluminium were very significant in the samples, indicating the presence of kaolinite ($Al_2Si_2O_5(OH)_4$). The alumina / silica: (Al_2O_3 / SiO_2) ratio is an indicator of the average permeability of the material in the studied case for the samples.

Table 3. Mineralogical composition of the studied soil

Elements	C	O	Al	Si	Ca
% Mass	6	46	14	28	6

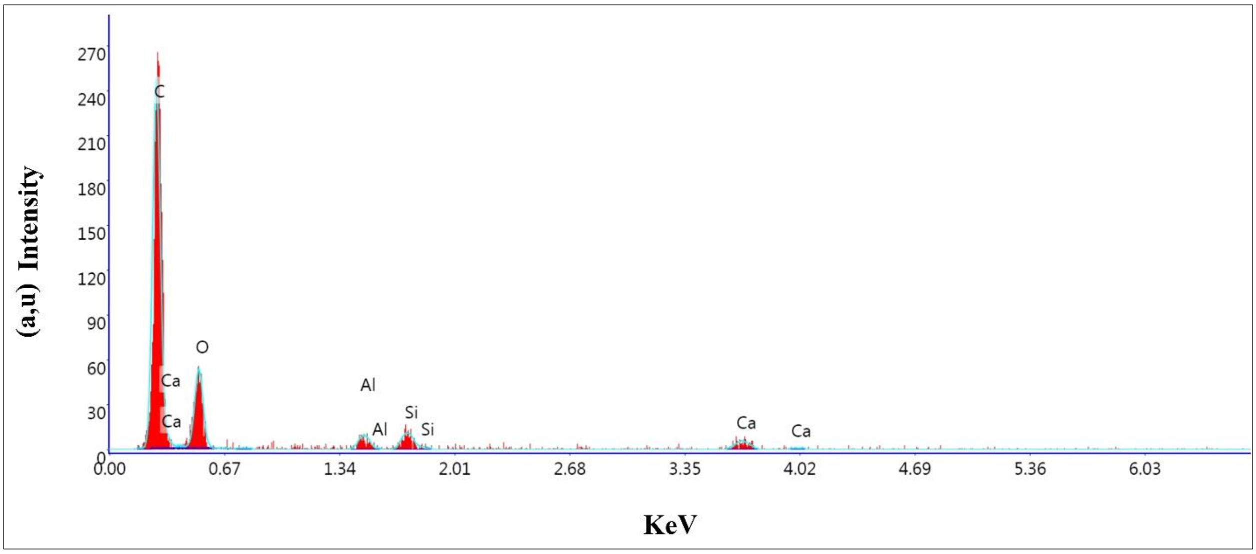

Figure 4. EDS spectrum carried out on the studied sample

SEM images of the clay sample are displayed in Figure 5. Clay particles are shown as clusters of fine aggregates and platelets. This morphology is found in poorly crystallized kaolinites and illites.

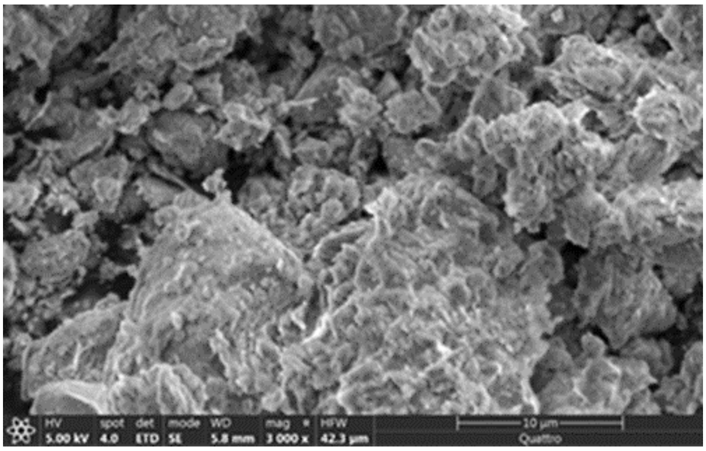

Figure 5. SEM observations of a sample

4. Characteristics of Polypropylene Fiber

The properties of the polypropylene fiber adopted in the presented research are plotted in Table 4. Figure 6 represents a SEM observation of polypropylene fiber, whereas Figure 7 is a photo of polypropylene fiber type PP12. The silky shape of the filament of the polypropylene fiber allows excellent entanglement of the latter with the clay particles.

