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INVESTIGATION OF THE SHEAR STRENGTH OF REINFORCED SILTY SAND

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Abstract
Introduction: This paper presents an experimental investigation that aims to study the influence of silt content, glass fiber content, and their combined effect on the shear behavior of silty sand. For this **purpose**, a series of tests using direct shear apparatus (as **methods**) were carried out on sand mixed with various silt and fiber contents. Samples were prepared with a relative density of 50 %, and each mixture was tested at three different normal stresses. The experimental **results** indicated an increase in shear strength at 10 % silt content, followed by a decrease in shear strength with increasing silt content from 10 % to 30 %. It was also found that 0.5 % is the optimal content that can be added to sand-silt mixtures to enhance their shear strength and friction angle, although the mixtures become more contractive.

Keywords: sand, silt, glass fiber, shear strength, cohesion, friction angle.

Introduction

It is widely recognized that the behavior of sand-fines mixtures, frequently encountered in nature, is largely affected by the type, plasticity, and content of the fine particles they contain. These soils can have instability problems under certain conditions due to their unfavorable geotechnical properties, which make them incapable of supporting the loads to which they are subjected. This type of soil, therefore, needs its properties enhanced to make it exploitable and suitable for construction. Soil improvement methods, widely used today, are numerous and varied. Han (2015) classified soil improvement methods according to their function into six categories: densification, replacement, drainage and consolidation, chemical stabilization, reinforcement, and thermal and biological treatment.

Geotechnical engineering has recently witnessed an increasing interest in the study of soils reinforced with randomly distributed fibers (Benziane et al., 2019; Chen and Loehr, 2008; Consoli et al., 2007; Diambra et al., 2010; Gray and Al-Refeai, 1986; Khebizi et al., 2019; Michalowski and Cermák, 2003; Benziane et al., 2022; Romero, 2003; Safdar et al., 2020; Tang et al., 2007). Various synthetic fibers are currently in use, including polypropylene, polyethylene, polyester, nylon, steel, and glass fibers (Rabab'ah et al., 2021). Glass fibers have been extensively utilized in common and demanding applications due to their numerous advantageous features, such as high tensile strength, low fabrication costs, and superior chemical resistance (Derradji et al., 2018). The mechanical behavior of soils mixed with glass fibers has been studied by numerous researchers. Consoli et al. (1998) found that glass fiber reinforcement increases both peak and residual triaxial strengths, decreases stiffness, and changes the brittle behavior of the cemented soil to a more ductile one. Consoli et al. (2004) also found that the peak friction angle of both cemented and uncemented sand increased, and the peak cohesive intercept decreased slightly when glass fibers were added to the sand-cement mixture. According to Ahmad et al. (2012), the inclusion of randomly distributed glass fibers with soil particles creates a soil-fiber matrix that provides an interlocking effect to reinforce soil by implicitly preserving soil integrity and improving its interparticle frictional interface. By conducting direct shear tests on sand samples mixed with different percentages of glass fibers (0 %, 0.1 %, 0.3 %, and 0.5 %), Benessalah et al. (2016) found that sand containing 0.3 % fiber content generally exhibits higher shear strength and friction angle than other mixtures. Additionally, it is the most dilatant, particularly in the dense state. Bouaricha et al. (2017) found that specimens of sand mixed with glass fiber have a maximum shear strength greater than that of unreinforced soil, and that the optimal

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value of the fiber content is 0.2 %. Bouaricha et al. (2017) also found that, for this optimal fiber content, adding fibers of 20 mm length gave the highest shear strength for both types of sand. The results obtained by Rabab'ah et al. (2021) showed that the addition of glass fiber to an expansive soil increases its unconfined compressive strength, indirect tensile strength, and CBR values, and decreases its swell potential. Benziane et al. (2022) found that glass fiber significantly improved the shear strength, cohesion interception, and friction angle of sand.

While there has been a significant amount of research on the mechanical behavior of granular and fine soils mixed with glass fibers, the impact of these fibers on the shear behavior of silty sands has not received as much attention as other soil types. The present study aims to investigate the shear behavior of sand mixed with different percentages of silt and glass fiber, focusing on the effect of silt content and fiber content, as well as their combined effect.

Methods and Materials

Sand-silt mixtures

The soil used in this study is sand extracted from the banks of the Chlef river, which flows through the city of Chlef to the west of Algiers. The decision to use this soil in an effort to improve it was not made randomly. Several researchers (Arab, 2009; Belkhatir et al., 2014; Della et al., 2011, 2014) showed that the soil in this region can exhibit instability problems under certain conditions. Durville and Meneroud (1982) also reported that, during the 1980 earthquake, liquefaction phenomena had appeared in the valley of the Chlef river where the soil was located.

