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A LABORATORY INVESTIGATION ON SHEAR STRENGTH BEHAVIOR OF SANDY SOIL: EFFECT OF GLASS FIBER AND CLINKER RESIDUE CONTENT

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Abstract: A study was undertaken to investigate the shear strength parameters of treated sands reinforced with randomly distributed glass fibers by carrying out direct shear test after seven days curing periods. Firstly, we studied the fiber content and fiber length effect on the peak shear strength on samples. The second part gives a parametric analysis on the effect of glass fiber and clinker residue content on the shear strength parameters for two types of uniform Algerian sands having different particle sizes (Chlef sand and Rass sand) with an average relative density $Dr = 50\%$. Finally, the test results show that the combination of glass fiber and clinker residue content can effectively improve the shear strength parameters of soil in comparison with unreinforced soil. For instance, there is a significant gain for the cohesion and friction angle of reinforced sand of Chlef. Compared to unreinforced sand, the cohesion for sand reinforced with different ratios of clinker residue increased by 4.36 to 43.08 kPa for Chlef sand and by 3.1 to 28.64 kPa for Rass sand. The feature friction angles increased from 38.73° to 43.01° (+4.28°), and after the treatment, clinker residue content of soil evaluated to 5% ($W_{RC} = 5\%$).

Key words: *direct shear test, glass fibers, clinker residue, peak shear stress, sand, normal stress, cohesion, frictional angle*

LIST OF SYMBOLS

γ_s – specific weight of solids [kN/m^3],
C_u – coefficient of uniformity [–],
D_r – relative density [%],
D_{10} – effective grain size [mm],
D_{50} – mean grain size [mm],
$e_{\max}$ – maximum voids ratio [–],
$e_{\min}$ – minimum voids ratio [–],
σ_N – normal stress [kPa],
τ – shear strength [kPa]
SSR – shear strength ratio [],
τ_{peak} – peak shear strength [kPa],
φ – friction angle of soil [°],
C – cohesion of soil [kPa],
w_f – fiber content [%],
w_{RC} – clinker residue content [%].

1. INTRODUCTION

Design of construction and other civil engineering structures on loose or soft soil is highly risky because such soil is susceptible to differential settlements, high compressibility, low shear strength and high permeability. In such situations, various soil improvement techniques have been used to enhance the engineering properties of soil [12]. It is a general technique to modify the soil properties by mixing with different materials such as lime, cement and fly ash or by reinforcing the soil. So, the primary purpose of reinforcing soil mass is to develop the parameters such as shear strength, to improve its stability, to increase its bearing capacity, to reduce settlements and lateral deformation [10], [25]. Therefore, soil reinforcement has been introduced into the field of geotechnical engineering since many years ago in order to improve the properties of ground soil in specific engineering projects. Compared to conventional geosynthetics, there are some advantages in using randomly distributed fiber as reinforcement. First, randomly distributed fibers limit potential planes of weakness that can develop parallel to oriented reinforcement [31]. Second, discrete fibers are simply added and mixed with the soil, much like cement, lime, or other additives [39]. Finally, soil reinforced with fibers has good environmental protection effect, it is easy to be constructed, and facilitates to take borrow materials in place with cost effective constructions [38]. Mechanical behavior of fiber reinforced sand has been studied by a number of researchers [1]–[3]. [18], [20], [29], [30], [35], [39]. Their research has demonstrated that shear strength of composite is increased and post-peak strength loss is reduced when discrete fibers are mixed with the soil. Fiber-reinforced soil can be advantageously employed in improvement of the structural behavior of soils and the effectiveness of the reinforcement is influenced by the properties of the fiber, such as fiber type, volume fraction, length, aspect ratio, modulus of elasticity, and orientation and soil characteristics (particle size, shape, and gradation) and also stress level, density of soil and sample preparation methods. In the same context, Consoli et al. [15], Anagnostopoulos et al. [4], Benessalah et al. [9], and Brahim et al. [11] performed triaxial tests and direct shear tests on the reinforced sands with varying physical characteristics: grain size between 0.075 mm and 2 mm, uniformity coefficient $1.9 < C_u < 4.13$, relative density $20\% < D_r < 100\%$, and reinforced by different types of fibers (geotextiles, nylon, polyester, polypropylene, glass fibers). They found that the addition of fibers increases the shear strength and the residual strength while the rigidity modulus did not seem affected by the inclusion of fibers. On the other hand, Yetimoglu and Salbas [39] showed that the addition of fiber does not increase the shear strength, therefore, does not improve the internal friction angle, and then, it slightly decreases the shear rigidity and slightly increases the residual strength of the sand. In addition, Dos Santos et al. [19] concluded that the effects of the inclusion of fibers on the shear strength of soil significantly depended on testing normal stress and claimed that the shear strength of fiber-reinforced soil was reduced along with an increase in normal stress. Nowadays, soil reinforcement technique by cement and glass fiber has also been studied by a number of researches. Maher and Ho [32] presented a basic study of the mechanical behaviour of sand artificially enriched in cement and reinforced with glass fibers. In another work, Maher and Ho [33] studied the behavior of kaolinite fiber and found that the increase in the unconfined compression strength (UCS) was more pronounced in the glass-fiber-reinforced specimens. On the other hand, Al-Refeai [3] reported that polypropylene fiber had better properties than glass fiber. In addition, Consoli et al. [16] conducted consolidated drained triaxial tests on sand reinforced with glass fiber and cement and found that the mixing glass fibers with silty sand effectively improves peak strength. In another work [14] Consoli et al. examined the effect of polyester, polypropylene and glass fibers on the mechanical behavior of fiber-reinforced cemented soils. Their results showed that the inclusion of glass fibers slightly increased the deviatoric stresses at failure and slightly reduced the brittleness. In addition, Guoxiang [21] concluded that the strength of soil stabilized with cement and fly ash varied when different fiber content and length was used. However, it is noticed in this context that the research carried out during the last twenty years on soils reinforced by fibers showed that the inclusion of fibers increases the shear strength of soil, though no general rule has been deduced from these studies because most of them reported rather controversial conclusions. Therefore, taking into account of these controversies, the main objective of this study was to investigate the mechanical behavior of two Algerian sands with different particle sizes, reinforced by randomly distributed glass fiber and treated with clinker residue. It should be noted that earlier studies on composite materials (soil-fiber-clinker residue) are very limited in terms of shear strength improvement. A second objective of the present research was to evaluate the influence of the fiber content (w_f), fiber length (L_f) and clinker residue content (w_{RC}) on the mechanical properties of glass fiber-reinforced treated sand.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1. MATERIALS

