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Improving silty sand performance with cement and fiber reinforcement: study of mechanical behavior

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Abstract:

Introduction/purpose: This study aims to valorize a local material from the western region of Algeria for potential use in road construction. The main objective is to investigate the effect of incorporating synthetic polypropylene fibers and natural Alfa plant fibers at varying contents (0%, 0.3%, 0.6%, and 0.9%) on the strength of a silty sand stabilized with 4% cement.

Methods: An experimental program was conducted using unconfined compression tests and unconsolidated-undrained triaxial tests. These tests were performed on soil–fiber–cement mixtures compacted statically at the Standard Optimum Proctor (SOP) conditions (γ_{dmax}= 17 kN/m^3 and wopt =16.6%) and cured for 1, 7, and 28 days in open air.

Results: The results revealed a significant improvement in the mechanical strength of the treated soil, with a change in the failure behavior from brittle to ductile. The addition of 0.3% fibers enhanced cohesion while reducing the internal friction angle. Furthermore, fiber-reinforced cemented samples exhibited greater stiffness compared to untreated soil. Moreover, the highest unconfined compressive strength was obtained with the combination of 0.9% fiber reinforcement and 4% cement.

Conclusion: The reinforcement of cemented silty sand with polypropylene and Alfa fibers significantly improves its mechanical strength and stiffness. The addition of 0.9% fiber content yields the highest compressive strength while effectively transitioning the soil's behavior from brittle to ductile. These findings confirm that valorizing local Algerian materials is a technically viable and sustainable solution for road infrastructure development.

Key words: silty sand soil, Alfa plant, polypropylene fibers, shear resistance, friction angle, cohesion, unconfined compressive strength.

Introduction

The stabilization or reinforcement of soils is performed through a set of techniques that aim to improve the soil strength and/or limit its deformation under structures. It is useful to note that the reinforcement of foundation or backfill soils consists of improving their mechanical characteristics. Over the past few years, fiber reinforcement techniques have been widely and successfully used in various applications, such as the stabilization of slopes, road construction, and embankments (Wang et al, 2018).

The first experimental studies conducted on fiber-reinforced soils focused primarily on soil-plant root systems. In this regard, Gray (1978), Waldron (1977), and Wu et al. (1988) indicated that plant roots increase the shear strength of soil as well as the stability of natural slopes. Additionally, it is worth noting that natural fibers have long been used in cementitious composites and earth blocks in developing countries due to their availability and low cost (Ghavami et al, 1999; Savastano et al, 2000). Moreover, natural fibers such as sisal (Mesbah et al, 2004), coconut (Pradani et al, 2017), and jute (Hossain et al, 2015) are potentially environmentally friendly materials that have been recognized in recent years as very important and have been widely used in experimental studies on fiber-reinforced soils.

Furthermore, unconsolidated undrained (UU) triaxial tests have previously been carried out by Dasaka and Sumesh (2011) and AbouDiab et al. (2016). The results obtained could be interpreted only in terms of shear strength because the pore water pressures were not measured during the tests. The authors reported that the integration of fibers of different lengths helps increase the internal friction angle of the reinforced soil to an optimal value. This angle then begins to decrease. However, the fiber-reinforced soil cohesion decreases to a minimum value and then starts to increase for an inclusion rate of 0.3% fiber. The authors concluded that this is due to the interaction between soil particles and the fibers, without providing a sufficiently detailed explanation of this phenomenon. Jiang et al. (2010) and Pradhan et al. (2012) reported similar findings. Furthermore, Mirzababaei et al. (2017) and Mirzababaei et al. (2018a et b) observed that the effective internal friction angle (ϕ') was not significantly influenced by the fibrous reinforcement but, on the other hand, the effective cohesion (c') of the soil was considerably improved. It was also observed that the effect of fibrous reinforcement on shear strength was evident at low confining pressure (50 kPa).

Furthermore, the results of the triaxial tests performed under low confining pressure (Consoli et al, 1998; 2009) showed that fiber reinforcement has a significant impact on cement-treated sand as it increases the compressive volumetric strain at a specific axial strain, which in turn increases the ductility of the soil. It has also been shown that the presence of fibers can improve strength and ductility. However, the improvement rate decreases as the confining pressure increases (Uddin et al, 2011; Wang et al, 2014; Shen et al, 2021). In 2016, Nguyen and Fatahi found that, under undrained conditions, higher fiber content results in excessive pore pressure, which is consistent with Athanasopoulos' postulate (1994), who suggests that the presence of fibers is in many situations similar to the presence of additional confining pressure. Falorca and Pinto (2011) used low plasticity clay reinforced with polypropylene fibers to study the effects of the fiber texture and normal stress level in direct shear tests. They reported that the shear strength decreases with the increase of the applied normal stress, which means that the fibers contributed more significantly at low normal stress levels. More recently, Araldi et al. (2018) and Imanzadeh et al. (2018) have studied the effect of plant fibers on improving the plastic behavior of soils in order to minimize cracks. The findings showed that, in general, the maximum and residual shear strength due to fiber reinforcement is relatively high, which can considerably improve the cohesion and the internal friction angle of the cement-treated soil.

Furthermore, other studies have been carried out to study the influence of cement treatment on soil ductility using the secant modulus E_{50} at maximum strength (Gray and Al-Refeai, 1986; Al-Refeai, 1991; Lee et al, 2005; Michalowski and Zhao, 1996; Falorca and Pinto, 2011). The authors concluded that this modulus increases with the percentage of fibers used. However, when the quantity of fibers exceeds an optimal value, the secant modulus begins to decrease due to the balling effect (Silveira et al, 2020).

Other studies on the unconfined compressive strength of cement-treated and fiber-reinforced soil have been conducted by Consoli et al. (2010, 2011, 2012), Xiao et al. (2013), Hamidi et al. (2013), Cristelo et al. (2017), Correia et al. (2015), Festugato et al. (2017), and Shen et al. (2021). The results showed that the increase in the compressive strength of soils due to their reinforcement with fibers is relatively significant. However, this strength remains much lower than that obtained when the cement content is increased (Consoli et al, 2010; Xiao et al, 2013). It is worth noting that the main objective of fiber reinforcement is to increase the ductility of the cement-treated soil. Michalowski and Cermak (2003) showed that the strength of sand can be improved by adding fibers. The present article aims primarily to carry out an experimental study in order to investigate the impact of two types of fibers, natural plant fiber (Alfa) and synthetic fiber (polypropylene), on the shear strength and unconfined compressive strength of silty sand treated with 4% cement.

