Geotech Geol Eng (2019) 37:1047–1057
https://doi.org/10.1007/s10706-018-0641-5

TECHNICAL NOTE

Shear Strength Response of Fibre Reinforced Chlef (Algeria) Silty Sand: Laboratory Study

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Received: 7 February 2018 / Accepted: 18 July 2018 / Published online: 23 July 2018

Abstract Algeria, like other Mediterranean countries, is highly exposed to seismic hazards. Several damages have been observed in previous earthquake such as, differential settlements of structures many slope failures and soil movements in Chlef region. This paper presents the results of a series of direct shear laboratory tests on medium fibre reinforced silty sand, highlighting the effect of including fibre content as reinforcement (0.1, 0.25, 0.3 and 0.5% as a fibre volumetric content). The results are analysed and compared with those of unreinforced sand. The tests are carried out for two soil sample states: dry and wet state with a water content of 3%. The experimental results show a clear improvement in the mechanical characteristics with the addition of polyester fibres especially for wet specimens. The fibre addition makes possible to improve not only the shear strength of the soil, but also reduces the volumetric change for a given stress loading, which can contribute to a limitation of the extension-contraction cracks of the soil samples. The percentage of fibres addition is an important parameter which presents an optimum of 0.25% for the undertaken study.

Keywords Direct shear test · Mechanical behaviour · Soil improvement · Fibre reinforced sand · Sand-silt mixtures

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List of symbols

φ	Internal friction angle
c	Cohesion
J	Secant modulus of geotextile under the deformation state ε_a
D_{50}	Mean grain size
δ_H	Horizontal displacement
δ_V	Vertical displacement
fc	Fines content
C_u	Uniformity coefficient
C_c	Curvature coefficient
Γs	Unit weight of sand particles
γ_f	Unit weight of geosynthetic fibres
ρ_a	Bulk density
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
e	Global void ratio

Dr	Relative density
ε_V	Volumetric deformation
τ	Shear stress
σ_n	Normal stress
Gs	Specific gravity of sand
G_f	Specific gravity of silt
D_{10}	Sand effective grain size
I_p	Plasticity index
Ss	Shear strength
Su	Shear strength at peak
F_{thre}	Threshold fines content in decimal
b	Active fraction of fines in force structure
ω	Water content
W_S	Mass of dry sand
W_f	Mass of fibre

1 Introduction

Algeria, located on a convergence zone between the African and the Eurasian plate, is highly exposed to seismic hazards. The region of Chlef (ex Orléans ville, ex El-Asnam) suffered during the last centuries from earthquakes, which are among the most destructive in 1922, 1934 and 1954. The last earthquake of magnitude 7.3 occurred on October 10, 1980 at 13:25:23.7; local time (12:25:23.7 GMT). The earthquake epicentre for the main shock was located at 12 km in the east region of *Chlef* City (210 km west of Algiers) at latitude 36.143° N and longitude 1.413° E with a focal depth of about 10 km. The approximate duration of the quake was between 35 and 40 s (Belkhatir et al. 2013; Benessalah et al. 2016). The city of Chlef is located on a broad alluvial valley flanked north and south by chains of hills rising to an altitude of about 1000 m. Although there has been clear evidence of different types of soil failure (Fig. 1), some of these failures are occurring in an area where civilian infrastructure existed, resulting in loss of life and property damage. Indeed soil failure was significant in several areas, particularly along the banks of the Chlef River, where sandy soils were ejected at the soil surface.

Fig. 1 Sliding of the Chlef River banks during the 1980 El-Asnam earthquake

In the modern history of soil stability, the reinforcement concept and principle through the use of fibrous materials has shown that this technique, developed by H. Vidal in 1966, is an economical and effective solution to improve the mechanical characteristics of soils, and also advantageous in terms of performance compared to metal reinforcements. For this purpose, several researchers have been interested in the application of fibrous materials and their effectiveness for soil reinforcement (Maher and Gray 1990; Maher and Ho 1994; Dos Santos et al. 2010; Consoli et al. 2011; Kumar et al. 1999; Feuerharmel 2000; Miller and Rifai 2004; Casagrande et al. 2006; Maliakal and Thiyyakkandi 2013). These studies have indicated that the fibre treated soils showed a reduction of cracking and an increase of the hydraulic conductivity in the case of compacted clay soils. Benessalah et al. (2015) conducted a series of direct shear tests on samples of fibre reinforced sand, emphasising the influence of the volumetric glass-fibres content for medium and high densities on the shear strength behaviour of a sandy soil. They found an improvement in the mechanical characteristics with the addition of glass-fibres, especially for wet specimens. It has been also showed that 0.3% of fibre content is a critical value for fibre contribution to improve the mechanical characteristics. By conducting triaxial tests on glass fibres reinforced silty sands, Consoli et al. (1998) have indicated that the inclusion of fibres improves the peak shear strength and the maximum resistance corresponding to the residual shear strength. Gray and Ohashi (1983) found through a series of direct shear tests conducted on dry sand reinforced with different types of fibres that the reinforcement by natural and synthetic fibres has a better performance than metal fibres. On the basis of these studies, researchers have shown that the effectiveness of fibre reinforcement is influenced by the properties of the used fibres, including their type, volumetric content, length, elongation, orientation and modulus of elasticity. On the other hand, the performance of the fibre-reinforced soil depends on the soil characteristics, including particle size, shape and gradation as well as the stress level and the density state.