Soils

Two alluvial sands were selected for this study. Chlef and Rass sand were extracted from the two river banks (two joined rivers with a radius of 20 km in the region of Chlef, formerly known as El-Asnam, located 200 km to the West of Algiers). The depth of extraction

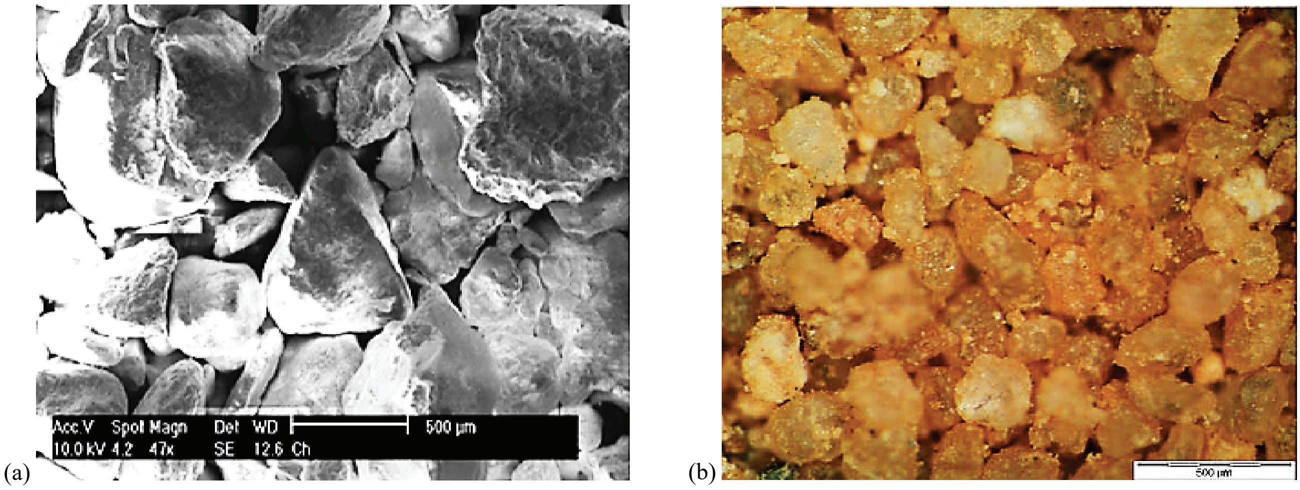

Fig. 1. Scanning electron microscope (SEM) view of tested sands: Showing particle's size and shape.
(a) Chlef sand (Belkhatir et al. [7]), (b) Rass sand (Krim et al. [26])

varied between 4.0–8.0 m. One was medium sand consisting of rounded particles named Chlef sand, while the other was fine sand with rounded particles named Rass sand. Numerous tests were carried out on this sand [5], [8], [17], [27]. Chlef sand, as the name suggests, comes from the Oued Chlef which crosses the city of Chlef (North Algeria). The Rass sand comes from the Oued Rass (junction of Chlef and Rass River). Figure 1 shows the scanning electron microscope (SEM) view of tested sands. The grain size distribution curves, and other selected properties of the two sands are shown in Fig. 2 and Table 1, respectively.

Reinforcement

Discrete glass fiber of name EWR300 (E fiber glass woven roving) was used in this study to build the examined sand specimens. Some characteristics of the EWR300 woven fabrics made of continue E-glass fibers are given by the manufacturer (Table 2). Figure 3a shows a picture of the glass fibers used in this study.

Table 1. Physical properties of Chlef and Rass Sand

Composition	Chlef sand	Rass sand
The average size, D_{50} [mm]	0.452	0.298
Effective grain diameter D_{10} [mm]	0.181	0.128
Uniformity coefficient, C_u [–]	3.029	2.747
Coefficient of curvature, C_c [–]	1.26	0.74
Specific weight of solids, γ_s [KN/m^3]	27.17	26.13
Minimum void ratio, $e_{\min}$ [.]	0.58	0.590
Maximum void ratio, $e_{\max}$ [.]	0.98	0.950
Classification USCS	SP	SP
Color	Greyish white	Clear brown
Particle shape	Rounded	Rounded
Fabric	River sand	River sand

Treatment

A clinker residue obtained from a local supplier was used throughout this investigation. Clinker residues are dust that comes from the rotary furnace at a temperature of about 1450 °C, obtained after crushing and homogenization of raw materials (limestone (80%) and clay (20%)). The clinker dust accumulates in great amounts in environment, is regained to verify the behavior of composite soil (sand-glass-fiber-clinker residue). However, clinker residue are cost-competitive compared to other materials and they are simply added and mixed with the soil, much like cement, lime, fly ash or treated using other chemical stabilization methods. The chemical composition and physical properties of clinker residue are given in Table 3 and the grain size distribution is represented in Fig. 2. Figure 3b shows a picture of clinker residue used in the study.

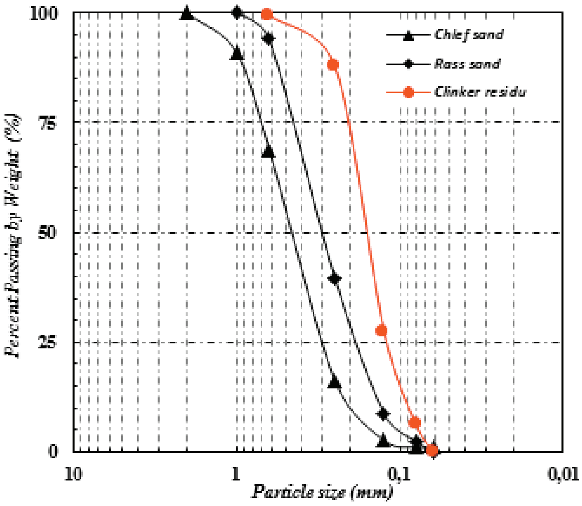

Fig. 2. Grain size distribution curves of tested sands (Chlef and Rass) and clinker residue