Unconsolidated undrained (UU) triaxial compression tests were conducted at two confining pressures (100 and 300 kPa) on mixtures of soil with different fiber percentages (0%, 0.3%, 0.6%, and 0.9%). In addition to the triaxial tests, unconfined compressive strength (UCS) tests were also carried out at different curing times in open air on mixtures (soil-fibers) and (soil-cement-fibers) in order to analyze the effect of fiber incorporation on the properties of cemented soil. Moreover, it was observed that adding a certain percentage of fibers to the mixture (soil-cement) caused an increase in cohesion and friction angle. The inclusion of fibers also made it possible to obtain soil that exhibited a ductile behavior. Hence, significant deformations were observed without stress peaks. The UCS results showed that the incorporation of fibers in the mixture (soil-cement) made the material more resistant. The characterization of the behavior of the soil was carried out by considering the secant modulus, which was defined on the basis of the compression curves of the specimens during the UU triaxial tests. The effect of fiber reinforcement on the stiffness increase was analyzed by comparing the evolution of the secant modulus of the reinforced samples with fibers and treated with 4% cement. It was shown that the secant modulus of the soil treated with cement and reinforced with 0.3% polypropylene fibers was significantly improved.

Materials and methods

Location and identification of the studied soil

The material used in this study was collected from a site located in the town of Telagh in the Sidi Bel Abbès region (North-West of Algeria), at a depth of approximately 1 meter. This soil has been subject of previous research (Ghembaza et al, 2023). Several tests were conducted to determine the physical and chemical characteristics of the soil, and the results are summarized in Table 1. The natural soil is predominantly composed of sand and silt, with a natural water content of 14.86% and a plasticity index (Ip) ranging from 6.25% to 8.42% (Ikhlef, 2015). As the organic matter content of the soil is very low (1.35%), it should not interfere with the treatment process.

According to the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO, 1978), the soil is classified as silty sand (SM) and as a granular material (A-2-4), respectively. Its chemical composition indicates high silica (SiO_2) and lime (CaO) contents, conferring pozzolanic properties (Janz and Johansson, 2002). Additionally, the soil's pH value of 9.06 (higher than 6) makes it suitable for stabilization (Vilenkina, 1956).

Table 1 - The identification parameters of the studied soil

	Parameters	Values
Sieve analysis	Gravel (%)	6.26
	Coarse sand (%)	20.06
	Fine sand (%)	35.42
	Silt (%)	25
	Clay (%)	13.21
Physical parameters	Natural water content (%)	14.85
	Liquidity limit, LL (%) (ASTM D-4318)	25.65- 28.22
	Plasticity limit, PL (%) (ASTM D-4318)	19.4 - 19.8
	Plasticity index (%) (PI = LL – PL)	6.25 – 8.42
Chemical parameters	SiO2 (%)	38.86
	CaO (%)	27
	pH	9,1
Compaction properties	Dry density at SPO (kN/m3) (ASTM D-698)	17
	Optimum water content (%) (ASTM D-698)	16,6

Characteristics of the used cement

The cement used as a stabilizing agent in this study is Portland cement type CEM I 42.5R, produced by Zahana Company (Algeria). Its main characteristics are presented in Table 2. As a hydraulic binder, Portland cement reacts readily with water, producing a significant amount of hydration products in a short time. Its high silica (SiO_2 = 20.71%) and calcium oxide (CaO = 62.07%) contents, present in the clinker, promote pozzolanic reactions that enhance the long-term mechanical properties of treated soils (Taylor, 1997; Janz and Johansson, 2002).

Table 2 - Physico-chemical properties of the cement

Parameters	Physical		Chemical							
Denomination	Specific surface	Setting time	SiO_2 (%)	CaO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	Perte au feu	CaO libre
Notation	cm^2/g	h								
Values	3500	2h13mn	20,7	62	5,99	3,47	1,12	1,66	5,14	0,7

Characteristics of the used fibers

Two types of fibers were used for soil reinforcement in this study. The first type consists of synthetic polypropylene fibers, whose properties are summarized in Table 1. These fibers act as mechanical links between soil particles, enhancing the overall bearing capacity of the soil–fiber mixture. According to Pakravan et al. (2012), polypropylene is hydrophobic and does not react with moisture from either the cement paste or the soil. Synthetic fibers have been widely used in previous experimental studies (Khattak and Alrashidi, 2006; Yetimoglu et al, 2005; Viswanadham et al, 2009; Olgun, 2013).

The second type consists of natural Alfa fibers obtained from the El-Bayadh region in South-West of Algeria. These plant fibers are primarily composed of cellulose, hemicellulose, lignin, and pectins. They are valued for their low density, thermal insulation properties, mechanical strength, biodegradability, and ecological benefits. The fibers were collected directly from the field, air-dried, cut into 18 mm lengths, and then pretreated and extracted using the traditional seawater retting method, with a salinity ranging from 37 to 40 g/l (Mediterranean Sea) and a pH value of 8. The main properties of Alfa fibers are listed in Table 3.

Table 3 - Characteristics of the used fibers (Hanana et al, 2015; Dallel, 2012)

Parameters	Unit	Polypropylene	Alfa
Length (l)	mm	18	18
Diameter (d)	µm	26 - 32	10-30
Specific density	g/cm^3	0,91	1,43 - 1,51
Tensile strength	MPa	(400-300)	75 ± 24,09
Young's modulus	MPa	(3,5-3,9)	8000 ± 2700

Sample preparation

The experimental program consists of producing mixtures composed of soil, cement, and fibers. The different tests were carried out on samples that were previously reworked and dried in an oven at a temperature of 60°C for 24 hours in order to avoid any alteration of the particles. The soil was treated with 4% of cement. It should be noted that the choice of the cement percentage was made in accordance with the nature of the material used and its pH, which is 9.1.

Then different percentages (0.3%, 0.6%, 0.9%) of synthetic (polypropylene) or vegetable (Alfa) fibers, 18 mm in length, were added to the natural soil. Afterwards, the dry soil-cement and fibers were mixed homogeneously with water for 15 minutes, according to the NF EN 197-1 standard. Then, the mixture (soil + cement + fibers) was prepared mainly by hand, rather than using a mixer that can cause the fibers to tangle or break. Table 4 presents the symbol sand proportions of the materials used in the composition of the different mixtures tested in this study.