This study presents the results of a series of direct shear laboratory tests using the Casagrande 60 × 60 mm square box on sand-silt mixtures reinforced with synthetic fibres made of polyester. The mixture can be considered as a matrix composed of two sub-matrices: one with coarse grains, consisting of sand particles; and the other fine-grained, consisting solely of the silt particles (Thevanayagan 1998). Several studies have shown that the behaviour of silty sands depends mainly on the fines content. Indeed, at low fines content, the presence of silty particles can create a great instability and compressibility of the soil structure (Lade and Yamamuro 1997). During the loading, the silty particles are dissipated in the voids, which cause instabilities of the soil structure, and result in a localized rupture under the effect of the surcharges. To evaluate this rupture, the direct shear test is adopted in the present study because of its simplicity and repeatability. An experimental program consisting of a series of direct shear tests; examines the key parameters that may influence the shear behaviour of medium sand-silt mixtures (Dr = 50%), reinforced with polyester geosynthetic fibres, with a fine content varying between 0 and 40%. In this paper, 80 laboratory direct shear tests are conducted on unreinforced and fibre reinforced silty sand samples under various vertical confining pressures (50, 100, 200 and 300 kPa) in a dry (ω = 0%) and wet state (ω = 3%).

2 Materials Used, Samples Preparation and Test Procedures

The experimental program consists on a series of direct shear tests carried out on a medium Chlef sand (Dr = 50%) with fines content varying between 0 and 40% coming from the valley zones. These tests are carried out respectively for unreinforced and reinforced with synthetic polyester fibres soils (emphasizing on volumetric content of fibres 0.10; 0.25; 0.30 and 0.50%), under different confining pressures (50, 100, 200 and 300 kPa), and for water content of 0% (dry state) and 3% (wet state). All of these tests were conducted at a strain rate of axial loading of 1.00 mm/min.

2.1 Materials

The tests were carried out on a mixture of the sand of Chlef (Fig. 2a), with fractions of fines (*fc*) or silt (Fig. 2b) not very plastic going up to 40%. The Chlef sand is taken from a soil horizon located at 6.00 m below the natural superficial ground, is an average sand composed of particles of round form, having a unit weight of ground γs equal 2.65 g/cm^{3}and a mean grain size D_{50} = 0.53 mm. The silt is not plastic with an index of plasticity (I_P) equal to 6. The microscopic sight of examined materials is shown in Fig. 2. The grain size distribution curves of these examined soils are shown on the Fig. 3. The basic properties of materials used are presented in the Table 1. Note that several researches were carried out to investigate the Chlef sand behaviour (Benessalah 2017; Benessalah et al. 2016; Arab 2008; Arab 2009; Arab et al. 2011, 2014 Arab and Belkhatir 2012; Belkhatir et al. 2011, 2013; Della et al. 2011).

The variation of the maximum and the minimum void ratio e_{max}, e_{min}, with the fines content is illustrated in Fig. 4. It can be observed that these two void ratios decrease with the increase of the fines content fc in the sand-silt mixtures until a value of fc near to 30% where the trends is inverted for higher value of fc.

The study was undertaken on samples reinforced by synthetic polyester fibres of geotextile woven of type Geoter FPET 150 (Fig. 2c). These fibres are provided by the manufacture AFITEX (Algeria).The Geoter FPET 150 mono is composed of a woven-knitted-screen structure in high tenacity polyester, associated with a woven. The technical characteristics of this material are summarized in Table 2.

The length of fibres was approximately 10 mm in all the tests. A preparation procedure of the samples was followed in order to obtain a uniform distribution of the fibres orientation in the soil samples. Calculations of the weight and the percentage of fibres in the reinforced samples are, for a given box volume (V) and a void ratio (e_0) similar to that of the unreinforced sample, based on the equations developed by Anagnostopoulos et al. (2013).

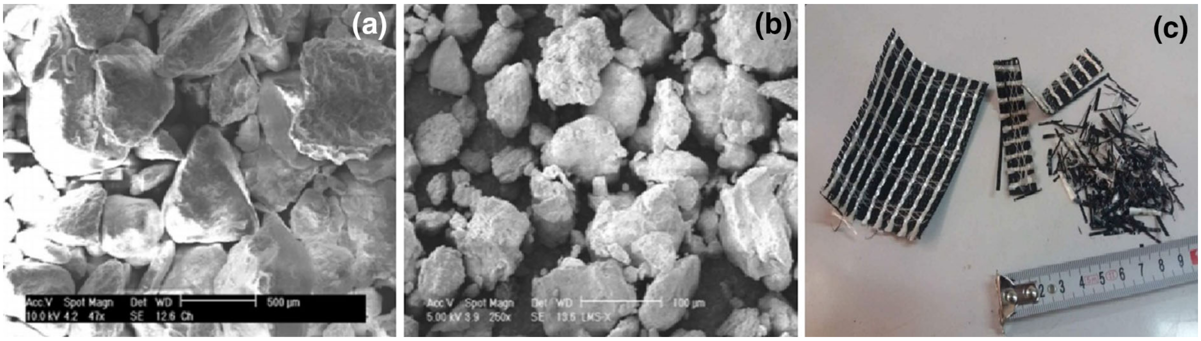

Fig. 2 Microscopic view of tested materials, **a** microscopic view of Chlef clean sand, **b** microscopic view of silt or fines elements, **c** polyester fibres used