Table 4. Characteristics of polypropylene fiber

Composition	100% polypropylene
Cross section	Round
Standards	TSE EN 14889 Part II Type 1.A and ASTM C-1116-1997 Type III
Tensile Strength	600-700 MPa
Young's modulus	3,000-3,500 MPa
Elongation	20-25%
Specific density	0.91 g /cm ^{3}
Color	white
Melting point	160°C

Figure 6. Photo of polypropylene fiber type PP12

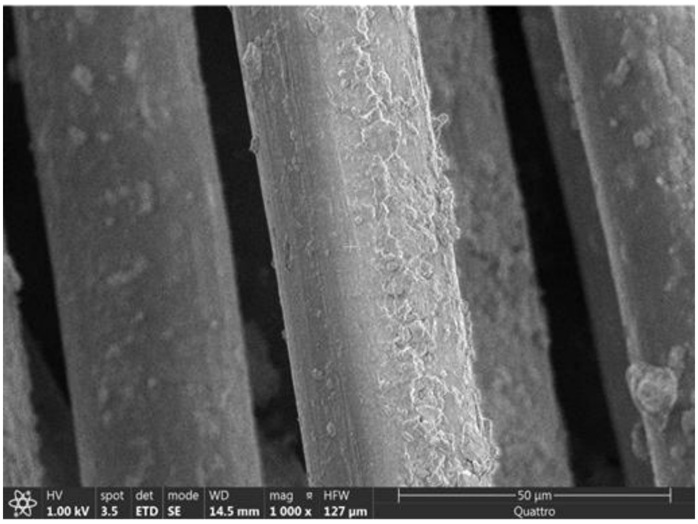

Figure 7. SEM observations of Polypropylene fiber

5. Results and Discussions

5.1. Identification of the Swelling Potential of the Studied Soils

In the presented study, the following parameters are used to assess swelling:

- The swelling pressure σ_g;
- Free swelling rate A_g;
- The swelling index C_g.

Cylindrical samples were cut from the clay cores extracted from the Proctor test; the samples were subjected to an odometer-free swelling test. In order to have a unified vision of the results when changing the percentages of fibers, a stress of 100 kPa is applied. This later is a stress chosen so that it is higher than the pressure of the earth at rest and less than the one of an earth that undergoes a great deal of pressure from very important infrastructure. Table 5 summarizes the various results of the odometer swelling tests.

Table 5. The results of the swelling tests on the studied clay

Swelling pressure σ_g (kPa)	Swelling rate A_g (%)	Cg swelling index (%)
100	26.0	09.82

Swelling pressure (100 kPa) is considered high [44]. The swelling rate (26%) found in the present study is also considered high [45]. Regarding the swelling index (Cg), it was found that the swelling potential of the studied samples is certain (greater than 9%) [46].

The different adopted tests to assess the swelling potential of the studied samples are the most widely used in this field because they consider the required mechanical parameters to correctly identify the swelling potential. The three parameters plotted in Table 5 indicate explicitly that the studied samples taken from the Mila region have a high swelling potential.

5.2. Study of the Swelling Potential of the Clay/Polypropylene Mixture

5.2.1. Sample Preparation

The fineness as well as the arrangement in the filament ensure a uniform diffusion of the fibers and facilitate their incorporation; however, during the sample preparation, it is difficult to achieve a uniform and equal distribution of the fibers in the soil, thus the difficulty in obtaining a homogenous mixture through manual mixing.

The clay samples were sieved through a 5 mm sieve and mixed with the polypropylene fibers in proportions of: 2%, 4%, and 6% of the dry soil weight. This mixture was then subjected to a series of mechanical tests, namely:

- Proctor tests;
- Free swelling tests;
- Oedometric test;
- Direct shear test.