On the other hand, unconsolidated and undrained (UU) triaxial compression tests were carried out on three series of cylindrical samples of 35 mm diameter and 70 mm height, which gives a length-to-diameter ratio of 2. It should be mentioned that this study examines three different samples: an untreated soil, a cement-treated soil, and a cement-treated soil reinforced with fibers. The samples were then compacted at the optimal water content (w_{opt}) and at 95% of the maximum dry density (γ_{dmax}) in a mold with two upper and lower pistons in order to have a homogeneous compaction stress distribution in three equal layers of soil using the static compression method.

Afterwards, the samples were slowly and carefully removed from the mold and were then immediately wrapped in a plastic film for 24 hours in order to avoid or minimize any change in moisture. It should be noted that,

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once the samples were prepared, they were subjected to confining pressure values equal to 100 and 300 kPa. Then, a piston was used to apply a vertical stress on the samples until failure. The vertical deformation Δh was measured using a 10-2 precision dial gauge. The testing speed used during the unconsolidated and undrained (uu) triaxial compression tests was set at 0.5 mm/min.

Furthermore, unconfined compression strength tests (UCS) were carried out on two series of cylindrical samples of 50 mm in diameter and 100 mm in height. Three types of samples are considered in this study: an untreated soil, a cement-treated soil, and a cement-treated soil reinforced with fibers. The samples were made at the SOP (Standard Optimum Proctor). Once the compacted specimens were removed from the steel mold, they were stored in a humid room at a temperature of (20± 1)°C for a curing time of 1, 7 and 28 days. The machine used in the tests is a compression press with a capacity of 50 kN, with a crushing speed of 1.27 mm/min. The vertical deformation was measured using a 10-2 mm precision dial gauge. The test was conducted until failure occurred or until the axial deformation reached approximately 10% of the total length of the specimen. In order to guarantee the reliability of the unconfined compressive strength results, the average of two values recorded on two standard samples was taken.

Table 4 - Mixture suggestions

Materials		Name of the mixtures studied
S0	Series 1	Natural Soil
S0 et Fpp 0,3%	Series 2	Soil and 0,3% polypropylene fibers
S0 et Fpp 0,6%		Soil and 0,6% polypropylene fibers
S0 et Fpp 0,9%		Soil and 0,9% polypropylene fibers
S0 et FA 0,3%		Soil and 0,3% Alfa fibers
S0 et FA 0,6%		Soil and 0,6% Alfa fibers
S0 et FA 0,9%		Soil and 0,9% Alfa fibers
S4 et Fpp 0,3%	Series 3	Soil with 4% cement and 0,3% polypropylene fibers
S4 et Fpp 0,6%		Soil with 4% cement and 0,6% polypropylene fibers
S4 et Fpp 0,9%		Soil with 4% cement and 0,9% polypropylene fibers
S4 et FA 0,3%		Soil with 4% cement and 0,3% Alfa fibers
S4 et FA 0,6%		Soil with 4% cement and 0,6% Alfa fibers
S4 et FA 0,9%		Soil with 4% cement and 0,9% Alfa fibers

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Results and analyses

Determination of the cement percentage

The measurement of the pH in materials allows the evaluation of the binder treatments necessary to react with the soil over time. The pH was determined using a pH meter equipped with a glass electrode in a soil suspension diluted in distilled water according to ASTM D-4972. The effect of cement content on pH for the treated and untreated samples is presented in Figure 1. The pH value increases with the percentage of cement to reach a value of 11.7 for samples containing 4% and 6% cement, from an initial value of 9.1 for the natural soil. It can be concluded that the amount of cement necessary to react with the soil is about 4%. This result is consistent with those of several researchers (Chew et al, 2004; Tran 2009; Kalkan, 2011; Portelinha et al, 2012).

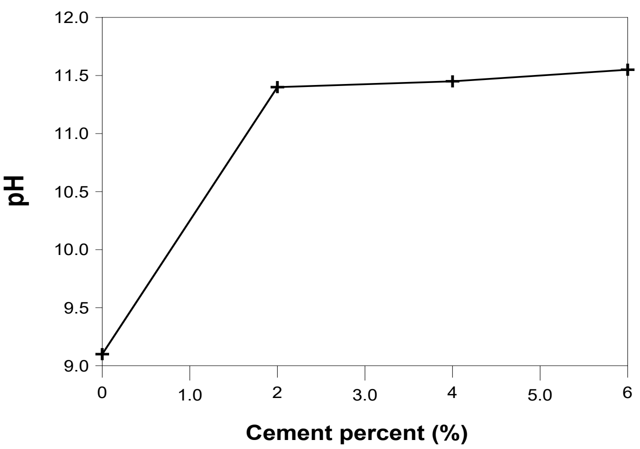


Figure 1 - Effect of the cement on the pH

Effect of fibers and cement on the shear strength

Figures 2a and 2b, and Figures 3a and 3b represent the variations of the deviatoric stress (q) and the axial strain (ε_1) for unreinforced and fiber-reinforced samples, using polypropylene and Alfa fibers at various fiber contents (0%, 0.3%, 0.6%, and 0.9%) under confining pressure values of 100 kPa and 300 kPa. The triaxial tests considered three key variables: fiber inclusion rate (ρf), type of fiber (polypropylene or Alfa), and confinement stress (σ_3), in order to study and analyze the behavior of both unreinforced and fiber-reinforced soils.

From Figure 2a, it can be seen that for the unreinforced samples, the deviatoric stress increases up to approximately 8% axial strain and then remains constant under a low confining pressure (σ_3 = 100 kPa). When the same confining pressure was applied to soil reinforced with polypropylene fibers at different inclusion rates (i.e., 0.3%, 0.6%, and 0.9%), no peak was observed in the deviator stress–strain curves up to approximately 12% axial strain. Similar findings have been reported by Michalowski and Cermak (2003), Yetimoglu and Salbas (2003), Kumar et al. (2007), Diambra et al. (2010), Li and Zomberg (2012), Maliakal and Thiyyakkandi (2013), Kumar et al. (2018), Diambra and Ibraim (2014), and Shen et al. (2021).

It was nevertheless observed that the presence of polypropylene fibers led to an increase in the deviatoric stress as the fiber content increased under the same confining pressure. For instance, a failure stress of 475 kPa was recorded for unreinforced samples at axial strains between 8% and 11.5% under a confining pressure of 100 kPa. In comparison, deviator stresses of 550, 551, and 575 kPa were obtained for fiber contents of 0.3%, 0.6%, and 0.9%, respectively, indicating a slight improvement ranging from 16% to 21%.