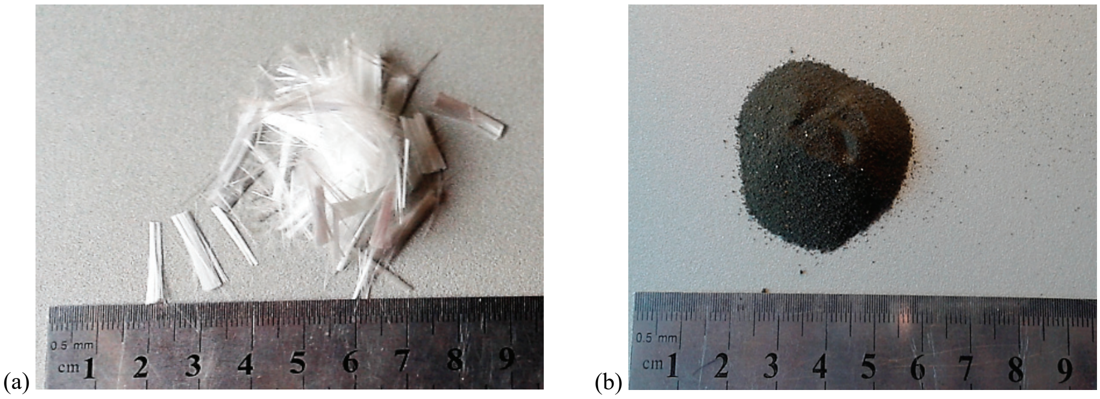

Fig. 3. Materials used in this study: glass fibers (a) and clinker residue (b)

2.2. SPECIMEN PREPARATION

2.2.1. UNREINFORCED AND REINFORCED SPECIMEN

Reinforced and unreinforced specimens were prepared using a moist tamping method. This technique is commonly used in laboratory studies of fiber-reinforced sand, because it enables the control of sample density, at the same time preventing the segregation of fibers specimens [18], [23], [37]. Each layer is compacted to desired density by measuring the height of the layer during compaction process. Fiber-reinforced sand mixtures were prepared with different fiber content (0.2, 0.4 and 0.6% by weight) and different fiber length (10, 15, 20, 25, and 30 mm). In the preparation of all samples, the required amount of water (w = 1.5%) was first added into the dry sand, and then the proposed content of fibers was mixed in small increments by hand to obtain a uniform mixture. After that, the specimens were compacted in three layers into the shear box of 60 × 60 mm, and horizontal cross section area 25 mm in depth until an average density D_r = 50% was obtained. Finally, the samples were directly formed in the testing apparatus.

Table 2. Physical and mechanical characteristics of glass fibers

Name	Unit	E-glass Woven Roving
Color	[–]	white
Width	[mm]	0.12
Filament diameter	[mm]	0.013
Specific gravity	[–]	2.62
Specific weight	[g/m^2]	300
Tensile strength	[MPa]	2500
Poisson's ratio	[–]	0.35
Shear modulus	[GPa]	29.2
Elastic modulus	[GPa]	73

Table 3. Chemical composition and physical properties of clinker residue

Elements	Value [%]
Chemical composition	
Silicon dioxide (SiO_2)	22.3
Aluminium oxide (AL_2O_3)	5.13
Ferric oxide (Fe_2O_3)	3.78
Calcium oxide (CaO)	66.76
Titanium oxide (TiO_2)	0.5
Magnesium oxide (MgO)	0.47
Mean grain size D_{50} [mm]	0.17
Physical properties	
Specific gravity, γ_s [kN/m^3]	1.30
Mean grain size D_{50} [mm]	0.17
Color	blackish

2.2.2. UNREINFORCED AND REINFORCED TREATED SPECIMEN

In previous studies, soils were also stabilized by other chemical materials such as lime, fly ash and cement. However, none of these studies have determined that clinker residue improves the mechanical behavior of the reinforced sand specimens, which is one of the main objectives of this study. In order to investigate the effect of Clinker residue on reinforced and unreinforced soil, several direct shear tests were carried out. The procedures were similar to that of Consoli et al. [13]. Samples were prepared by mixing soil and water, with different content of Clinker residue (i.e., 0, 1, 3 and 5% by weight) and glass fiber. Water had been added to the fibers to prevent floating issues. Visual examination of exhumed specimens proved the mixtures to be satisfactorily uniform. Afterwards, the under-compaction process proposed by Ladd [28] was used. Specimens were compacted in three layers into a mould of dimensions 60 × 60 × 25 mm, to a relative density of 50% and a moisture content of 1.5%. Finally, the moulds were cured in a wet room at a temperature of 25 ± 2 °C and relative moisture of over 90% for seven days before testing. The average concentration of fibers and clinker residue (*RC*) included in a composite is defined as a percentage of dry weight of sand, according to Eqs. (1) and (2):

$$w_{RC} = \frac{W_{RC}}{W_s} \times 100\,[\%]\,, \tag{1}$$

$$w_f = \frac{W_f}{W_s} \times 100\ (\%) \tag{2}$$

where W_{RC} is the weight of clinker residue, W_f is the weight of fiber, and W_s is the weight of the dry sand.

2.3. DIRECT SHEAR TEST

A total of 84 direct shear tests were performed using unreinforced and reinforced treated sand specimens of different mean grain sizes. Figure 4 shows the automated direct shear test machine which was used to run the shear test. The shear box has a 60 × 60 mm horizontal cross section area, and the specimen height is 25 mm. The tests were conducted according to ASTM D-3080 [6] at constant displacement rate of 1.00 mm/min. The shear stress was recorded as a function of horizontal displacement up to an average shear strain of 12.50%. Tests were performed at three different vertical normal stresses of σ_N = 100, 200 and 300 kPa in order to completely define the shear strength parameters such as the friction angle (φ) and cohesion (c) for both unreinforced and fiber-reinforced treated sand mixtures. In Table 4 controlled factors considered in the present study, and the investigated levels were presented.

Table 4. Description of variables in present study

Factors		Levels
Fiber type		EWR300 glass
Fiber content	w_f [%]	0; 0.2; 0.4; 0.6
Fibre length	F_l [mm]	10 , 15 , 20 , 25 , 30
Sands type		Chlef; Rass
Normal stresses	σ_N [kN/m^2]	100, 200, 300
Relative density	D_r [%]	50
Clinker residue	w_{RC} [%]	0, 1, 3, 5
Curing time	[days]	7
Water content	w [%]	1.5

3. EXPERIMENTS RESULTS AND ANALYSIS

Mechanical behavior of two sands having different particle sizes reinforced randomly by glass fiber and treated with clinker residue was analysed concentrating on the influence of normal stress and reinforcement inclusions (fiber and clinker residue) on the variation of the shear strength parameters (C and φ). First, we studied the fiber content and fiber length effect on the peak shear strength on samples with an average relative density (D_r = 50%) and normal stress (σ_N = 300 kPa). Next, a parametric analysis of the combined effect of the content of clinker residue and glass fiber on the shear strength parameters of the two sands was conducted.