After collecting the sand and transporting it to the laboratory, sand particles with a diameter greater than 2 mm were removed through dry sieving. Particles smaller than 0.08 mm, which typically represent silt grains used in this study, were separated from the sand by dry sieving and washing. The clean sand and silt were then dried to a constant mass (Fig. 1).

The silty sand samples were obtained by mixing clean sand (Sc = 0 %) with different silt fractions (Sc = 10 %, 20 %, and 30 % by dry soil mass). Fig. 2 presents the grain size distribution curve of sand-silt mixtures, and their properties are given in Table 1.

Glass fiber

The fibers used are white glass fibers with circular cross-sections, which have a length of 12 mm and a diameter of 18 μm (Fig. 4). The physical and mechanical characteristics of fibers are presented in Table 2.

Testing procedure

To investigate the combined effect of silt and fiber reinforcement on the shear behavior of fiber-reinforced sand-silt mixture at a medium-dense state (Dr = 50 %), a series of 48 direct shear tests, divided

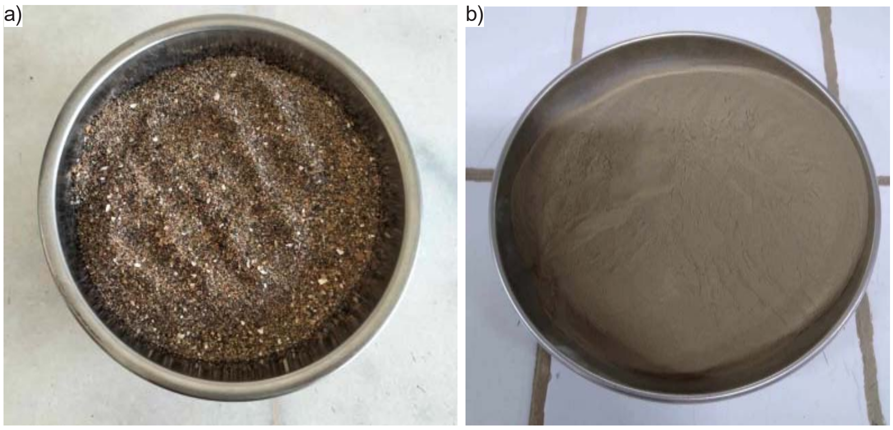

Fig. 1. Basic materials used: (a) clean Chlef sand, (b) Chlef silt

Table 1. **Physical properties of sand and sand-silt mixtures**

Properties	Sand	Sand-silt			Silt
Silt content	0 %	10 %	20 %	30 %	100 %
Uniformity coefficient C_u	2.00	5.00	13.33	21.11	–
Coefficient of curvature C_c	0.82	1.95	4.41	3.29	–
Medium size D_{50} (mm)	0.45	0.36	0.34	0.30	0.029
Maximum diameter D_{max} (mm)	2.00	2.00	2.00	2.00	0.08
Specific density G_s	2.741	2.698	2.692	2.686	2.667
Maximum void ratio e_{max}	0.91	0.81	0.77	0.76	1.563
Minimum void ratio e_{min}	0.61	0.49	0.42	0.40	0.991

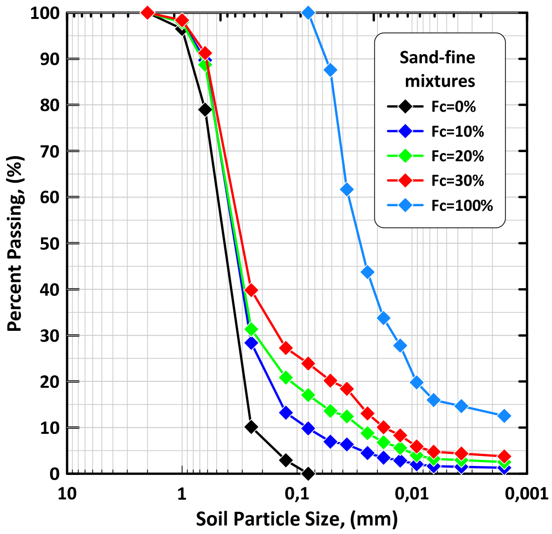

Fig. 2. Grain size distribution curve of Chlef sand-silt mixtures

into three sets, was considered for this laboratory experiment. The first set of samples was obtained by mixing clean Chlef sand with various silt fractions (*Sc* = 0, 10, 20, and 30 %) to investigate the impact of silt fractions on the behavior of the sand-silt matrix. The second set was obtained using clean Chlef sand reinforced with various fiber contents (*Fc* = 0, 0.3, 0.5, and 0.8 %) to assess the reinforcing potential of glass fibers. The final set was obtained using unreinforced and reinforced sand-silt mixtures with glass fibers to evaluate the combined effect of silt fractions and fiber contents on the shear behavior of Chlef sand.