With regard to reinforcement with polypropylene fibers under a confining pressure of 300 kPa (Figure 2b), it was observed that the maximum strength increased as the fiber content in the soil increased (0.3%, 0.6%, and 0.9%). The corresponding deviatoric stresses were 1000, 1150, and 1200 kPa, indicating strength increases of 25%, 44%, and 50%, respectively. This improvement could be explained by the emergence of contact forces leading to particle locking. Similar findings were reported by Shen et al. (2021) based on triaxial tests conducted on low-plasticity clay reinforced with fibers.

On the other hand, in the presence of Alfa fibers, an opposite effect of fiber reinforcement on the maximum shear strength was observed under low confining pressure (Figure 3a). Specifically, for a confining pressure of σ_3 = 100 kPa, the deviatoric stress decreased with the increase in fiber content of 0.3%, 0.6%, and 0.9%, reaching 350, 300, and 250 kPa, respectively. At higher confining pressure (σ_3 = 300 kPa) (Figure 3b), the soil samples were more confined and thus more resistant to deformation, resulting in a higher deviatoric stressat failure compared to samples tested at 100 kPa. In the case of Alfa fiber-reinforced soil, it was noted that under the same confinement (σ_3 = 300 kPa), the deviatoric stressslightly exceeded that of the unreinforced soil, reaching 850 kPa for a fiber content of 0.3%. For higher fiber contents (0.6% and 0.9%), the deviatoric stressvalues were approximately 750 and 790 kPa, respectively. However, a decrease in strength was observed in soil samples reinforced with Alfa fibers, compared to the resistance of soil samples reinforced with polypropylene fibers.

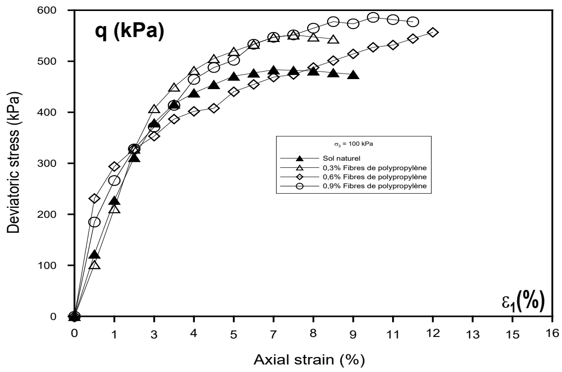


Figure 2a - Relationship between deviatoric stress and axial strain for polypropylene fiber-reinforced and unreinforced soils specimens under a confining pressure of 100 kPa

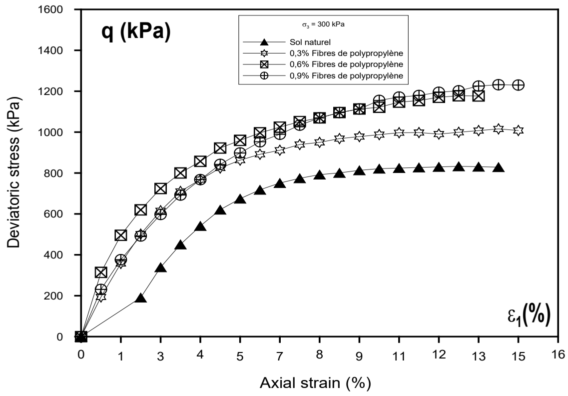


Figure 2b - Relationship between deviatoric stress and axial strain for polypropylene fiber-reinforced and unreinforced soils specimens under a confining pressure of 300 kPa

When the soil was treated with 4% cement and reinforced with fibers (Figures 3a, 3b, 4a and 4b), it was noted that its deviatoric stress became much larger than that of the untreated and unreinforced soil.

However, for a low confining pressure (σ_3 = 100 kPa) (Figure 4a), the Alfa fiber-reinforced and cemented soil presented a deviatoric stress ranging from 525 to 620 kPa corresponding to 0.3% to 0.9% of fibers content. On the other hand, for a high confining pressure (σ_3 = 300 kPa) (Figure 4b), an increase in the maximum shear strength was observed to reach 800, 900 and 1100 kPa for 0.3%, 0.6% and 0.9% of Alfa fibers.

Comparing with the natural sample, a maximum increase of 27% and 38% was obtained for low and high confining pressure, respectively.

Under low confining pressure (σ_3 = 100 kPa), samples reinforced with polypropylene fibers and cemented (Figures 5a), presented a maximum deviatoric stress values of 700, 760, and 850 kPa, corresponding to an increase of 78%, 73%, and 68% with 0.3%, 0.6%, and 0.9% of fibers, respectively. At high confining pressure (σ_3 = 300 kPa) (Figure 5b), the maximum deviatoric stresses were 1170, 1400 and 1430 kPa, corresponding to an increase of 46%, 75% and 79%, respectively.

In general, no peak shear strength was observed in cemented and fiber-reinforced samples, which explains the ductile behavior of the soil. Except for the case of those treated and reinforced with 0.6% and 0.9% Alfa fibers, under a low confining pressure (σ_3 =100 kPa) where a strength peak was observed, followed by a residual strength for a low confining pressure.

It can consequently be asserted that the incorporation of fibers, regardless of their nature, influences the behavior of the soil and enhances its deformation capacity. In other words, the soil becomes more ductile. The studies cited above indicate that the shear strength of the soil can be improved through the addition of reinforcing fibers. Furthermore, it is observed that there is a confining pressure limit which affects the shear strength of the soil. Similar observations were reported by Gray and Ohashi (1983), Estabragh et al. (2011, 2012), and Shen et al. (2021), who noted that below a certain confining pressure, fibers tend to slide or detach.

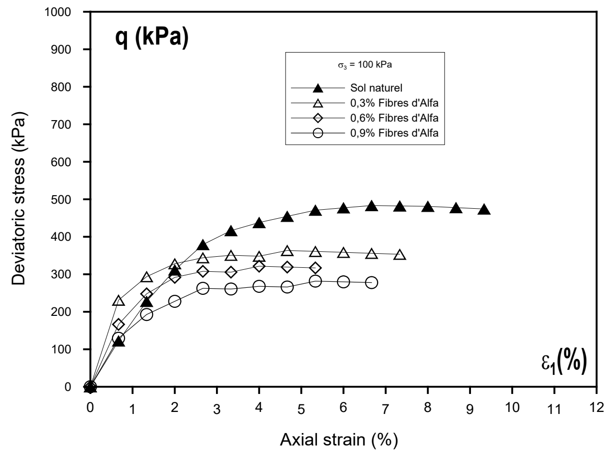


Figure 3a - Relationship between deviatoric stress and axial strain for Alfa fiber-reinforced and unreinforced soils specimens under a confining pressure of 100 kPa