Fig. 4. Direct shear test machine

3.1. STRESS–STRAIN RELATIONSHIP OF GLASS FIBER TREATED SOIL

3.1.1. CHLEF SAND

The stress–strain relationship is important to determine the mechanical behavior of stabilized soils [22]. Therefore, by studying the shear stress–strain curves, a better understanding can be developed as to how fiber reinforcement and clinker residue affect behavior of the composite. Figure 5 shows the stress–strain relationships of unreinforced and reinforced sample of Chlef sand under three normal stress of 100 kPa, 200 kPa and 300 kPa and an average relative density D_r = 50%. A proportional increase in the shear strength with the horizontal displacement has been observed in Fig. 5a for reinforced specimens (0.2% fiber content) and unreinforced specimens (0% fiber content). It can be seen that fiber inclusion enhanced the peak stress of Chlef sand, but the contributions of further increase

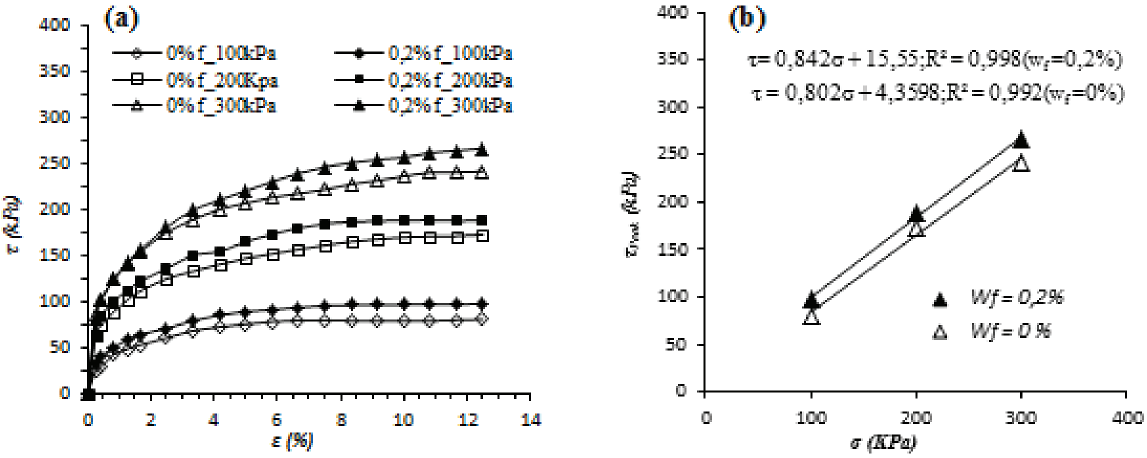

Fig. 5. Variation of shear stress versus horizontal deformation
for unreinforced and reinforced Chlef sand (D_r = 50%)

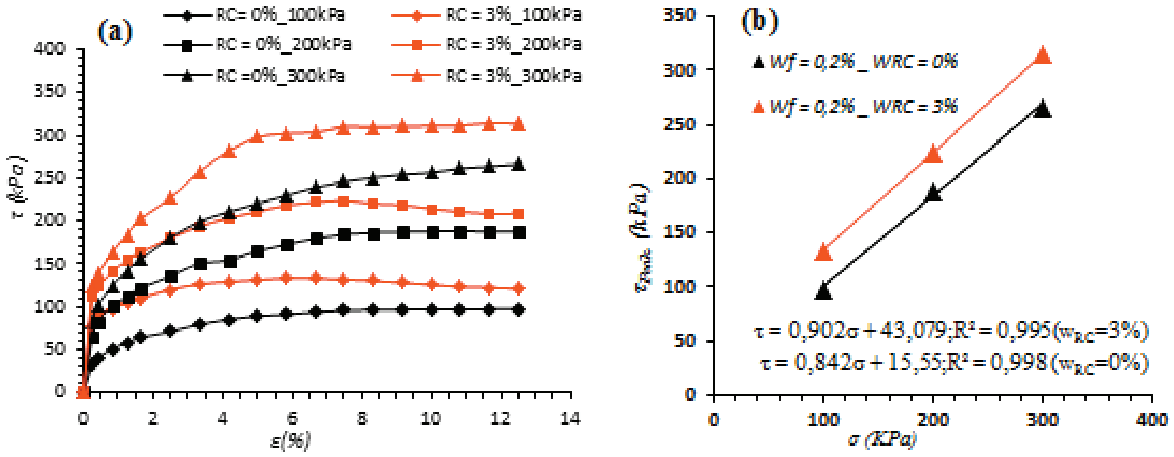

Fig. 6. Variation of shear stress versus horizontal deformation
for treated and untreated reinforced Chlef sand (Dr = 50%; w_f = 0.2%)

of fiber content to peak stress was insignificant. It can also be seen that fiber-reinforced soil exhibits more ductile behavior and smaller loss of post peak strength than unreinforced one.

The failure envelopes corresponding to shear strengths obtained from direct shear tests are presented in Fig. 5b. The observed shear parameters (C and φ) in Fig. 5b indicate that the reinforced soil exhibits an increase in the friction angle (φ) and the cohesion (C) along with an increase in fiber content by weight ranging from 0% to 0.2%. The effect of fiber reinforcement on treated soil behavior described above can be better observed in Fig. 6, where the stress–strain curves obtained for 3% clinker residue contents and for all normal stress 100 kPa, 200 kPa and 300 kPa are shown. It is readily observed that fiber inclusion improves the overall behavior of treated soil, as it increases peak strength (Fig. 6a), cohesion and friction angle (Fig. 6b).

3.1.2. RASS SAND

The stress–strain curves obtained for unreinforced and reinforced Rass sand under three values of normal stress (100 kPa, 200 kPa and 300 kPa) and an average relative density Dr = 50% are given in Figs. 7 and 8. Figure 7 shows the stress-strain relationships of fiber-reinforced untreated soil (w_{RC} = 0%) and Fig. 8 shows the stress–strain relationships of fiber-reinforced treated soil (w_{RC} = 3%) after curing for seven days. It is readily observed from Figs. 7 and 8 that the overall soil behavior was significantly influenced by the investigated variables. Peak strength, cohesion and friction angle of Rass sand changed as a consequence of either the separate or the joined effects of fiber and clinker residue inclusions (Fig. 8). Also, it can be seen from Fig. 8a that fiber inclusion enhanced the peak stress of untreated soil, but further increase in fiber content up to peak stress was insignificant. It can also be seen