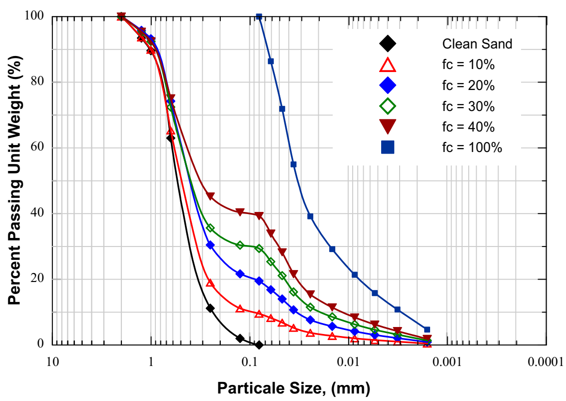

Fig. 3 Grain size distribution of tested materials

used in this study; dry pluviation and wet deposition (ω = 3%). Dry pluviation has been shown to create a grain structure similar to that of naturally deposited sands. Therefore, the dry pluviation method was selected as a suitable depositional technique for the samples preparation. The mass of sand-silt mixture used to reconstitute the sand sample in the shear box was calculated referring to the initial relative density (Dr) using the equation:

$$m_s = (V_T * \gamma_s)/(1 + e_{\max}(1 - Dr) + Dr * e_{\min})$$

The wet deposition consists of mixing the previously dry sand-silt mixtures with the desired water content

Table 1 Index properties of sand-silt mixtures

Materials	Fc (%)	G_s	D_{50} (mm)	C_u	C_c	E_{min}	e_{max}	I_p (%)
Sand	0	2.650	0.53	2.60	1.06	0.556	0.809	–
Sand-silt mixtures	10	2.652	0.50	6.30	2.12	0.407	0.742	–
	20	2.653	0.42	15.29	3.54	0.385	0.681	–
	30	2.655	0.40	26.14	1.38	0.376	0.673	–
	40	2.657	0.31	37.51	0.51	0.445	0.749	–
Silt	100	2.667	–	–	–	0.991	1.563	6.00

2.2 Sample Preparation and Test Procedure

In order to investigate the effect of the reinforcement on a medium fibre reinforced sand-silt mixture of Chlef valley (Dr = 50%) on the shear strength, an experimental laboratory program contains a series of 80 direct shear tests carried out on unreinforced and polyester fibre reinforced samples (sand-silt mixtures). The tests are conducted using the Casagrande box of 60 × 60 mm square section on samples having a thickness of 25 mm. Two mode of deposition were (ω = 3%), and then placing the wet soil in the shear box in successive layers. For a direct shear test, a sample is placed in the entire box, and then a confining pressure is applied to the sample using a vertical stress and perpendicular to the shear plane. We can then start moving the lower half-box and measure the tangential force generated at the shear plan between the two half-boxes respecting to a horizontal displacement created by a constant velocity.

Shear failure occurs when the tangential stress reaches a maximum. Several tests are performed on

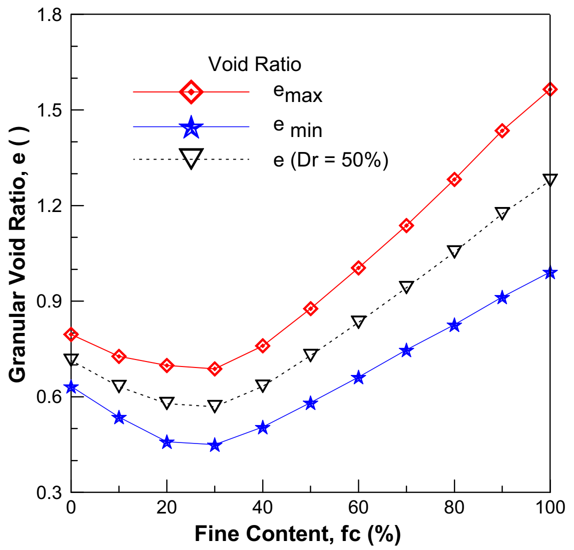

Fig. 4 Variation of the maximum and minimum void ratios versus fines content

3.1 Behaviour of Chlef Sand Without Reinforcement

Firstly, the influence of the water content on the mechanical behaviour of the medium sand is studied. The results obtained for clean and silty sand at a dry state are compared to those of a wet state (ω = 3%).