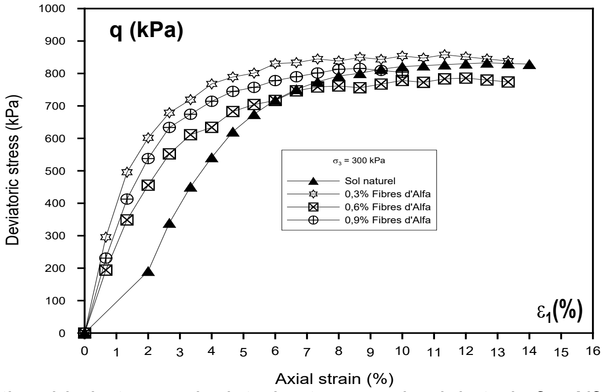


Figure 3b - Relationship between deviatoric stress and axial strain for Alfa fiber-reinforced and unreinforced soils specimens under a confining pressure of 300 kPa

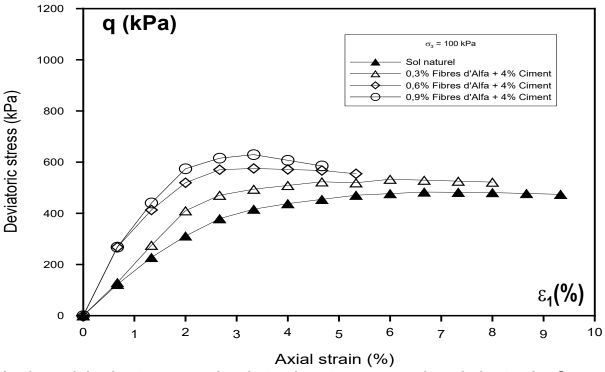


Figure 4a - Relationship between deviatoric stress and axial strain for cement-treated, Alfa fiber-reinforced, and unreinforced soil specimens under a confining pressure of 100 kPa

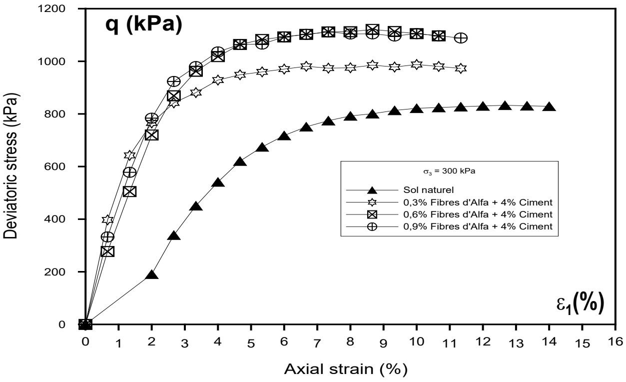


Figure 4b - Relationship between deviatoric stress and axial strain for cement-treated, Alfa fiber-reinforced, and unreinforced soil specimens under a confining pressure of 300 kPa

Figure 5 shows the variation of undrained maximum strength (q_{max}) as a function of fiber content for untreated and treated-reinforced samples. The results indicate that q_{max} of the fiber-reinforced cemented soil is influenced by both the confining pressure (σ_3) and the fiber content.

The q_{max} of the fiber-reinforced soil decreases with the percentage of Afla fibers (Figure 5a) and increases with the percentage of polypropylene fibers for both confining pressure (Figure 6b). In the case of Alfa fibers, the decrease in q_{max} could be due to the absorption of water by the latter, which alters their mechanical behavior and strength capacity. The increase of q_{max} for the polypropylene fibers (Figure 5b) can be attributed to their random distribution within the soil matrix, which forms a reinforcing structure that limits particle displacement and deformation of the soil. Conversely, for the reinforced and cemented samples, qmax increases consistently with fiber content, regardless of their nature. This can be explained by the cementation between particles of the soil and fibers.

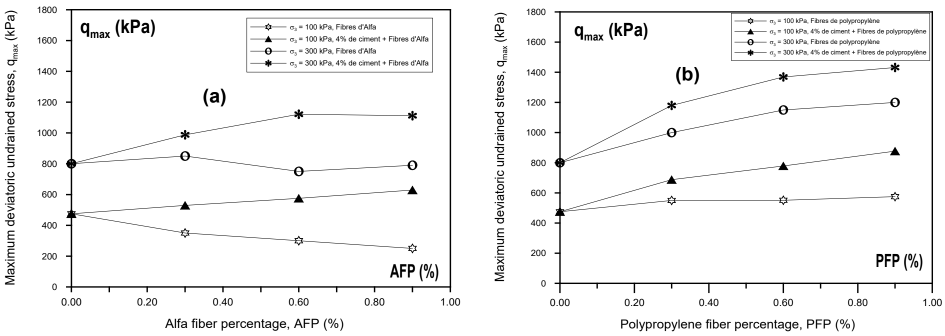


Figure 5 - Variation of undrained shear strength with fiber content at different confining pressures for untreated and cement-treated reinforced soil
(a) Alfa fibers, (b) *p*olypropylene fibers

Furthermore, the effect of cement treatment and reinforcement with two types of fibers on the mechanical strength parameters was examined in detail by analyzing the internal friction angle (ϕ_u) and cohesion (C_u), which were determined using Mohr's circles. Figure 6 illustrates an example of the determination of cohesion and the friction angle for the untreated samples.

It was observed that both parameters are influenced by the fiber content and the amount of cement used. Additionally, the variation of cohesion (C_u) and friction angle (ϕ_u) seems to be different between the samples that are only reinforced and those reinforced and cemented.

Figures 7 and 8 illustrate the effect of fiber reinforcement and treatment with 4% cement on the cohesion and internal friction angle of the soil. The results show a significant reduction in cohesion, for Alfa fiber-reinforced samples (Figure 7a), decreasing from 100 kPa to 20 kPa as the fiber content increases from 0% to 0.9%, which corresponds to an 80% reduction. In contrast, samples reinforced with polypropylene fibers exhibit only a slight decrease in cohesion, from 100 kPa to 78 kPa (Figure 7b). This reduction in cohesion can be attributed to sliding between fibers, which reduces the interlocking effect and, hence, the cohesive strength. These observations are consistent with the findings of Consoli et al. (1998).