All tests were conducted at the Laboratory of Materials Science and Environment (LMSE) at the Hassiba Benbouali University of Chlef in Algeria. This experimental study was carried out using a standard laboratory direct shear apparatus with a square box measuring 60 × 60 inches. Fig. 5 presents a general

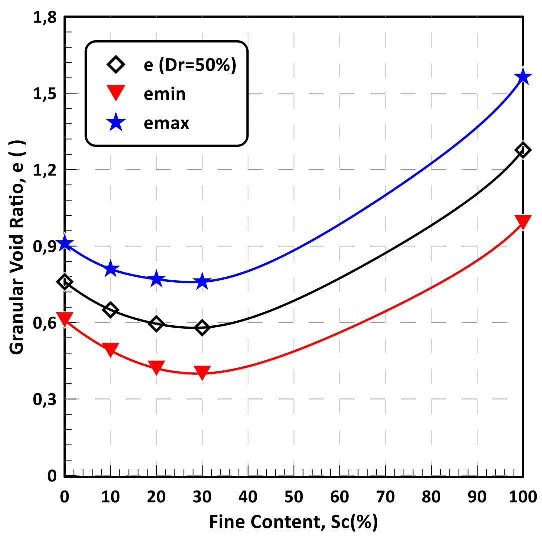

Fig. 3. Variation of the minimum and maximum void ratio as a function of fines content

Fig. 4. Glass fiber reinforcement

Fig. 5. View of the direct shear apparatus

Table 2. **Glass fiber characteristics**

Properties	Specific gravity	Length (m)	Diameter (mm)	Mean tensile strength (MPa)	Elastic modulus (GPa)
Glass fiber	2.62	12	18	485	73

view of the setup, showing the direct shear apparatus and the data acquisition system. Each test was repeated multiple times to ensure the reliability of the results. All the parameters considered in the testing program are listed in Table 3.

Sample preparation

The tested samples are mixtures composed of sand, silt, and glass fibers, prepared in a dry state (w = 0 %). The initial height of the samples is constant and equal to 2.5 mm. To determine the dry mass of the sand-silt mixture needed to fill the required volume, the initial density of the sample is proposed, and the following equations are used:

$$Ws = \frac{V_T \cdot Gs}{1 + e_{\max} - Id\left(e_{\max} - e_{\min}\right)},$$

where V_T and *Id* are the total sample volume and the desired density index, respectively. The fiber mass was then calculated. The fiber concentration (Fc) to be added is defined as a percentage of the dry mass of the sand-silt mixture.

Sample preparation begins by securing the half-boxes with two screws. Next, the holding plate is placed at the bottom of the shear box, followed by the grid plate. Once the masses of the constituents are determined, the sand, silt, and fibers are perfectly mixed until a homogeneous mixture is obtained (Fig. 6). This mixture is then deposited in the cavity of the shear box in three layers using the dry deposition method. To achieve the medium dense state (Dr = 50 %), no compaction was necessary; only the surface of each layer was leveled off.

After depositing the sample, the second grid plate is placed above it, followed by the loading piston.

Fig. 6. Sand-silt-fiber mixtures

The shear box must then be returned to its place in the frame if it has been moved to prepare the sample.

Consolidation and shearing

Each mixture was tested under three different normal stresses: 50, 100, and 200 kPa. Consolidation is considered complete when the vertical displacement stabilizes.

At the end of the consolidation, the two fixing screws of the two half-boxes are removed. Then, the sample is sheared at a constant speed of 1 mm/min until a horizontal displacement of approx. 7.5 mm is reached.

Results and Analysis

Influence of silt content

The results of direct shear tests conducted on sand-silt mixtures under a normal stress of 200 kPa are illustrated in Fig. 7. The shear stress (τ) evolution

Table 3. **Experimental program**

Test set	Fine fractions, *Fc* (%)	Glass fiber content, *Sc* (%)	Normal stress, σ (kPa)
1st set	0; 10; 20, and 30	0	50; 100, and 200
2nd set	0	0; 0.3; 0.5, and 0.8	
3rd set	10; 20, and 30	0; 0.3; 0.5, and 0.8	