Figure 5a, b present the effect of water content on the mechanical properties of clean sands (*fc* = 0%). From Fig. 5a, it can be seen that the shear strength of the dry sand, increases significantly with the progress of horizontal displacement, due to the good adhesion between the grains of dry sand. The values of the shear strength at the peak are 39.8, 78.2, 145.5, and 222.3 kPa for confining pressures of 50, 100, 200 and 300 kPa, respectively. After each peak, there is a decrease of shear strength until a residual value. For wet samples, Fig. 5b shows that the shear stress increases continuously with the progress of the test without reaching a level of plasticity. The residual values obtained at the end of the test are 42.7, 73.4, 136.3 and 205.4 kPa for a confining stress of 50, 100, 200 and 300 kPa, respectively.

Table 2 Physical and mechanical characteristics of fibres of the used geotextile

Characteristics	Standard	Unity	Value		Tolerance
Surface mass	NF EN ISO 9864	g/m^2	363		± 10%
Thickness under 2 kPa	NF EN ISO 964-1	mm	/		± 20%
Tensile strength in tension	NF EN ISO 10319	kN/m	SP*	150	Val. mini
			ST*	10	
Deformation at break in tension	NF EN ISO 10319	%	SP*	11	± 20%
			ST*	8	
Dynamic perforation	NF EN 13433	mm	14		± 20%
Static punching CBR	NF EN 12236	kN	3.8		− 10%

*SP, production sense; ST, weft direction

samples with different vertical stresses of 50, 100, 200 and 300 kPa, prepared under the same conditions, in order to define the mechanical characteristics of shear strength.

3 Results and Discussion

In the sequel, the shear strength obtained from direct shear tests is presented in order to analyse the influence of the key parameters on the mechanical behaviour of the Chlef sand before and after its reinforcement under different confining stress.

In order to analyse the effect of the fines content before the introduction of fibres reinforcement, Fig. 5c, d show the effect of fine contents on the shear strength at a confining stress of 100 kPa, for both dry and wet samples, respectively. For medium samples; it can be noticed that the horizontal displacement corresponding to the peak of shear stress is higher for sand-silt mixture than that of the clean sand (*fc* = 0). On the other hand, for 2 mm horizontal displacement, the shear strength shows a linear decrease with the percentage of fine contents, while the residual strength remains constant.

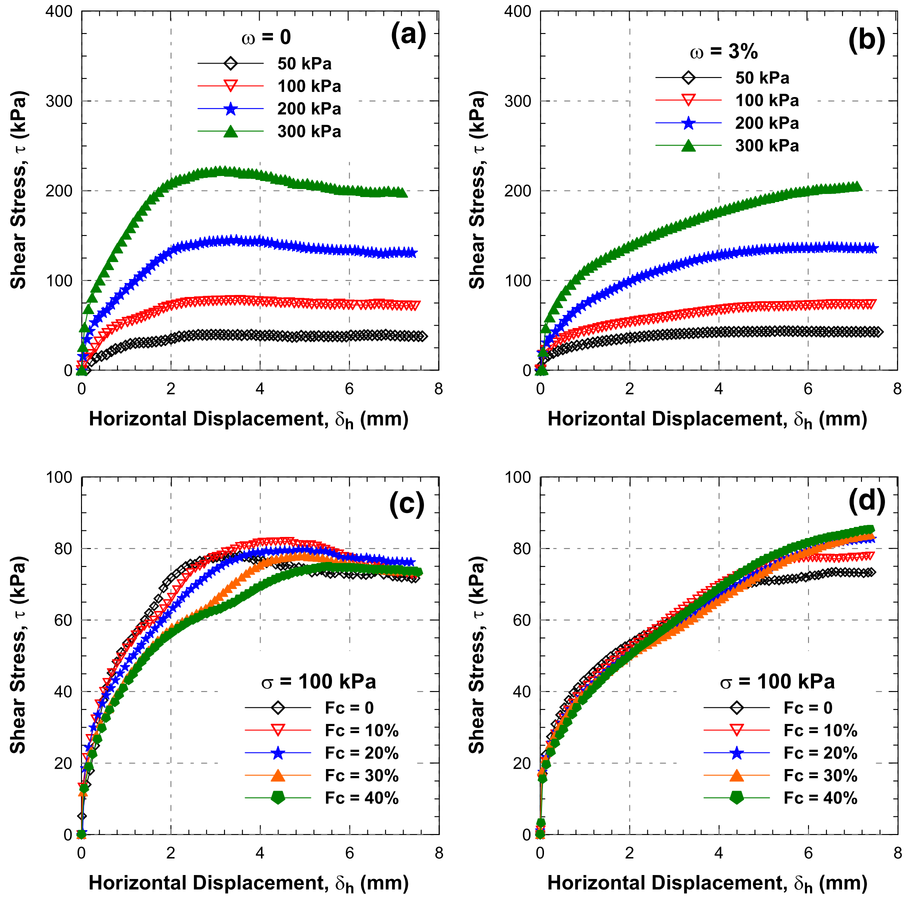

Fig. 5 Evolution of shear stress versus horizontal displacement: **a** dry samples (clean sand), **b** samples with water content ω = 3% (clean sand), **c** dry samples (silty-sand mixtures), **d** samples with water content ω = 3% (silty-sand mixtures)

The results obtained for wet samples (ω = 3%) are emphasized in Fig. 5d. As for clean sand, the sand-silt mixtures show a similar trend where the shear stress grows with the horizontal displacement without reaching a plateau. This behaviour is governed by the effect of moisture (the water content increases the macro-pores especially for small deformations), and that plays a role of delaying the time to get to the maximum resistance of the sand. This maximum value is reached at the end of the test where the macro-pores are minimized, and which is well established in the figure of the vertical displacements (Fig. 6b).