5.2.2. Free Swelling over Time

Figure 8 shows the variations of relative swelling (S) against the logarithm of time for stabilized and unstabilized expansive clays with fiber contents of 2%, 4%, and 6%, with equal external pressures of 100 kPa. For all mixtures, the swelling initially increased slowly with the logarithm of time, then increased more rapidly, finally approaching an asymptotic value. This behavior corresponds to the three usual stages of swelling:

1) Low initial swelling due to low unsaturated hydraulic conductivity;
2) Intermediate primary swelling when clay structure attracts water particles, resulting in a large volume change;
3) A weak secondary swelling phase because the conditions are close to saturation.

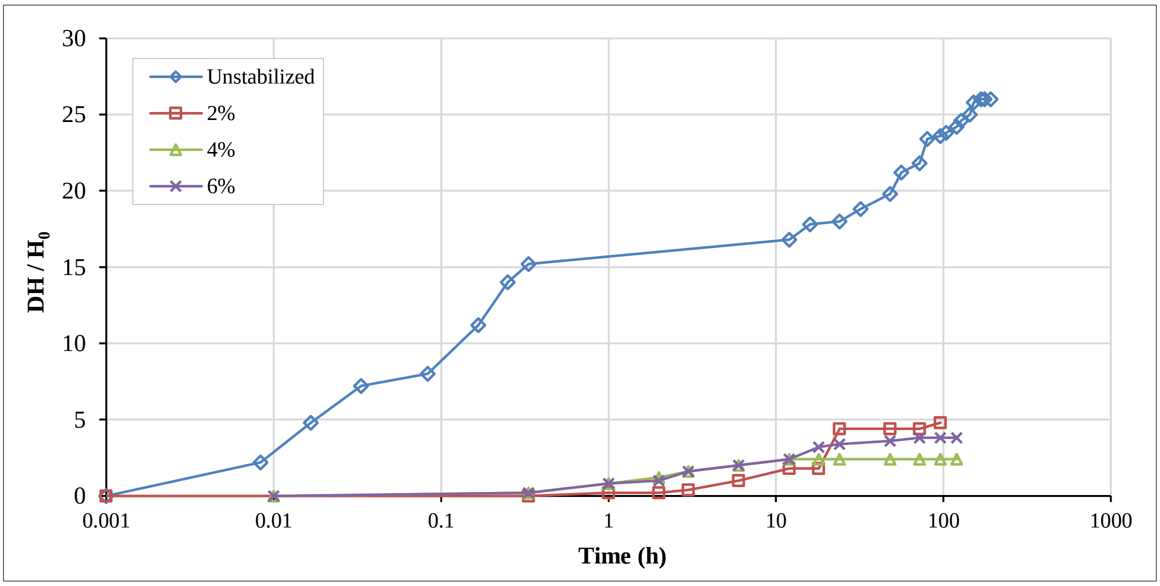

Figure 8. Free swelling curves relative to time for stabilized and un-stabilized sample

The required swelling volumes and times for the stabilized clays were, in the majority of cases, lower than those of the un-stabilized expansive clays. Smax values of the clay stabilized under an external pressure of 100 kPa were 4.8%, 2.4%, and 3.8% for the polypropylene fiber percentages of 2%, 4%, and 6%.

Quasi-equilibrium was reached in about a hundred hours for un-stabilized expansive clays. The impact of the reinforcement is noticeable; for the 2% fiber content, the swelling was reduced by 81.5%; for the 4% content, the reduction was 90.7%; whereas for the 6% content, it was 85.3 %. From the obtained results regarding free swelling of the un-stabilized and stabilized samples, the impact of the polypropylene fiber on reducing swelling potential is noticeable; furthermore, it was found that the reinforcement rate of 4% gives the highest gain.

5.3. Study of the Shear Strength of the Clay/Polypropylene Mixture

Direct shear tests were performed in order to assess the shear strength of the studied samples reinforced with polypropylene fiber. For this purpose, clay/polypropylene mixtures were prepared with different concentrations of 0%, 2%, 4%, and 6%. First, a reference shear test was assessed on the clays without reinforcement in order to characterize their mechanical behavior. The tests were carried out in unconsolidated and undrained modes (the consolidation stress was applied at a speed of 1 mm/min under normal stresses of 100, 200, and 300 kPa). The results of the shear strength of the studied sample are plotted in Figure 9.