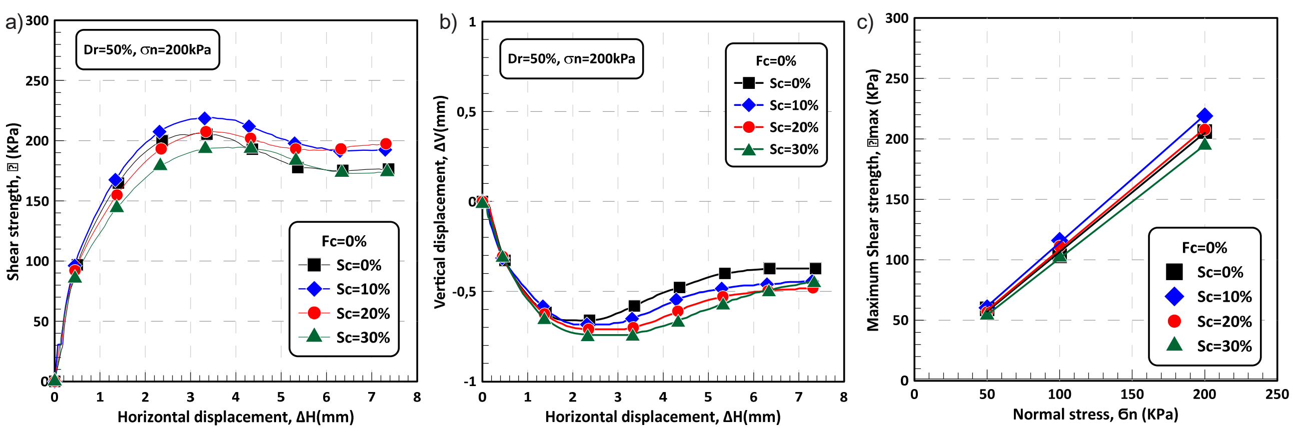

Fig. 7. Effect of silt content on the shear behavior of Chlef clean sand, *Dr* = 50 %, σ_N = 200 kPa: (a) variation of shear strength versus horizontal displacement, (b) variation of vertical displacement versus horizontal displacement, (c) intrinsic curve equation τ = σ·tgφ+*c*

curves show that all mixtures reach a maximum shear stress (τ_{max}) between approx. 2 and 5 mm of horizontal displacement (ΔH), after which the shear stress decreases slightly with the development of ΔH (Fig. 7a). Additionally, an increase in maximum shear strength is observed with increasing silt content up to 10 %, which represents a threshold content (Sc_{th} = 10 %). Beyond this point, the maximum shear strength decreases proportionally with increasing silt content (Fig. 7a). This result is in good agreement with those of Aouali et al. (2019) and Missoum Benziane et al. (2022). According to Belkhatir et al. (2010), the overall void ratio does not accurately represent the intergranular interface in sand-silt mixtures. When granular soil contains fines, the overall soil void ratio (e) can no longer accurately describe soil behavior. Below the threshold, fines only occupy the void spaces and do not significantly affect the mechanical behavior of the mixture. However, if the fines content increases beyond the threshold level, the behavior of the soil is governed by the fine matrix, and the coarse grains float in the fines. The interchange of this governing role can be expressed through the intergranular void ratio concept (Fig. 8). The intergranular void ratio e_s is defined according to Monkul and Ozden (2007) as the following relationship:

$$e_s = \frac{e + \dfrac{G \cdot Fc}{G_f \cdot 100}}{\dfrac{G}{G_s}\left(1 - \dfrac{Fc}{100}\right)},$$

where G_s and G_f are the specific gravity of the sand and finer grain matrices forming the soil, respectively. G is the specific gravity of the soil. G values are assumed to be the weighted average of the specific gravities of the grain matrices forming the mixtures.

The curves showing vertical displacement versus horizontal displacement for medium-density sand-silt mixtures under a confining pressure of 200 kPa are depicted in Fig. 7b. The results obtained show an increase in the contractive nature of the silty sand soil with the addition of silt content. Yamamuro and Lade (1997) attributed this behavior to the tendency of fines to occupy the void spaces after shearing, which generates a contractive behavior that results in the phenomenon of static liquefaction under undrained conditions.

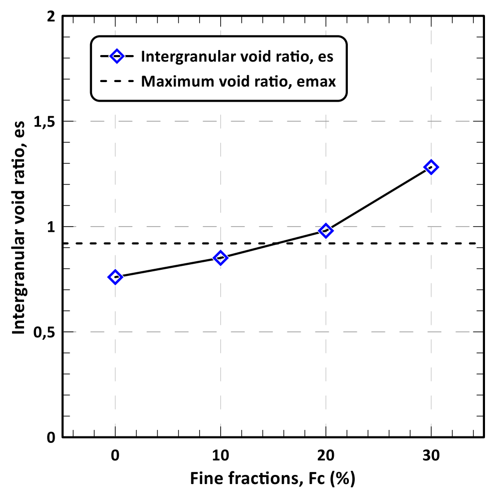

Fig. 8. Variation of intergranular void ratio versus fine fraction

Fig. 7c represents the evolution of maximum shear strength as a function of normal stress and silt content. It is clear that the maximum shear strength of the samples increased with increasing normal stress. However, sand-silt mixtures showed a decrease in maximum shear strength values after reaching the threshold fines content. Additionally, the shear strength parameters of sand-silt mixtures, obtained from the Mohr–Coulomb failure envelope (Fig. 7c) and summarized in Table 4, indicate that an increase in silt content leads to an increase in cohesion and internal friction angle up to a silt content of 10 %. After this point, the cohesion and friction angle of the mixture decrease. Missoum Benziane et al. (2022) attributed this loss of strength to the large volume that silt occupies in the voids between sand grains, causing them to dissociate and preventing them from interacting with each other.