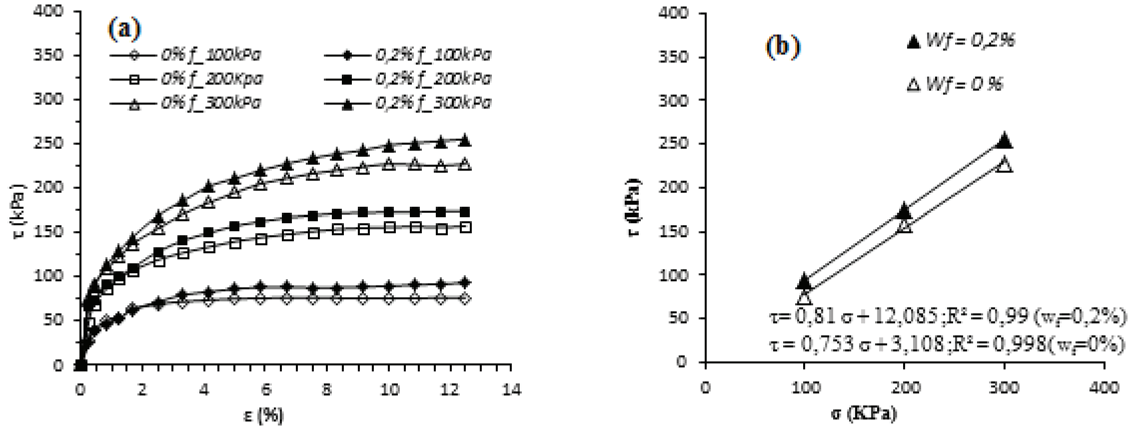

Fig. 7. Variation of shear stress horizontal
unreinforced and reinforced Rass sand ($Dr = 50\%$)

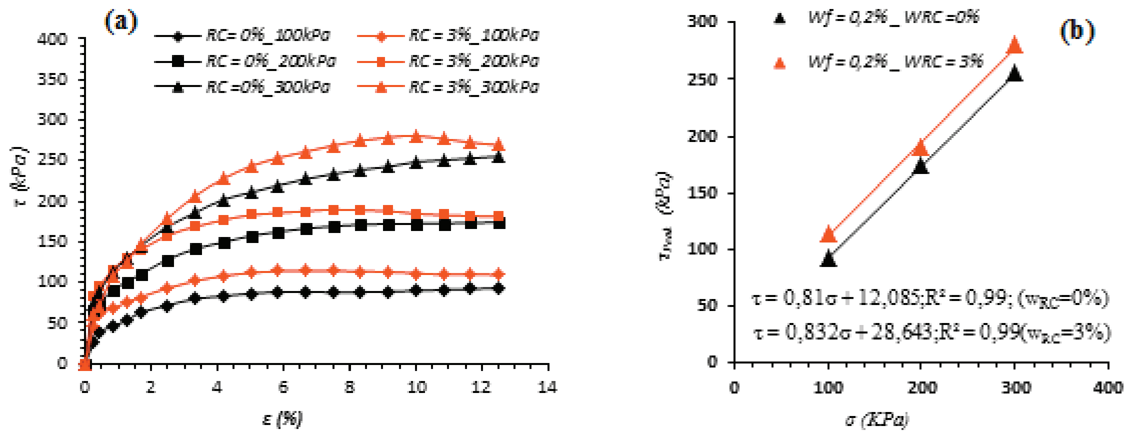

Fig. 8. Variation of shear stress versus horizontal deformation
of treated and untreated reinforced Rass sand ($D_r = 50\%$, $w_f = 0.2\%$)

that fiber-reinforced untreated soil exhibits more ductile behavior and smaller loss of post-peak strength than treated soil.

Combined effect of fiber and clinker residue inclusions on the behavior of stress–strain is shown in Fig. 8a. It is readily observed that the values of shear stress increase along with an increasing fiber and clinker residue content. Upon comparison with Fig. 8b, it can be seen that the inclusion of fibers within the treated soil improves the overall behavior of the soil, as it increases peak strength, cohesion and friction angle.

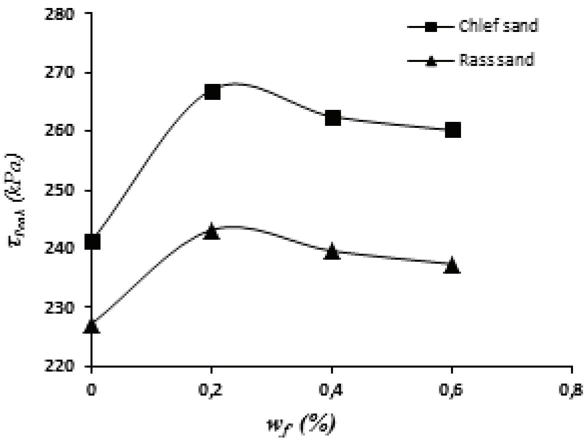

Fig. 9. Variations of peak shear strength
versus fiber content for Chlef and Rass sand

3.2. EFFECT OF FIBER CONTENT AND FIBER LENGTH ON PEAK SHEAR STRENGTH

3.2.1. EFFECT OF FIBER CONTENT

In this study, the effect of fiber content was evaluated by testing specimens with different fiber content ($w_f = 0\%$, 0.2%, 0.4% and 0.6%), but all other significant test variables were controlled. Specimens with glass fiber of various content but the same length ($L_f = 15$ mm) were used to study the effect of fiber content on the improvement of the peak shear strength of the two types of sand at constant normal stress of 300 kPa and an average density of 50%. It can be seen from Fig. 9 that the inclusion of reinforcement increases the peak shear strength compared to that of unreinforced soil and the critical value of the fiber content approach is 0.2% for two types of sands. The trend of the present results is similar to the experimental work reported by Jones et al. [24] and Sadek et al. [36].

3.2.2. EFFECT OF FIBER LENGTH

The effect of length of fiber added to reinforce Chlef and Rass sand was evaluated by testing specimens with fiber length varying from 10 mm to 30 mm, but all other variables in test were fixed. The effect of changes in fiber length was determined for the two type of sand (Chlef sand and Rass sand). Specimens with various lengths (L_f = 10, 15, 20, 25 and 30 mm) but the same fiber content (w_f = 0.2%) were used to study the effect of fiber length on the improvement in the peak shear strength of the soil at a normal stress of 300 kPa and an average density 50%. Figure 10 shows the effect of fiber length on the peak shear strength of the Chlef sand and Rass sand. It can be seen from Fig. 10 that for two types of soil the addition of 20-mm fiber gives distinctly higher peak shear strength. For a given fiber content, an increase in the length of fibers results in an increase in the shear strength [40]. This increase in shear strength of the composite is a scale effect which depends on the relative sizes of fibers and soil grains, where the reinforcement is more effective when the fiber length is large compared to the size of the grains [34].