The evolution of vertical displacement versus horizontal displacement curves for the sand-silt mixture in its dry state, under a confining pressure of 100 kPa and an average relative density of 50%, is shown in Fig. 6a. For samples with 10 and 20% fine content, slight contractant behaviour is observed at the beginning, followed by dilatancy phase until the end of the test. For higher value of fine content (30 and 40%), the behaviour of the sand-silt mixture is purely contractant. For wet samples, Fig. 6b reveals pure contractant behaviour of the soil that results in a reduction of the sample volume. This contractant behaviour is more pronounced for higher values of fine contents and in comparison with the trend observed for dry samples. These results are in good agreement with those obtained by Benessalah et al. (2015).

Figure 7 shows two intrinsic lines of Mohr–Coulomb plan which is obtained directly by plotting the normal stress (σ) applied during the direct shear test and the shear stress (τ) measured for a given horizontal displacement, i.e. 2 mm. The results showed that the tangential stress of clean sand in its dry or wet state increases in a linear way with the increase of the normal stress. In addition, it is noted that the slope of the shear line M and which varies proportionally with the internal friction angle, is greater for dry samples (M = 0.688) compared to

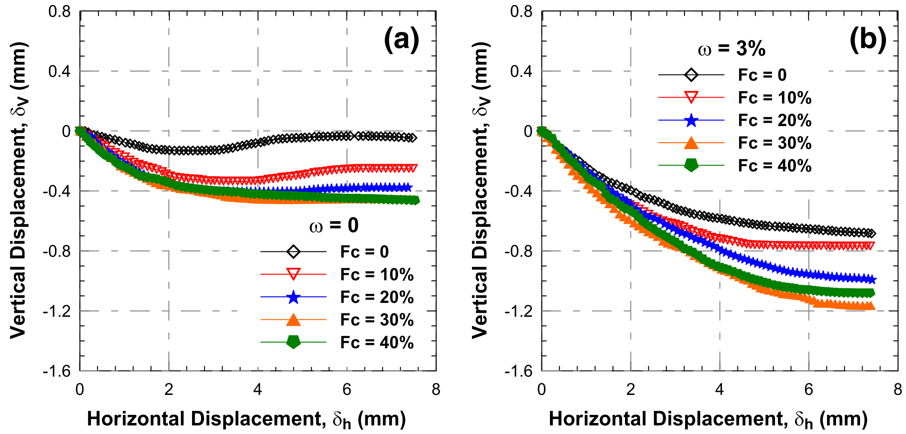

Fig. 6 Evolution of the vertical displacement shear stress versus horizontal displacement: **a** dry samples (silty-sand mixtures), **b** samples with water content ω = 3% (silty-sand mixtures)

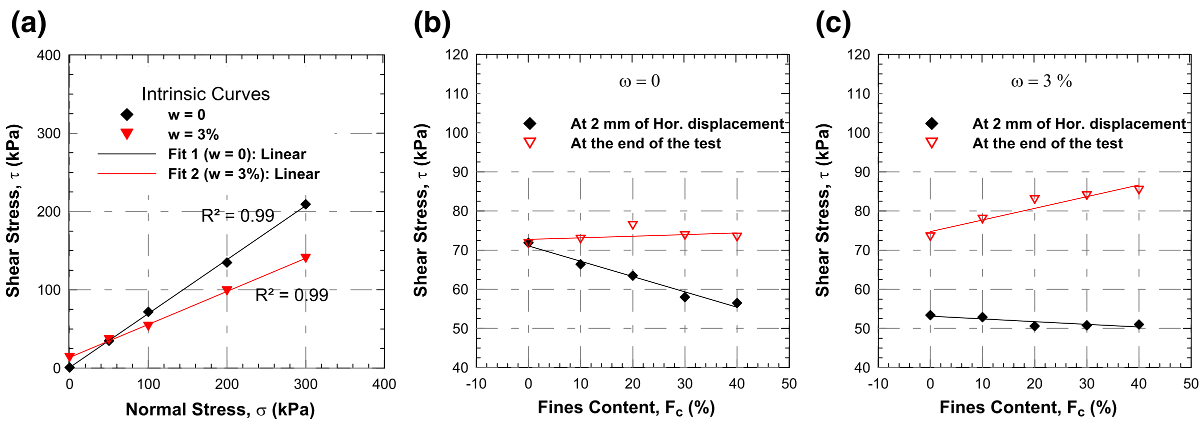

Fig. 7 **a** Intrinsic curves at 2 mm of horizontal displacement (clean sand), **b** shear strength of unreinforced dry sand-silt mixtures under 100 kPa vertical stress, **c** shear strength of unreinforced dry sand-silt mixtures with (ω = 3%) under 100 kPa vertical stress

clean wet sand with a water content ω = 3%; (M = 0.422).

On the other hand, it can be noticed from Fig. 7, that there is an increase of the apparent cohesion in wet samples compared to the dry samples.