Influence of fiber content

Fig. 9 illustrates the effect of glass fibers on the shear strength behavior of sand at a relative density of 50 % under a normal stress of 200 kPa. It has been found that the shear stress of unreinforced and fiber-reinforced sand increases steadily until it reaches its maximum value, and then it begins to decrease slightly with the development of horizontal displacement until the end of the test (Fig. 9a). Furthermore, it should be noted that the maximum shear strength (τ_{max}) increases with increasing fiber content up to 0.5 % (Fig. 9a). Once the optimal fiber content is exceeded, the maximum shear strength of the sand-fiber composite decreases. Wei et al. (2018) stated that this behavior is attributed to the reinforcing mechanism of fibers. Initially, fiber-reinforced specimens show an increase in strength due to the rise in interfacial friction between the soil particles and fibers. As the shearing process continues, the shear stresses in the soil mobilize tensile resistance in the fibers, which in turn imparts greater strength to the soil. At the same time, fibers produce numerous crossing sites and form fiber networks that create a spatial confinement effect on the soil, resulting in an increase in the composite strength to its maximum. However, after reaching peak strength, the fiber content exceeds the permissible value, leading to an uneven distribution of fibers due to overlapping and stacking. This creates weak interfaces that decrease the resistance of the soil-fiber mixture.

The variation of the vertical displacement (ΔV) of the sand-glass fiber mixtures as a function of the

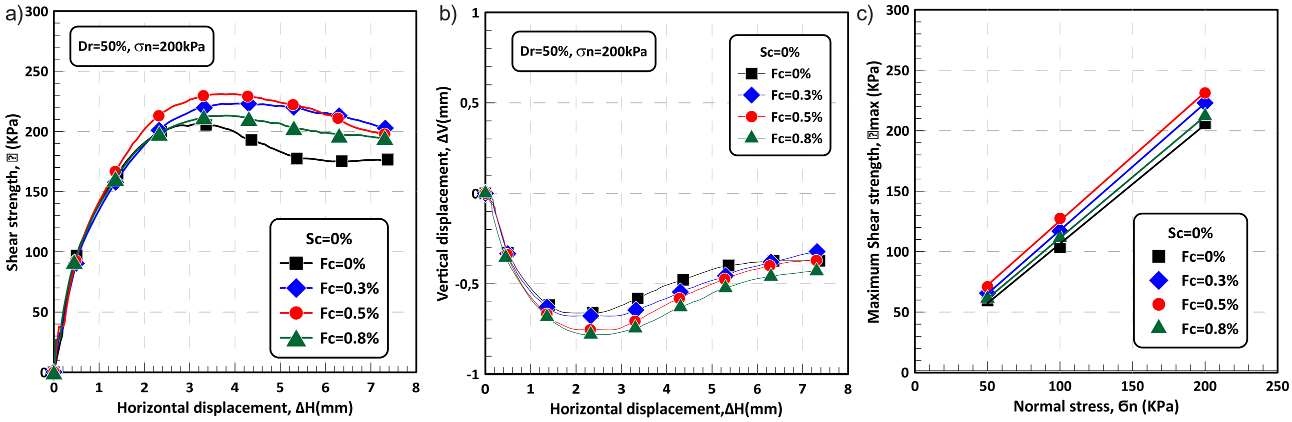

Fig. 9. Effect of fiber content on the shear behavior of Chlef clean sand, *Dr* = 50 %, σ_N = 200 kPa: (a) variation of shear strength versus horizontal displacement, (b) variation of vertical displacement versus horizontal displacement, (c) intrinsic curve equation τ = σ·tanφ + *c*

horizontal displacement (ΔH) is presented in Fig. 9b. All specimens initially show a contraction phase until a threshold is reached, at approx. 2 to 3 mm of horizontal displacement, after which a slight increase in their volume is noted. Additionally, adding glass fiber to the sand promotes its contractive behavior. This can be attributed to the role of fibers in improving the soil confinement stress. A similar observation was made by Romero (2003).

Fig. 9c illustrates the evolution of maximum shear strength as a function of fiber content (*Fc*) and normal stress (*σn*). It can be observed from this figure that the maximum shear resistance increases proportionally with increasing normal stress, and that the optimal fiber content is 0.5 % (Fc_{opt} = 0.5 %), which provides the best shear resistance for the three normal stresses. The shear strength parameters obtained from the Mohr–Coulomb failure envelope for the sand-fiber mixtures are presented in Table 4. An increase in the internal friction angle and cohesion of the sand-fiber mixture is observed when the fiber content increases from 0 to 0.5 %. This can be attributed to the special confinement effect of the fiber network. These results are in good agreement with those found by Benziane et al. (2022). Increasing the fiber content beyond 0.5 % leads to opposite results.