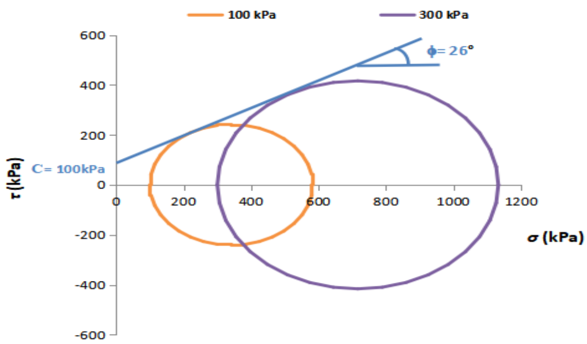


Figure 6 - Determination of shear strength parameters (C_u, ϕ_u) from Mohr's circles for the untreated samples

On the other hand, for samples treated with 4% cement and reinforced with Alfa fibers, the results show a slight increase in cohesion, from 100 kPa to 120 kPa, as the fiber content increases up to 0.9%, as shown in Figure 7a. This increase in cohesion is more pronounced in the case of polypropylene fiber reinforcement, where cohesion rises from 100 kPa to 160 kPa, representing an increase of approximately 60% compared to initial value (Figure 7b). The findings suggest that artificial fibers, in the presence of cement, promote better cementation of the soil matrix, thereby enhancing cohesion. Similar behavior was observed by Sivakumar Babu et al. (2008), Harichane et al. (2011), and Shen et al. (2021). Conversely, the presence of fibers in untreated soil tends to reduce cohesion. This may be due to grain sliding caused by the presence of fibers.

For samples treated with 4% cement and reinforced with Alfa fibers, the friction angle increased from 26° to 31° up to 0.3% fiber content, followed by a decrease of 3° when the fiber content exceeded 0.3%, as shown in Figure 8a. Conversely, in untreated soil samples reinforced with Alfa fibers, the friction angle increased up to 0.3% fiber content and then remained constant up to 0.9%.

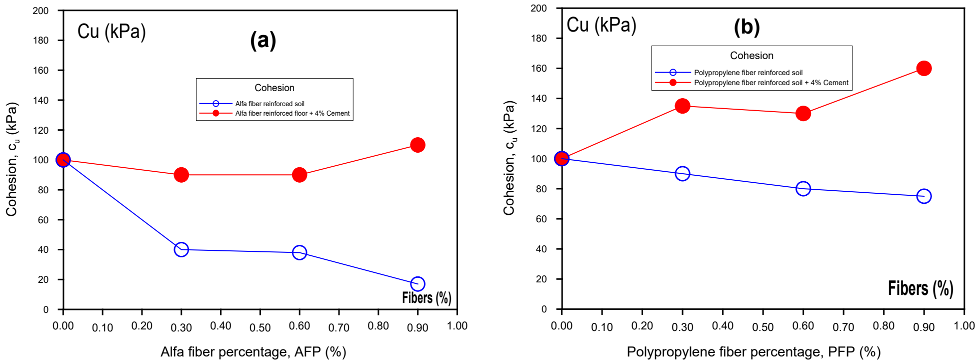


Figure 7 - Effect of fiber reinforcement and 4% cement treatment on soil cohesion: (a) Alfa fibers, (b) polypropylene fibers

With regard to the influence of cement treatment and fiber reinforcement on the friction angle, an increase from 26° to 34° was observed for samples treated with 4% cement and reinforced with 0.3% polypropylene fibers to an optimal content (Figure 8b). However, when the fiber content exceeded 0.3%, a slight angle decrease in the friction angle of about 2° was recorded. In contrast, untreated samples containing polypropylene fibers showed a continuous increase in friction angle with increasing fiber content (Figure 8b).

A simple comparison of the results regarding the influence of fibers on the friction angle and cohesion of samples treated with 4% cement and reinforced with fibers shows a general trend: an increase in cohesion for soils treated with 4% cement and reinforced with fibers (Figures 7a and 7b), as well as an increase in the internal friction angle for fiber-reinforced soils (Figures 8a and 8b).

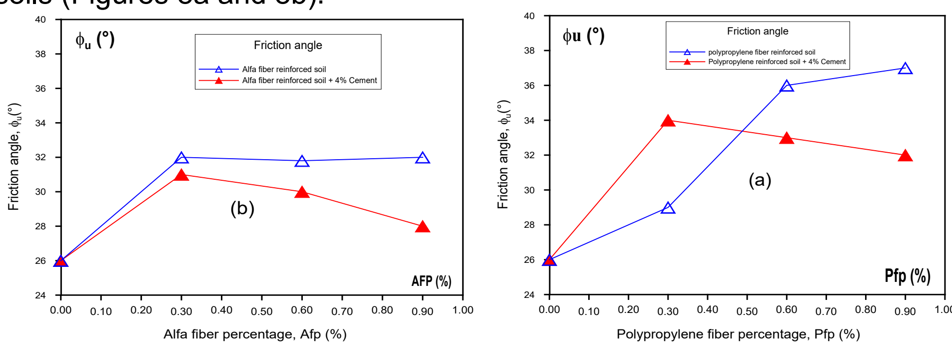
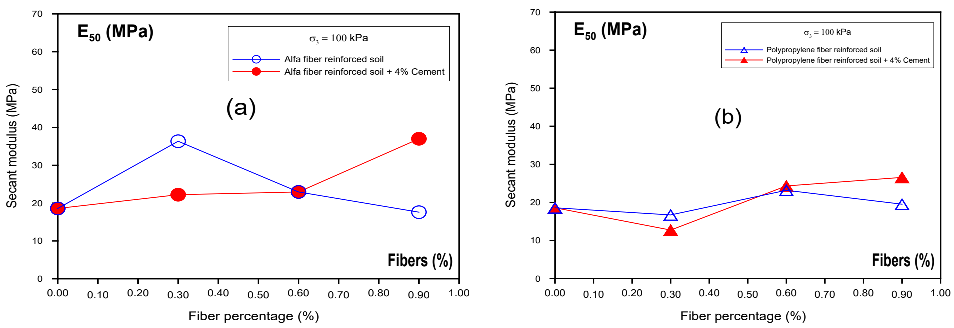


Figure 8 - Effect of fiber reinforcement and 4% cement treatmen on internal friction angle of the soil: (a) Alfa fiber, (b) polypropylene fiber

These findings can be attributed to the improvement of interfacial bonding and interlocking mechanisms between the fibers and soil particles as fiber content increases. It is important to note that fibers have the potential to generate multiple points of intersection, leading to the formation of a fiber network that enhances the confinement effect within the soil matrix (Wei et al, 2018). However, a general tendency toward reduced cohesion was observed in fiber-reinforced soils, regardless of fiber type (Figures 7a and 7b), along with a decrease in the internal friction angle in cement-treated, fiber-reinforced soils beyond a fiber content of 0.3% (Figures 8a and 8b). This reduction can be attributed to fiber overlapping and fibers wrapping, which may cause the formation of weak interfaces, thereby reducing the friction angle. In addition, no optimum fiber content could be identified in terms of improving the cohesion of reinforced soils, as shown in Figures 7a and 7b.