Figure 8 shows the influence of the fines content on the mechanical characteristics, in terms of cohesion and friction angle of the sand-silt mixture in its dry and wet state.

For dry soil, it can be noted a linear relationship between both of the cohesion and the friction angle with the fines content. However, the value of the cohesion that increases with fines contents, still relatively low. On the other hand, the friction angle show different trend, it decreases from 40° for clean sand (fc = 0) to about 30° for fc = 40%. This behaviour is associated to an increase in the contractant phase with the increase of fines content.

The results related to wet samples are summarized in Fig. 8b. The effect of fine contents is negligible on the friction angle. Concerning the cohesion, it can be observed a decrease with the addition of fines and reaches a constant value of about 8 kPa for a fines content higher than 20%.

3.2 Behaviour of Fibre Reinforced Chlef Sand

Maher and Ho (1994) concluded that the inclusion of glass-fibres with content varying from 1 to 4% of reinforced sand produces an increase of 1.5 times of the compressive strength compared to the unreinforced sands. Consoli et al. (1998) Indicated that the inclusion of glass fibres in silty sand effectively improves resistance at the peak. An improvement in tension resistance of the fibre-reinforced soil is observed which contributes to higher peak and post-

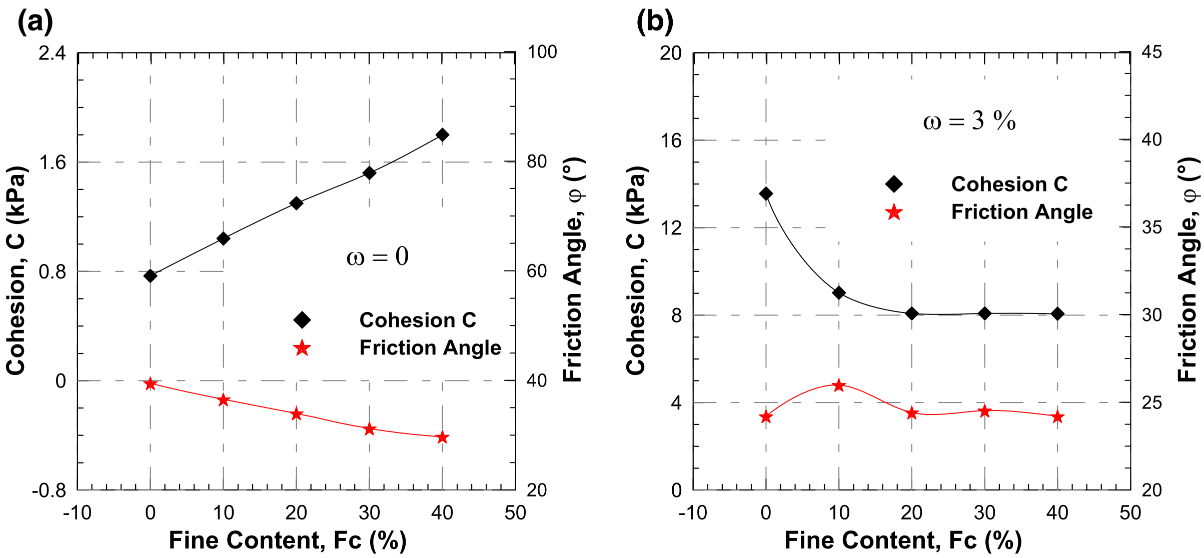

Fig. 8 Influence of fines content on the mechanical characteristics at 2 mm of horizontal displacement **a** dry samples, **b** wet samples; ω = 3%

peak shear strength values of reinforced soils (Babu and Chouksey 2011).

After detailing the mechanical behaviour of the Chlef sand with and without fine contents and for dry and wet state, it was observed dominant contractant behaviour for the case of wet soil, that's why this section presents the results of direct shear tests on a fibre reinforced wet sand-silt mixtures.

The influence of the fibres addition on the soil mechanical behaviour (fibre reinforced sand) is investigated in term of the shear strength and soil deformability at different level of confining stress σ_n = 50, 100, 200 and 300 kPa. The results are compared to those of the unreinforced soil.

The volumetric contents of fibres adopted in the present survey are: 0.10, 0.25, 0.30 and 0.50%. Figure 9 presents the effect of polyester synthetic fibre inclusions on the mechanical properties of the clean Chlef sand for a confining pressure of 100 kPa. It can be noticed that all the fibre reinforced samples shows a better performance regarding the shear strength in comparison with the unreinforced soil. However, the trends is not regular, where the optimal performance is obtained for a volumetric fibre content of 0.25% that reveals a maximum shear strength around 3 mm horizontal displacement followed by a slight diminution until the end of the test (Fig. 9a). The samples with higher value of fibre content of 0.30 and 0.50% possess a lower value of maximum shear strength in comparison to that obtained with 0.25%. Figure 9b shows the effect of fibre inclusions on the evolution of vertical displacement. It confirms the trends observed for the shear strength. Indeed, the contractancy phase observed for unreinforced soil is reduced with the introduction of fibres that induce a dilatant behaviour for a horizontal displacement higher than 2 mm. The optimal value of volumetric reinforcement is 0.25% where the maximum vertical displacement is significantly reduced in comparison to unreinforced sample. The results will be compared, with those of wet clean sand unreinforced presented on the Fig. 6b. The unreinforced grounds indicates a contractiveness phase, followed by a dilatancy phase after a certain horizontal displacement represented by an increasing of in the vertical displacement after this critical horizontal displacement. For the reinforced samples; one observed that the vertical displacements decreases as important as the fibre content increase; which indicate a more contractiveness character with the increase in the content of fibres of the sample. It is noticeable also that the contractiveness character increase until a value of fibre content of 0.25% than it will be reduce for the higher values of fibres content.