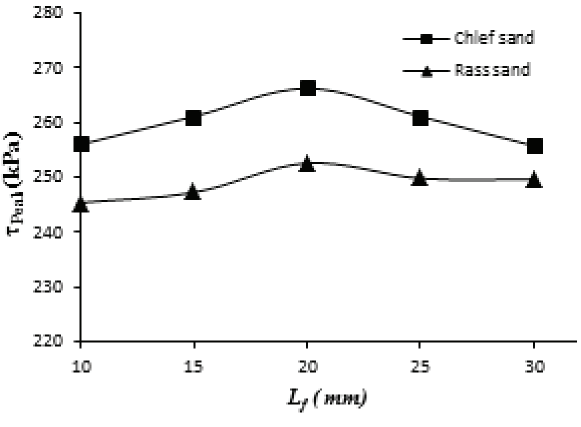

Fig. 10. Variations of peak shear strength versus length of fibers for Chlef and Rass sand

3.3. EFFECT OF GLASS FIBER AND CLINKER RESIDUE CONTENT ON THE PEAK SHEAR STRENGTH

Figure 11a, b, c, d shows the variation of the envelope of Mohr–Coulomb envelope circles between the shear stress τ (kPa) at the normal stress σ_N (kPa) for both types of sand (Chlef and Rass sand), unreinforced sand (Fig. 11a) and fiber reinforced sand Fig. 11b, c and d), following a linear equation, accordingly to Eq. (3):

$$\tau_{\text{peak}}(\text{kPa}) = A \times \sigma_N(\text{kPa}) + B \qquad (3)$$

where A slope of the line and B intercept.

The different equations fitted with their correlation coefficients are included in Table 5.

For both types of sand, there is a marked improvement in reinforced sands with fiber and clinker residue (w_f = 0.2% and w_{RC} = 3%) compared to unreinforced sand (w_f = 0% and w_{RC} = 0%). For Chlef sands, the values of peak shear stress τ_{peak} (kPa) change from normal stress σ_N = 100 kPa to 84.64 kPa for unreinforced to 133.33 kPa for a combination of reinforcement (w_f = 0.2% and w_{RC} = 3%) a strength gain estimated at 48.70 kPa and for a reinforcement either to (w_f = 0.2%, w_{RC} = 3%) or (w_f = 0.2%, w_{RC} = 0%), the shear stress remains substantially constant with a value estimated at σ_N = 100 kPa. It was noted that the highest resistance values were observed for Chlef sand, considering the good embedding of the filaments of fiber between the grains particles of sand and effect of non-slip of fibers between the coarse grain particles from Chlef sand.

The maximum values of maximum normal stress σ_N = 300 kPa recorded for Chlef sands were around of 313.3 kPa for reinforced treated sand (w_f = 0.2% and w_{RC} = 3%) compared to unreinforced sand, which was 245.20 kPa, a strength gain estimated around of 68.10 kPa. This explains the key role played by the combined action of the glass fibers and the clinker residue content on the behavior of composite.

In addition to this, it is clear that in Fig. 12 the peak shear strength of the two sands reinforced with fiber and clinker residue significantly increases when the normal stress increases from 100 kPa to 300 kPa, for unreinforced and reinforced soils. The highest values are indicated for the Chlef sand reinforced with 0.2% fiber and 3% of clinker residue. Its value reaches 320 kPa and the minimum value recorded for the Rass sand is 125 kPa an increase of 41.7% for Chlef sand that of Rass.

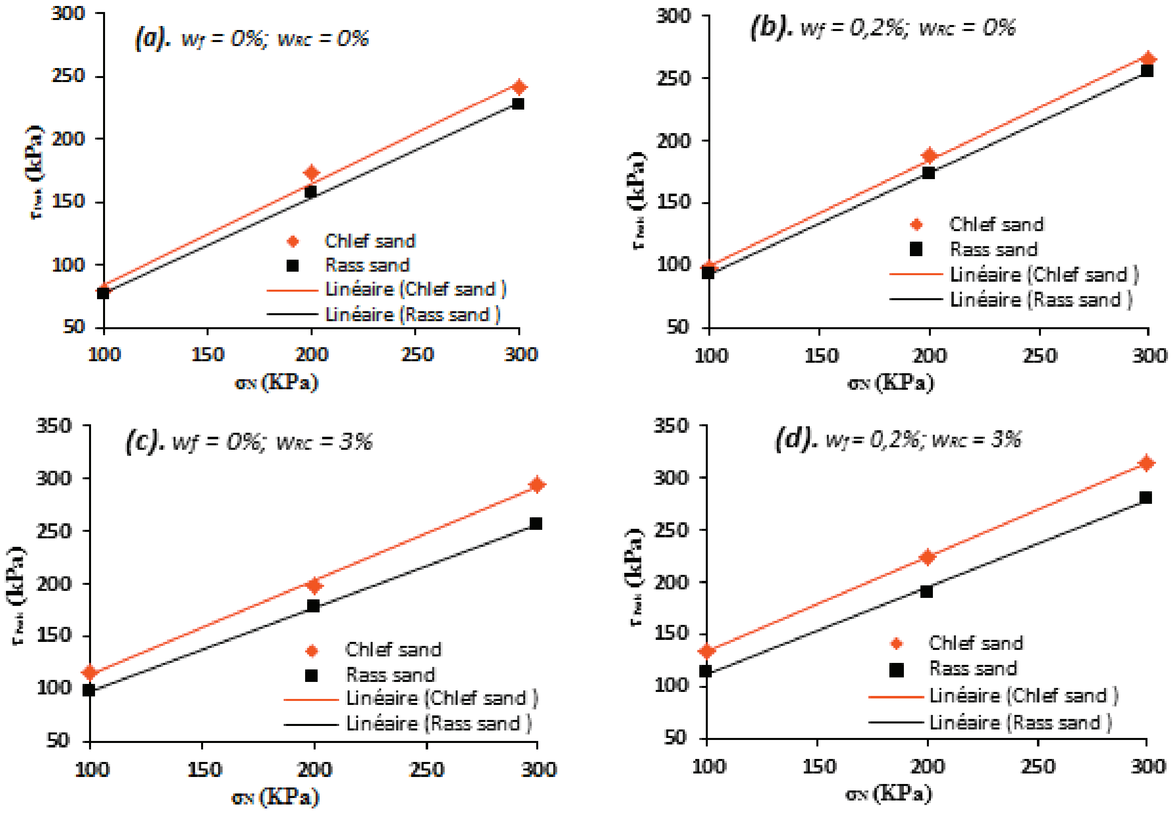

Fig. 11. Reinforcement effect on the peak shear strength for: (a) unreinforced sand, (b) reinforced sand, (c) unreinforced treated sand and (d) reinforced treated sand