Influence of silt-fiber combination

The results of direct shear tests carried out on unreinforced and fiber-reinforced sand-silt mixtures, at an initial density of 50 % under a constant normal stress of 200 kPa, are presented in Figs. 10, 11, and 12. The evolution of the shear strength of unreinforced and reinforced sand-silt mixtures as a function of horizontal displacement (Δ*H*) shows that it increases significantly at the beginning until reaching a maximum value, then it gradually decreases with the development of horizontal displacement (Fig. 10). Fig. 10a shows that the maximum shear stress of the mixture containing 10 % silt (*Sc* = 10 %) increases with the rising fiber content from 0 to 0.5 % (Fc_{opt}=0.5 %), and then decreases when the fiber content increases to 0.8 %. The same trend is observed for sand-silt mixtures containing 20 % and 30 % silt (*Sc* = 20 % and 30 %) (Figs 10b and 10c). However, it can be seen from Fig. 10 that the maximum shear strength of fiber-reinforced sand-silt mixtures increases with an increase in silt content until it reaches a ratio of 20 %. Then it starts to decrease. This result is due to an opposing effect between the fines matrix and the fiber inclusions. As mentioned earlier, when the fines content exceeds the threshold, the fines matrix dissociates the sand grains and prevents their interaction, leading to a decrease in strength. The fines matrix governs the behavior of the entire specimen. Conversely, fiber inclusion increases the contact area between the sand grains as a consequence of the confining effect of the fiber network, reducing the influence of the fines matrix and therefore increasing the strength of the sand-silt-fiber composite. The shear strength behavior of fiber-reinforced sand-silt mixtures is mainly

Table 4. **Shear strength parameters of unreinforced and fiber-reinforced sand-silt mixtures**

Fiber content	***Sc* = 0 %**		***Sc* = 10 %**		***Sc* = 20 %**		***Sc* = 30 %**	
	c (kPa)	*f* (°)	*c* (kPa)	*f* (°)	*c* (kPa)	*f* (°)	*c* (kPa)	*f* (°)
***Fc* = 0 %**	8.14	44.54	8.74	46.52	8.55	45.01	7.99	42.9
***Fc* = 0.3 %**	12.63	46.41	13.91	46.61	11.59	45.17	10.81	43.2
***Fc* = 0.5 %**	19.05	46.78	14.71	47.19	15.26	45.85	11.12	44.12
***Fc* = 0.8 %**	10.8	45.16	13.55	45.75	12.86	44.95	4.6	43.5

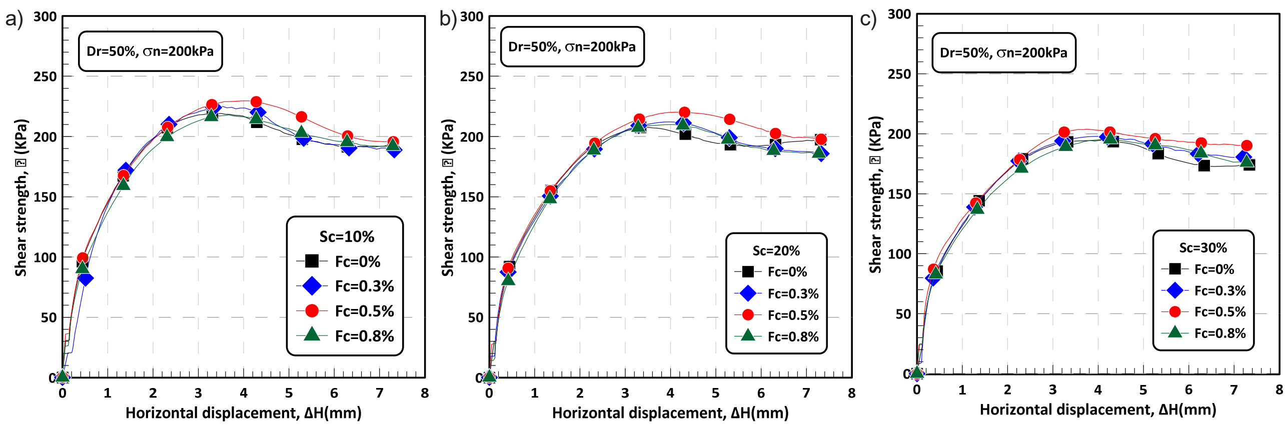

Fig. 10. Shear strength versus horizontal displacement of Chlef sand-silt mixtures reinforced with glass fibers: (a) *Sc* = 10 %, (b) *Sc* = 20 %, (c) *Sc* = 30 %