Effect of fibers on the secant modulus of a cemented soil

Figure 9 illustrates the variation of the secant modulus(E_{50}%) as a function of fiber content determined from the deviator stress–strain curves. Two levels of confining pressure, i.e., 100 kPa and 300 kPa, were applied. For samples treated with 4% cement and reinforced with different percentages of fibers, the secant modulus values increased. However, the inclusion of fibers, regardless of their type, reduces the stiffness of untreated (cement-free) soils under low confining stress (100 kPa) (Figures 9a and 9b). These findings are in agreement with those reported by Ozkul and Baykal (2006), Ekinci and Ferreira (2012), Maliakal and Thiyyakkandi (2013), Ekinci (2016), and Mirzababaei et al. (2017, 2018). It is also worth noting that under higher confining stress (300 kPa), a clear increase in the secant modulus is observed, as illustrated in Figures 9c and 9d. In all cases, specimens treated with cement and reinforced with fibers (either polypropylene or Alfa) exhibited significantly higher stiffness compared to unreinforced samples.



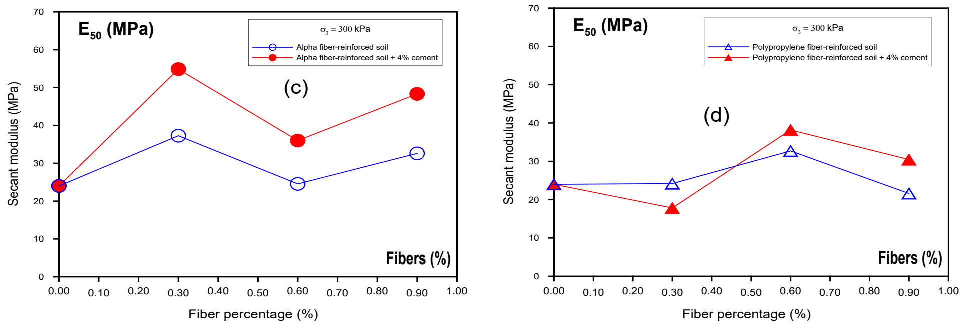


Figure 9 - Effect of fibers reinforcement and treatment at 4% cement on secant modulus of the soi: (a) Alfa and (b) polypropylene at 100 kPa confining pressure, (c) Alfa and (d) polypropylene at 300 kPa confining pressure

Effect of fibers on the unconfined compressive strength

Figures 10a and 10b present the evolution of the maximum unconfined compressive strength over curing time in open air for 1, 7, 14, and 28 days. A large number of tests were conducted in this study; however, only a selection of representative results is presented to illustrate the influence of fiber type and content. The findings clearly indicate that the unconfined compressive strength of specimens treated with 4% cement is significantly affected by both the nature and dosage of the added fibers.

Furthermore, in all cases analyzed, an increase in unconfined compressive strength was observed with the inclusion of polypropylene fibers in the presence of 4% cement, for fiber contents ranging from 0.3% to 0.9% (Figure 10a). This may be due to the entanglement of fibers and the bonding forces between soil particles, which have contributed to improved contact between the fiber surface and the soil matrix. The unconfined compressive strength reached its maximum values after 7 days of curing and remained nearly constant. The maximum UCS values recorded were 1380 kPa, 1510 kPa, and 1575 kPa for 0.3%, 0.6%, and 0.9% of fiber content respectively. Accordingly, an increase in unconfined compressive strength of approximately 47%, 43%, and 41% was observed for fiber contents of 0.3%, 0.6%, and 0.9%, respectively, compared to untreated soil. On the other hand, the compressive strengths of samples treated with 4% cement and reinforced with Alfa fibers after 7 days of curing time were lower than those reinforced with polypropylene fibers. However, at 14 days of curing time, the strength of samples reinforced with 0.9% Alfa fibers reached 1800 kPa, representing a 36% increase compared to the corresponding polypropylene fiber-reinforced samples (Figure 10b). These findings suggest that, overall, the combination of fibers and cement significantly enhances the compressive strength of silty sand soils.

Similar findings have been reported by other researchers, such as Anggraini et al. (2015), Wei et al. (2018), Choobbasti et al. (2019), Shen et al. (2021), and Xiao et al. (2022), who demonstrated that the compressive strength of soils treated with hydraulic binders can be significantly improved.

It can be observed that the optimal compressive strength was achieved after 7 days of curing for all samples treated with cement and reinforced with polypropylene fibers (FP). Beyond this curing period, the strength values remained nearly constant up to 28 days (Figure 10a). In contrast, for samples treated with cement and reinforced with Alfa fibers (FA), the maximum compressive strength was reached after 14 days of curing (Figure 10b).

To better illustrate the influence of fiber content on the soil matrix, the variation in unconfined compressive strength (Rc) as a function of fiber percentage is presented in Figures 11a and 11b. It can be observed that uniaxial compressive strength increases with the fiber percentage. This is in agreement with several researchers (Kumar et al, 2007; Consoli et al, 2011; Shao et al, 2014; Kumar et al, 2018).

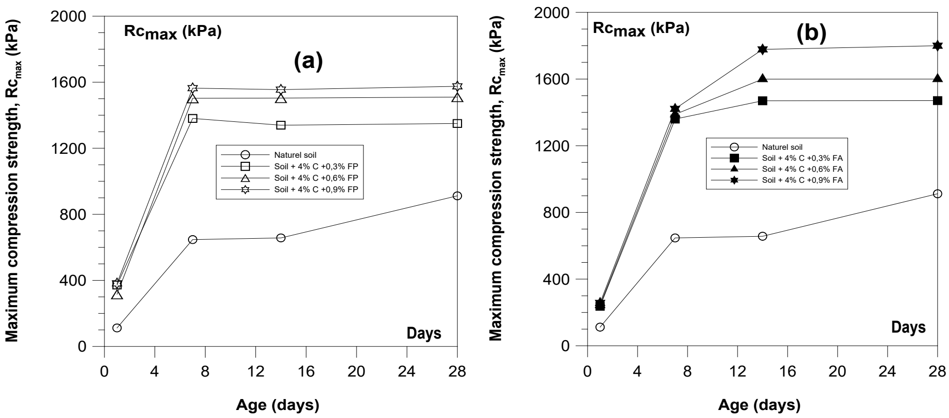


Figure 10 - Effect of curing time on the maximum compressive strength of soil specimens reinforced with fibers and stabilized with 4% cement in open-air condition: (a) polypropylene fibers, (b) Alfa fibers