Figure 10 presents the results of the direct shear tests carried out at a confining stress of 100 kPa on medium sand-silt fibre reinforced mixtures with a

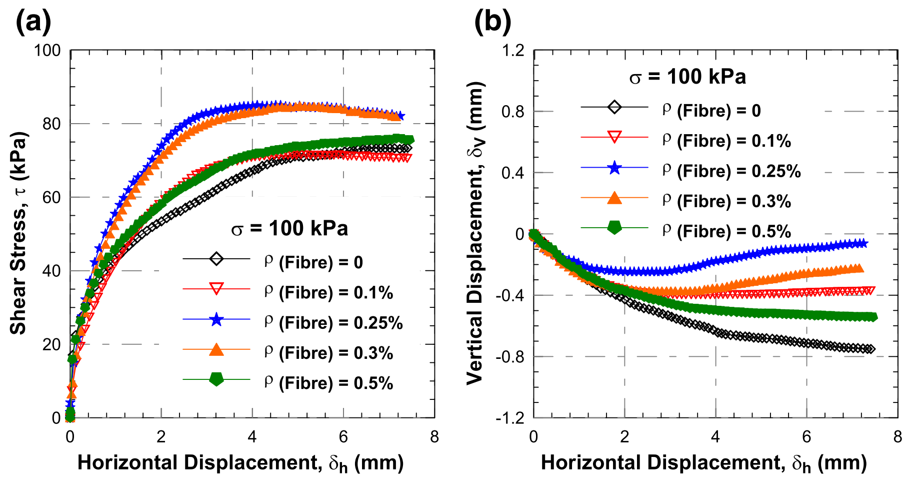

Fig. 9 Shear strength response of reinforced clean sand under a confining stress of 100 kPa (ω = 3%), **a** shear stress versus horizontal displacement, **b** vertical displacement versus horizontal displacement

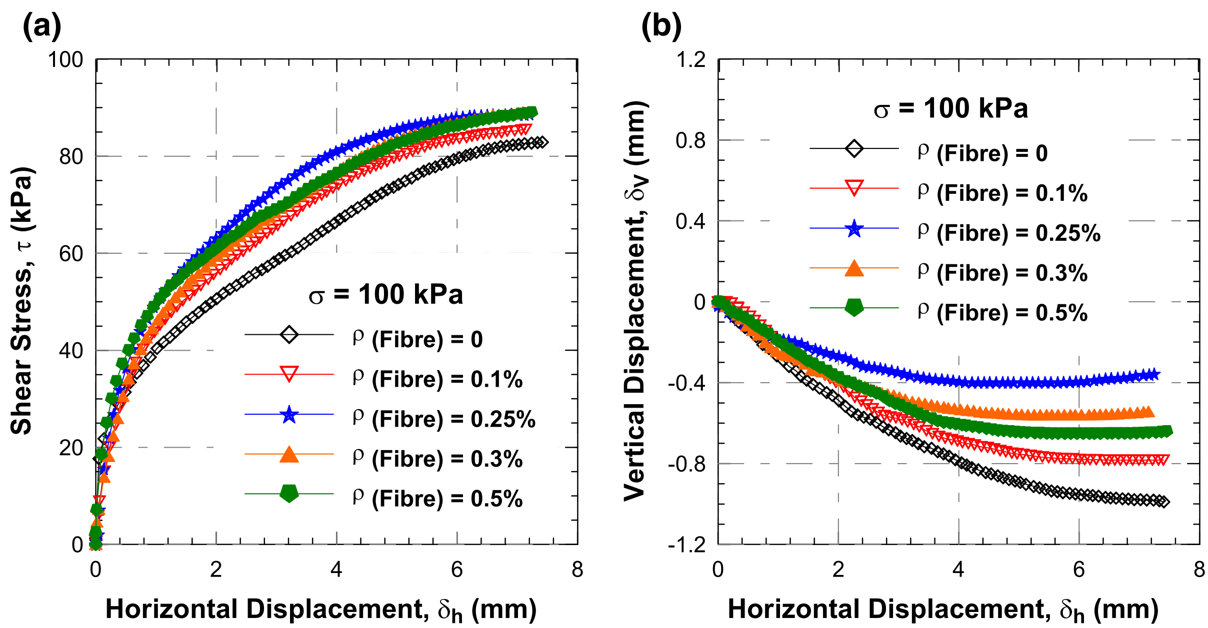

Fig. 10 Shear strength response of reinforced silty sand (Fc = 20%) under a confining stress of 100 kPa (ω = 3%), **a** shear stress versus horizontal displacement, **b** vertical displacement versus horizontal displacement

volumetric fibre content ranging from 0.1, 0.25, 0.3 to 0.5% and with a fines content of 20% at its wet state (ω = 3%).