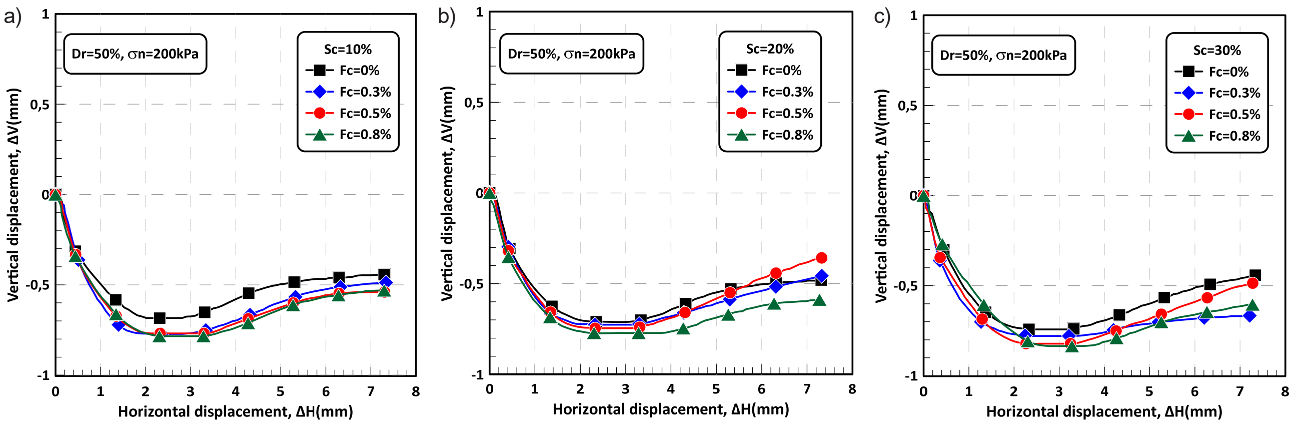

Fig.11. Vertical displacement versus horizontal displacement of Chlef sand-silt mixtures reinforced with glass fibers: (a) *Sc* = 10 %, (b) *Sc* = 20 %, (c) *Sc* = 30 %

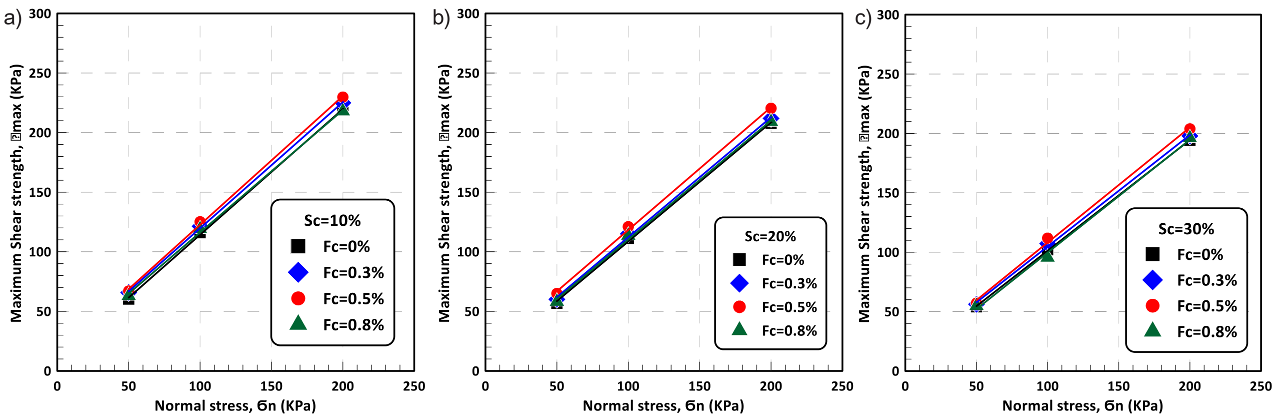

Fig. 12. Variation of maximum shear stress versus normal stress of Chlef sand-silt mixtures reinforced with glass fibers: (a) *Sc* = 10 %, (b) *Sc* = 20 %, (c) *Sc* = 30 %

governed by the silt threshold content and the optimum fiber content. It was found that the specimens with the most unsatisfactory results were those with Sc_{th} > 20 % and Fc_{opt} = 0.5 %.

The variation of vertical displacement of unreinforced and fiber-reinforced sand-silt samples as a function of horizontal displacement is shown in Fig. 11. It is clear that all samples generally exhibit a contractive character followed by a dilative one at approx. 2–3 mm of horizontal displacement. The figure also shows that an increase in fiber content and silt content tends to accentuate the contractive behavior of fiber-reinforced sand-silt mixtures.