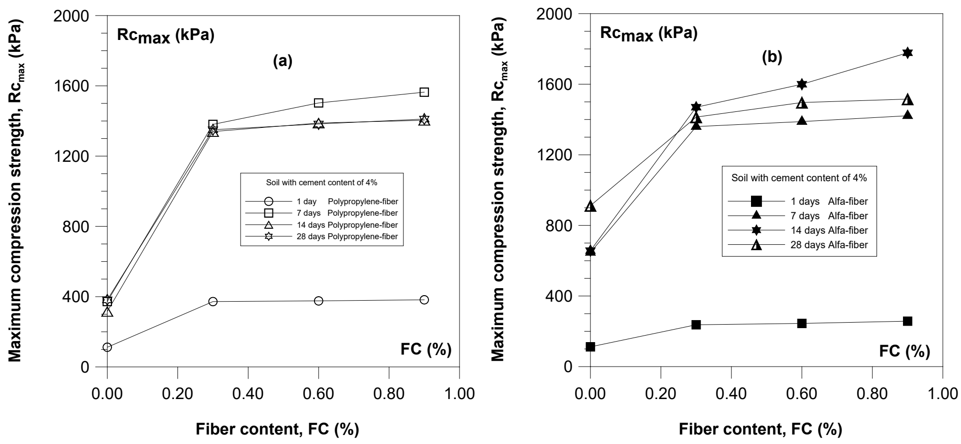


Figure 11 - Effect of fiber type and content on UCS in open-air curing conditions: (a) polypropylene fibers, (b) Alfa fibers

Conclusion

This study investigated the effects of two types of fibers (polypropylene and Alfa) on the mechanical properties of silty sand through unconsolidated undrained triaxial and unconfined compression tests. The results show that fiber reinforcement significantly improved the geotechnical properties of the soil, particularly its shear and compressive strength. The key findings are as follows:

1. Polypropylene fibers (0.9%) significantly increased shear strength, thanks to their high tensile strength and the strong frictional bond between soil particles and fibers. Alfa fibers (0.3%) also improved shear resistance, but to a lesser extent.

2. Soil samples treated with 4% cement and reinforced with polypropylene fibers exhibited ductile behavior across both confining stresses (100 and 300 kPa). In contrast, cement-treated samples reinforced with Alfa fibers were slightly brittle at low confining stress but became more ductile under higher confining stress.

3. The cohesion of the samples treated with 4% cement increased as the fiber content increased. This increase was higher in the case of cement-treated samples reinforced with polypropylene fibers. The cohesion value was equal to 160kPa for samples reinforced with 0.9% polypropylene fibers. However, the samples treated with cement and reinforced with Alfa fibers had a cohesion value of 110 kPa for the same reinforcement percentage.

4. The friction angle for cement-treated samples reinforced with 0.3% polypropylene fibers increased from 26° to 34°. On the other hand, the friction angle for untreated and fiber-reinforced samples also increased with fiber content. In general, the friction angles of the untreated and reinforced samples were higher than those of treated and reinforced samples.

5. The secant modulus (E50%) of the cemented and Alfa fiber-reinforced samples was higher than those reinforced with synthetic fibers. Nevertheless, the stiffness of the reinforced samples with synthetic fiber was greater than the natural samples. The optimal stiffness was achieved with 0.3% Alfa fibers and 0.6% polypropylene fibers.

6. The UCS test showed that both polypropylene and Alfa fibers increased the compressive strength of the soil. The soil reinforced with polypropylene fiber exhibited a higher compressive strength (42%) than the untreated soil. Furthermore, the compressive strength of Alfa fiber-reinforced samples increased by 36% at 14 days of curing. The fiber entanglement and bonding forces between the soil particles contributed to this improvement.

Overall, the combination of cement treatment and fiber reinforcement is highly effective in improving the soil's mechanical properties, offering a cost-effective solution with environmental benefits, particularly with the use of natural fibers like Alfa in civil engineering and road construction projects.

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Poboljšanje performansi muljevitog peska primenom cementa i vlaknaste armature: studija mehaničkog ponašanja

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Sažetak:

Uvod/cilj: Cilj ovog rada je valorizacija lokalnog materijala iz zapadnog regiona Alžira za potencijalnu primenu u izgradnji puteva. Glavni cilj je ispitivanje uticaja dodavanja sintetičkih polipropilenskih vlakana i prirodnih biljnih vlakana Alfa u različitim količinama (0%, 0,3%, 0,6% i 0,9%) na čvrstoću muljevitog peska stabilizovanog sa 4% cementa.

Metode: Ispitivanje se vrši testovima jednoaksijalne (nekonfinovane) čvrstoće i nekonsolidovanim nedreniranim triaksijalnim testovima. Ispitivanja se sprovode na mešavinama sastava tlo–vlakna–cement koje su statički zbijene u uslovima standardnog Proktorovog optimuma (SOP) (γdmax = 17 kN/m³ i wopt = 16,6%) i očvrsle su na otvorenom u vremenskom periodu od jedan, sedam i 28 dana.

Rezultati: Rezultati su pokazali značajno poboljšanje mehaničke čvrstoće tretiranog tla, uz promenu ponašanja pri lomu iz krhkog u duktilno. Dodatak 0,3% vlakana povećao je koheziju uz istovremeno smanjenje ugla unutrašnjeg trenja. Pored toga, uzorci ojačani vlaknima i cementom pokazali su veću krutost u poređenju sa netretiranim tlom. Takođe, najveća jednoaksijalna čvrstoća na pritisak postignuta je kombinacijom 0,9% vlakana i 4% cementa.

Zaključak: Ojačavanje cementiranog muljevitog peska polipropilenskim i Alfa vlaknima značajno poboljšava njegovu mehaničku čvrstoću i krutost. Dodatak od 0,9% vlakana daje najveću čvrstoću na pritisak, uz efikasan prelaz ponašanja tla iz krhkog u duktilno. Ovi rezultati potvrđuju da je valorizacija lokalnih alžirskih materijala tehnički izvodljivo i održivo rešenje za razvoj infrastrukture puteva.

Ključne reči: muljeviti pesak, biljka Alfa, polipropilenska vlakna, otpornost na smicanje, ugao trenja, kohezija, jednoaksijalna čvrstoća na pritisak.

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