Firstly, Fig. 10a depicts the variation of the shear stress with horizontal displacement. As for clean sand, a significant improvement of the shear strength is obtained at the beginning of test in particular for the samples with a volumetric fibre content of 0.25%. It is noted that the shear stress increases gradually with the increase in horizontal displacement without reaching a plasticity plateau for all samples which is directly related to the moisture (ω = 3%).

Figure 10b presents the contribution of fibres reinforcement on sand-silt mixtures to the reduction of the soil deformation against the applied loading. Fibre reinforced samples show less deformability in comparison with unreinforced samples. Figure 11 illustrates another presentation of the results. If confirms the optimal performance obtained for a volumetric fibre reinforcement of 0.25% for both cases of clean sand and sand-silt mixtures, associated to the

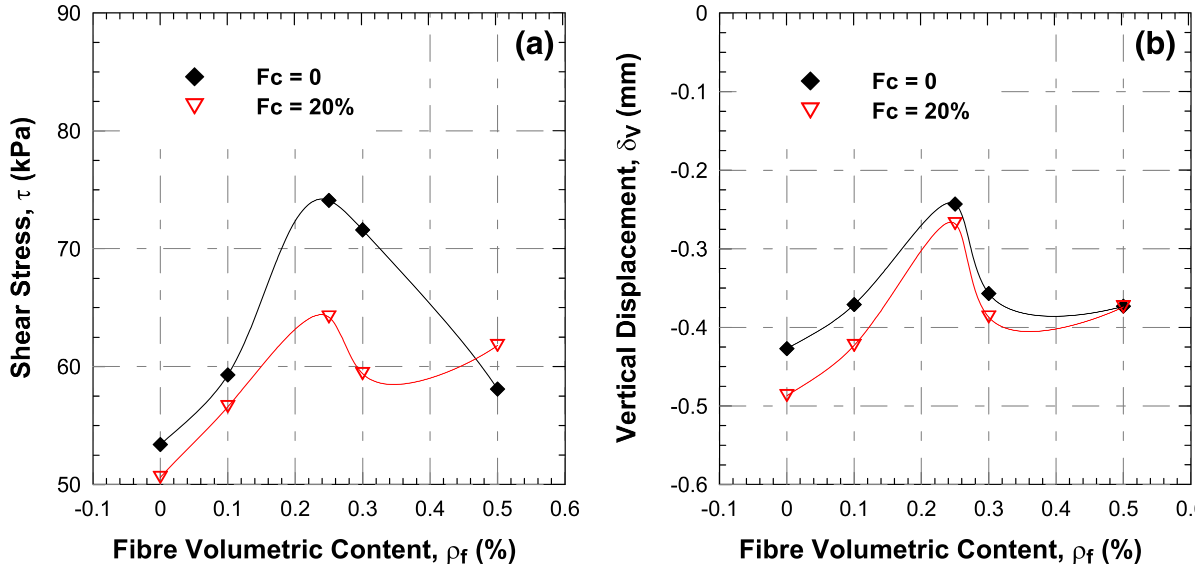

Fig. 11 Influence of volumetric fibre content on the mechanical properties for a confining pressure of 100 kPa **a** shear stress at 2 mm of horizontal displacement, **b** vertical displacement at 2 mm of horizontal displacement

higher shear strength and the lower vertical displacement.

4 Conclusions

This paper included a thorough study about the effect of the polyester fibre inclusion on shear strength behaviour of Chlef sand soils. The experimental results lead to the following conclusions:

1. The shear stress of studied sand is strongly affected by the water content, confining pressure and the quantity of fibres.
2. At the density which the samples were tested (Dr = 50%), it is noted a reduction in the maximum and residual shear strengths with the increase in the water content, which involves a reduction of the physical characteristics such as the internal friction angle.
3. The addition of polyester fibres has a beneficial effect on the mechanical characteristics of the soil through a better and faster mobilization of the shear resistance, and a reduction of the soil deformability which can contribute to a reduction of the extension-contraction cracks of the soil. For the studied clean sand and sand-silt mixtures, the optimal percentage of volumetric fibre content is 0.25%.

As recommendations, fibres reinforcement would be an interesting solution to face the instability and the deformability of the sand. From this, it would be interesting to perform tests on loose reinforced specimens. This work is in progress where monotonic undrained triaxial tests and dynamic triaxial tests on samples of fibres reinforced silty sand are conducted in order to investigate the behaviour of such synthetic material against liquefaction. This issue is of great importance for the Chlef sand that is vulnerable and liquefiable soil when subjected to earthquake and even in some cases under static loads, especially when it possesses important fines content.

Acknowledgements The authors would like to thank the reviewers for their constructive and detailed comments. Testing was performed in the Laboratory of Material Sciences and Environment (LsmE) at Univ. Hassiba Benbouali of Chlef. The authors would like to thank also AFITEX Algeria, for giving the geosynthetic material as support to the experimental program.

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