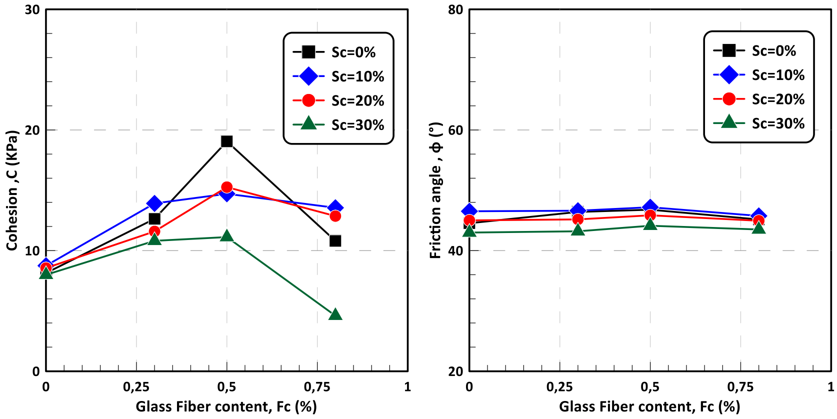

Fig. 13. Evolution of cohesion and friction angle as a function of silt content and glass fiber content

Fig. 12 represents the variation of the intrinsic curves for unreinforced and fiber-reinforced silty sand. The silty sand containing 0.5 % fiber generally exhibits the highest maximum shear stress (Fc_{opt} = 0.5 %), regardless of silt content or applied normal stress. The maximum shear stress for sand-silt mixtures reinforced with fibers increases with an increase in silt content from 10 % to 20 %, then decreases at 30 %. Fig. 13 shows the variation of shear strength coefficients for unreinforced and fiber-reinforced sand-silt mixtures, as summarized in Table 4, as a function of fines content and fiber inclusion. It can be noted that adding 10 % to 20 % silt to the sand, along with a 0.5 % increase in fibers, generally enhances the cohesion and internal friction of the sand-silt mixture. However, a further increase in fines content to 30 % leads to a decrease in both shear strength parameters, even with an increase in fiber content. This decrease in resistance is probably due to the presence of fine particles between the grains of sand, which promotes a reduction in the contact between sand particles. Arab (2009) found a similar trend in saturated sand. Additionally, Fig. 13 demonstrates that the shear strength parameters of sand-silt mixtures increase with the rising fiber content from 0 % to 0.5 %, and then decrease as the fiber content increases to 0.8 %.

Discussion

An experimental investigation was conducted to study the effects of glass fiber and silt content, as well as their combined effect, on the shear behavior of silty sand. Direct shear tests were conducted on sand mixed with different percentages of silt (0 %, 10 %, 20 %, and 30 %) and glass fibers (0 %, 0.3 %, 0.5 %, and 0.8 %). Samples were prepared with an initial relative density of 50 %, and each mixture was tested under three normal stresses (50, 100, and 200 kPa). Based on the experimental evidence, the following conclusions can be drawn:

The silt content has a significant effect on the shear behavior of the sand-silt mixture. Indeed, adding 10 % silt to sand increases its shear strength, cohesion, and friction angle. Beyond the threshold content (*Sc* = 10 %), a further increase in the silt content leads to an opposite trend.

The shear strength and shear strength characteristics of fiber-reinforced sand increase with increasing fiber content up to an optimum content of 0.5 %. On the other hand, the addition of glass fiber reinforces the contractive nature of the sand.

The shear behavior of fiber-reinforced silty sand is mainly governed by the silt and fiber content. The results obtained indicate that 0.5 % of glass fibers is the optimum content, which can be used to improve the shear strength of sand-silt mixtures and their shear strength parameters. However, it is necessary to consider the increase in the contractive behavior of the mixture when adding glass fibers.

Reinforcing silty sand with fibers is a promising solution for problematic soils because of the presence of fines fractions. Further studies on the subject should be carried out to assess the influence of other parameters on its shear response, such as relative density (loose and medium dense states), water content, and different types of fiber.

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ИССЛЕДОВАНИЕ ПРОЧНОСТИ АРМИРОВАННОГО АЛЕВРИТОВОГО ПЕСКА НА СДВИГ

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Аннотация
Введение: в данной работе представлено экспериментальное исследование, целью которого является изучение влияния содержания ила, содержания стекловолокна и их совместного воздействия на поведение алевритового песка при сдвиге. С этой **целью** использованы следующие **методы**: проведена серия испытаний песка, смешанного с различным содержанием ила и волокон, с использованием аппарата для испытания на сдвиг. Образцы были подготовлены с относительной плотностью 50 %, и каждая смесь проходила испытания при трех различных нормальных напряжениях. **Результаты** эксперимента показали увеличение прочности на сдвиг при содержании ила 10 %, а также последующее снижение прочности на сдвиг с увеличением содержания ила от 10 до 30 %. Также было установлено, что 0,5 % — это оптимальное содержание, которое может быть добавлено в песчано-иловые смеси для повышения их прочности на сдвиг и угла трения, хотя при этом смеси становятся более сжатыми.

Ключевые слова: песок, ил, стекловолокно, прочность на сдвиг, когезия, угол трения.