Table 5. Equations straight Mohr–Coulomb for unreinforced soil and reinforced stabilized soil

Equation	Sand	B	A	R^2
(a) w_f = 0%, w_{RC} = 0%	Chlef	4.3598	0.8028	0.9928
	Rass	3.1086	0.7531x	0.9982
(b) w_f = 0.2%, w_{RC} = 0%	Chlef	15.55	0.8423	0.9985
	Rass	12.085	0.81	0.9999
(c) w_f = 0%, w_{RC} = 3%	Chlef	24.17	0.8958	0.9982
	Rass	19.077	0.7916	0.9999
(d) w_f = 0.2%, w_{RC} = 3%	Chlef	43.079	0.9025	0.9999
	Rass	28.643	0.8315	0.9971

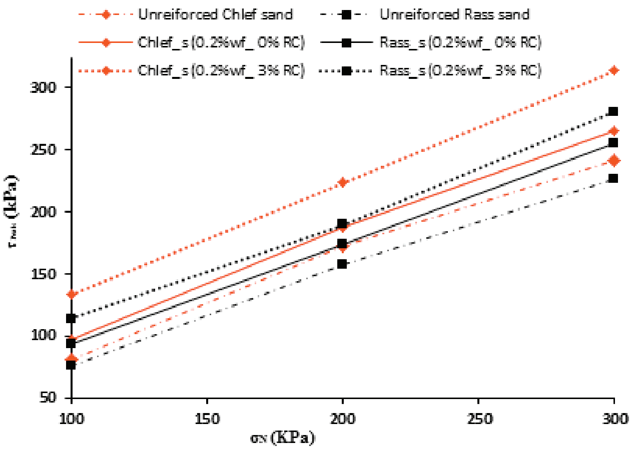

Fig. 12. Evolutions of peak shear strength versus normal stress of composite (sand-fiber-clinker residue)

3.4. EFFECT OF GLASS FIBER AND CLINKER RESIDUE CONTENT ON SHEAR STRENGTH PARAMETERS

Figures 13 and 14 illustrate the relationship between shear strength parameters and clinker residue content for unreinforced and reinforced sands. Figure 13 (a, b) shows the variation in the cohesion C (kPa) according to the clinker residue content for two types of soil, Chlef sand coarse (D_{50} = 0.452 mm) and fine Rass sand (D_{50} = 0.298 mm). It should be noted that the different curves cohesions increase when clinker rate increases to a maximum threshold estimated at w_{RC} = 2%, then decrease to the Rass sand has stabilized w_{RC} = 5% and Chlef sand

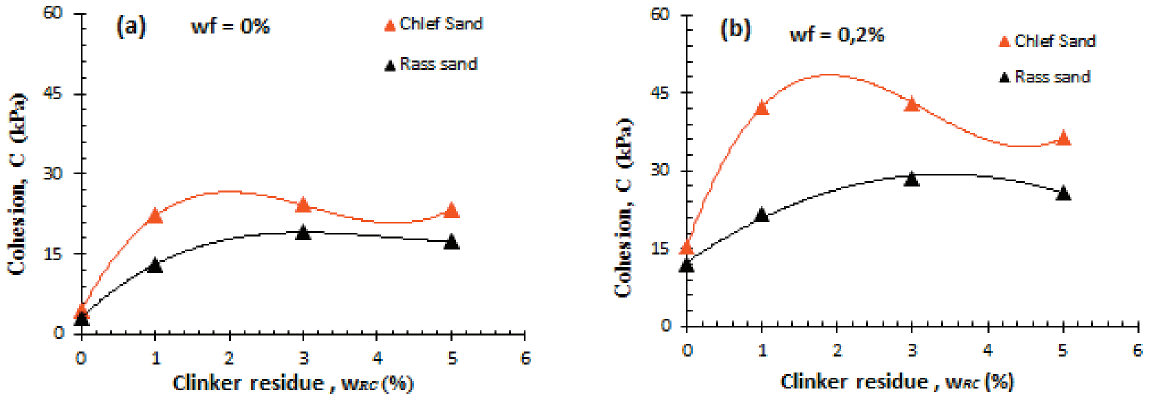

Fig. 13. Evolution of cohesion versus clinker residue of Chlef and Rass sand for:
(a) unreinforced sand, (b) reinforced sand

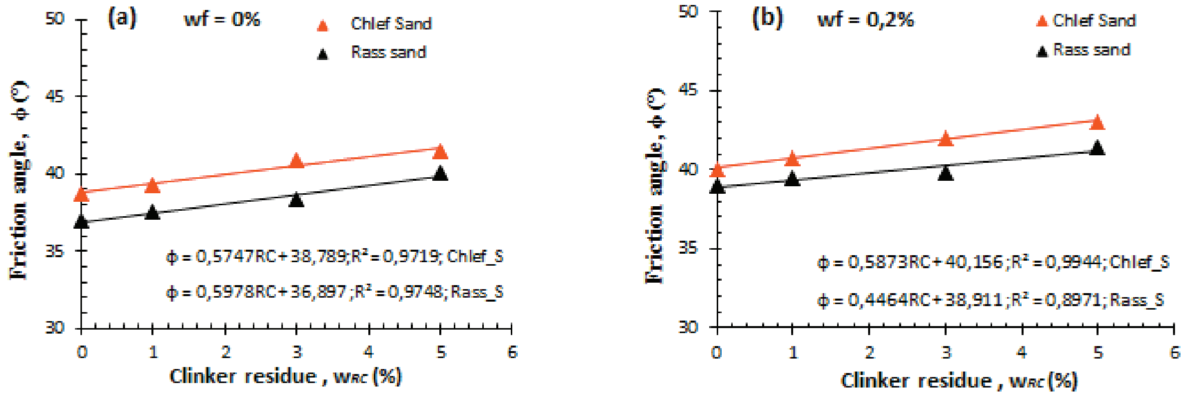

Fig. 14. Evolution of frictional angle versus clinker residue of Chlef and Rass sand for:
(a) unreinforced sand, (b) fiber reinforced sand

branches and changes of slope from a clinker rate estimated to $w_{RC} = 4\%$.

Generally, Chlef sand in reinforced condition ($w_f = 0.2\%$) is very efficient and more ductile than Rass sand, having low values of the cohesion given the fine nature of the latter compared to the diameter of the fiber, which cannot transfer loads (horizontal and vertical) through the fibers as there are fibers slipping in the matrix of deformation process [34].