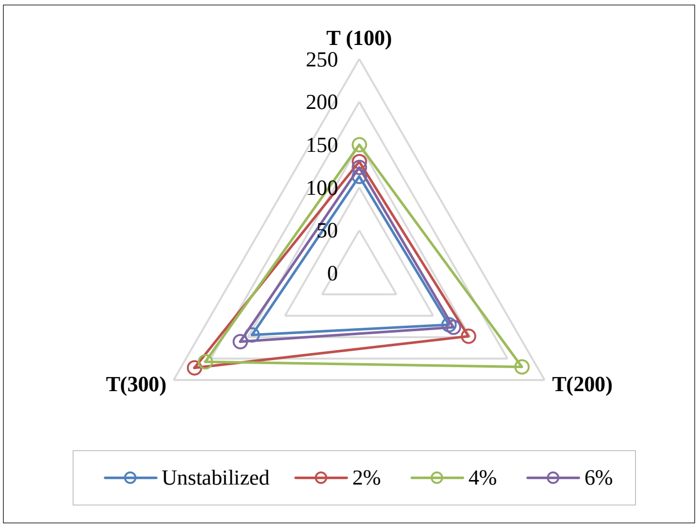

Figure 9. Shear strength under normal stresses of 100, 200 and 300 kPa for the studied samples

It is noticeable that the shear strength of the clay increases with the increase in the percentage of fiber for concentrations 2, and 4 %. However, for 6%, the value of shear strength drops.

The sample without polypropylene fiber reinforcement (0%) shows the lowest shear strengths for normal stresses of 100, 200, and 300 kPa. As the fiber concentration increases to 2 %, the increase in shear strength is noticeable under all the three normal stresses. As for the fiber mass of 4%, the highest shear strength is reached for normal stresses of 100 and 200 kPa; however, for the normal stress of 300 kPa, the shear strength of the sample of 2% is higher than that of 4%. When the polypropylene fiber concentration is increased to 6%, the shear strength drops. For the normal stresses of 100, 200, and 300 kPa, the shear strength is basically close to that of the samples without reinforcement.

From the obtained results regarding the shear strengths of the un-stabilized and stabilized samples, the presence of polypropylene fiber increases the shear strengths of the samples at concentrations of 2% and 4%. However, for a higher reinforcement percentage, practically no impact is recorded.

6. Conclusions

This paper represents an experimental approach that aims to understand the swelling and mechanical behavior of Mila's clays before and after being stabilized with polypropylene fibers. The studied samples were extracted at a depth of two (02) meters to avoid the layer of topsoil or backfill that may alter the results, and then the physical, mechanical, and mineralogical identification tests were performed. The swelling identification techniques of swelling pressure, swelling rate, and swelling index were adopted to assess whether the studied samples were expansive or not. The obtained results show real swelling potential for the studied samples.

Afterwards, the impact of the reinforcement using polypropylene fibers was investigated. It was found that the incorporation of the fibers considerably lowered the rate of free swelling of the studied clays. The impact of the polypropylene fiber on reducing swelling potential is clear; taking, for example, the percentage rate of 4% (the optimum reinforcement rate in this case), the swelling was reduced by 90.7%. Regarding the shear strength of the stabilized samples, the presence of polypropylene fiber increases the shear strength of the samples at concentrations of 2% and 4%. However, for a higher reinforcement percentage, practically no impact is recorded.

The presented study shows that the fiber percentage of 4% is the effective reinforcement rate to both reduce the potential of swelling and increase the shear strength of Mila's clay. Thus, the polypropylene fibers can be effective reinforcements for stabilizing soils.

7. Declarations

7.1. Author Contributions

Conceptualization, D.M.Y. and S.M.; methodology, D.M.Y. and S.M; software, D.M.Y.; validation, D.M.Y., S.M., and D.M.; formal analysis, D.M.Y., S.M., and D.M.; investigation, D.M.Y. and S.M.; resources, D.M.Y. and S.M.; data curation, D.M.Y., D.M., and S.M.; writing—original draft preparation, D.M.Y. and D.M.; writing—review and editing, D.M., D.M.Y., and S.M.; visualization., D.M.Y., D.M., and S.M.; supervision, S.M. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Acknowledgements

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7.5. Conflicts of Interest

The authors declare no conflict of interest.

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