In Chlef sand, the cohesion varies from 27 kPa for unreinforced treated sand ($w_f = 0\%$ and $w_{RC} = 2\%$) to 48 kPa for fiber-reinforced treated sand ($w_f = 0.2\%$ and $w_{RC} = 2\%$), an increase of 21 kPa. While for Rass sand the cohesion varies from 18 kPa for unreinforced treated sand to 24 kPa for fiber-reinforced treated sand, an increase of 6 kPa. These differences may be explained by the interweaving of glass fiber filaments having a high capacity in tension between the grain particles, the grain size and the role played by the fine particles of clinker in improving the composite. Figure 14a, b shows the variation of the friction angle φ[°] depending on the variation of the clinker residue content for the two types of sand: unreinforced sands (Fig. 14a) and fiber-reinforced sands (Fig. 14b).

In this laboratory investigation, for the range 0 to 5%, the following expressions are suggested to evaluate the frictional angle as function of clinker residue for both types of sand ($R^2 = 0.9595$).

$$\phi(°) = \alpha \times w_{RC}(\%) + \beta \tag{4}$$

where:

α – slope of the line,
β – intercept.

The indicated above approximately maintain the same straight slope of about $\alpha = 0.5565$. We also note that, the friction angle for Chlef sand varies from of 38.73° for unreinforced treated sand to 40.09° for fiber reinforced treated sand and the maximum recorded value of the friction angle is estimated at $\varphi = 43.01°$ for clinker residue content $w_{RC} = 5\%$. For Rass sand, the friction angle varies from 36.97° for unreinforced treated sand to 39° for reinforced treated sand, an increase of 2.03°. The maximum recorded value of the friction angle for Rass sand is $\varphi = 41.49°$ for clinker residue content $w_{RC} = 5\%$.

3.5. EFFECT OF REINFORCEMENT AND CLINKER RESIDUE ON SHEAR STRENGTH RATIO

We introduced the shear strength ratio parameter (SSR) to evaluate the effects of fiber and clinker residue on the shear strength of the reinforced treated sands. The variation of shear strength ratio (SSR) with normal stress can be evaluated according the relation (5) and presented in Table 6.

$$\text{SSR} = \frac{\text{shear strength of reinforced sand}}{\text{shear strength of unreinforced sand}} \tag{5}$$

Figure 15 shows the variation of normalized shear strength ratio of reinforced treated sands to an unreinforced sands under different normal stresses (σ_N = 100, 200, 300 kPa). The results indicate that the rate of increase in the shear strength of fiber-reinforced treated sand mixtures increases with fiber and clinker residue content increase and decreases under higher normal stress for both types of sand (Fig. 15). It can be noted that between 100 kPa to 200 kPa a resistance to normalized peak falls sharply for both types of sands, except for reinforced Chlef sand w_f = 0.2% where a slight normalized strength was stabilized. However, by the normal stress range: 200 kPa < σ_N < 300 kPa, the stress at the normalized peak showed a constant evolution for both types of sand except Rass sand where a significant rise was observed. The same trends were observed in previous results [19].

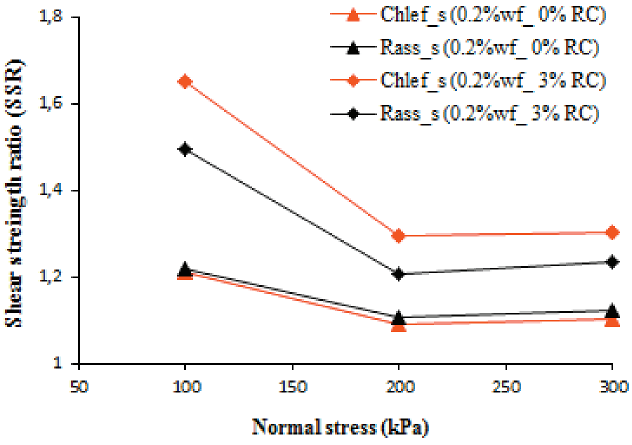

Fig. 15. Variation of shear strength ratios versus normal stress for Chlef and Rass sand

Therefore, the treated fiber reinforcement technique is more effective for samples at low vertical normal stress and using of these techniques is suggested to improve mechanical properties of the near surface geotechnical applications such as designs of subgrade, shallow foundation, earth retaining walls and slope [37].

4. CONCLUSIONS

Based on the results of 84 direct shear tests conducted in this study, the following conclusions can be drawn regarding the parameters affecting the shear strength of treated fiber-reinforced sands. First of all, the inclusion of fiber and clinker residues in the composite material significantly improved the shear strength for both types of sand. However, the various tests show that the response of the reinforced Chlef sand is more advantageous than that of the Rass sand.

Secondly, the influence of fiber inclusion on the mechanical properties of the composites depends fundamentally on the mechanical properties of the fibers and matrix. Under constant normal stresses (σ_N = 300 kPa), there is an optimum of fiber length equal to 20 mm and the maximum of peak shear strength was arrived at fiber content of 0.2% for both types of sand.

Next, for both sands reinforced with different ratios of fiber, both cohesion and friction angle have exhibited a significant increase along with an increase of clinker residue content for reinforced and unreinforced sands. Compared to unreinforced sand, the cohesion for sand reinforced with different ratios of clinker residue increased by 4.36 to 43.08 kPa for Chlef sand and by 3.1 to 28.64 kPa for Rass sand. For the same reinforcement material, the shear strength ratio of reinforced treated sands decreased significantly with the increase of vertical normal stress from 100 to 200 kPa. However, the shear strength ratio in-

Table 6. Summary of peak shear strength ratios

	$\text{SSR} = \frac{\text{Reinforced sand (Fiber)}}{\text{Unreinforced sand}}$			$\text{SSR} = \frac{\text{Reinforced sand (Fiber + Clinker)}}{\text{Unreinforced sand}}$		
	100 kPa	200 kPa	300 kPa	100 kPa	200 kPa	300 kPa
Chlef sand	1.21	1.09	1.10	1.65	1.29	1.30
Rass sand	1.22	1.10	1.12	1.49	1.21	1.24

creased slightly along with an increase of vertical normal stress from 200 to 300 kPa. And the maximal value of shear stress ratio was registered at 1.65 corresponding to 3% of clinker residue for reinforced Chlef sand.

Finally, it is recommended that future triaxial testing programs should be conducted to confirm the observations and conclusions presented in this study for more precise results.

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