

Research Article

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Shear Strength Enhancement of Cemented Reinforced Sand: Role of Cement Content on the Macro-Mechanical Behavior

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Abstract: Sands reinforced by hydraulic binders (cement) have constituted in recent decades a major asset for the expansion of several areas of engineering. The mechanical behavior of sand-cement mixtures has undergone some controversies studied on the Chlef sand. In this paper, we present an experimental study to investigate the mechanical behavior of a sandy soil reinforced by a hydraulic binder (cement), using the direct shear apparatus emphasizing on the shear strength characteristics and the vertical deformation variation of cemented reinforced sand. The parameters used in this study are mainly: relative density ($D_r = 80\%$), normal stress ($\sigma_n = 100, 200, 400$ kPa), water content (3, 7 and 10%), cement content (2.5, 5, 7.5 and 10 %) and cure time (7, 14 and 28 days). The experimental results show that the mechanical characteristics in terms of internal cohesion (C) and internal friction angle (φ) give a better mechanical performance with the binder inclusion, and the cure conditions play an effective role on the improvement of the shear strength. This result also showed that 10% of the cement content gave us a maximum value of shear strength and an optimal influence on the mechanical characteristics. The addition of cement not only improves the shear strength of soil, but also provides diversity in the resistance against the deformations imposed load, which can be established by a dilatant character.

Keywords: Cemented reinforced sand; direct shear test; water content; curing time; dilatant character.

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List of symbols

φ	Internal friction angle
C	Interlocking or intercept cohesion
D_r	Relative density
D_{50}	Mean grain size
δH	Horizontal displacement
δV	Vertical displacement
C_{unif}	Uniformity coefficient
C_{curv}	Coefficient of curvature
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
e	Global void ratio
γ_s	Specific weight of solids
σ_n	Normal stress
τ	Shear strength
τ_{max}	Peak shear strength
SEM	Scanning electron microscope
CC	Cement content
G_s	Specific gravity of sand
G_f	Specific gravity of silt
D_{10}	Sand effective grain size
I_p	Plasticity index
IB	Brittleness index
ω, w	Water content

1 Introduction

The reinforcement of soil in place remains an important activity area in the field of geotechnical engineering. It aims to improve the mechanical qualities of soil by increasing its resistance, reducing its permeability and controlling its deformability. Several methods are used in this area including the methods involving the use of planar or continuous inclusions (e.g., metal strips, geogrids, geotextiles) within earthen structures. Plans of weakness can be introduced along the interface between the reinforcement and the ground because the shear

strength of the interface is generally greater than that of the ground. And other possibilities are conceivable such as the traditional methods: densification, treatment with hydraulic binders (cement, lime, etc.) and the incorporation into the ground reinforcement structures. The interest is then to find reliable, safe, inexpensive and quick to implement solutions.

The technique of reinforcing poor quality soil by cement is more and more necessary, given the growth of humanity and its activities. Certain types of soil, hitherto neglected because they have weak mechanical characteristics, must be reinforced to ensure the stability of buildings and civil engineering infrastructures. The method of including a hydraulic binder to improve the mechanical characteristics of soils is to homogeneously mix the cement in the soil with certain water content and play the role of reinforcement locally.

Several researchers have demonstrated the effectiveness of adding cement to the mechanical behavior of soils (such as Coop et al, 1993; Consoli et al., 1998; Schnaid et al., 2001; Asghari et al., 2003; Haeri et al., 2006; Sharma et al., 2011; Baxter et al., 2011; Heathcote et, 1994). They showed that cemented sands show brittle behavior with an apparent peak in the stress-strain curve. Increasing the cement content increases the shear strength and the expansion rate. Venkatarama et al. (2005) studied the characteristics of blocs of cemented soil using mixtures of very sandy soils. The cement content of the block is varied by keeping the soil mixing and block density constant, they found that the compressive, flexural and direct tensile strength of the soil-cement blocks increased by about 2.5 times for a cement content of 6%. Maher and Ho. (1993) conducted static and dynamic triaxial compression and extension tests on cemented sand containing randomly distributed fibers and reported more shear strength and energy absorption for soil containing fiber. A study of DOS Santos et al. (2010), whose experiments reported on fiber-reinforced cemented sand under pressures up to 40 MPa, reported that the fiber-reinforcement reduced fracture propagation and cracks in the cemented sand particles. Improved mechanical properties of soils due to fiber reinforcement cannot be a general rule to destroy, and due to this, contradictory conclusions of the majority of researchers can be explained by the kind and the shape of the fibers used or the physical characteristics of the soil, their relative density and the method of samples preparation. Mateus et al. (2016) presented an analysis carried out from the axial compression of the

mixture between sand and Portland cement and water, the composition was prepared with 3% and 7% cement and 10% water content for five different curing times, the results show that the higher percentage of cement has generated low void levels, which consequently increases the resistance. Experimental data obtained from the drained triaxial compression tests on cemented sand by Marri et al. (2010) indicate the importance of the degree of cementation and the confining pressure on the stress-strain behavior of the cemented sand. However, the influence of cementation is greater at low confining pressures and decreases with increasing confining pressures that made the effect of this parameter becomes dominant. In addition, scanning electron microscope SEM analysis of cemented samples revealed that stress level and cement content affect particle breakage. New requirements concerning the method and the material have been accumulated: increase in strength, rigidity, impermeability, homogeneity, durability, prediction of the resistance according to the type of soil, and so on. Numerous studies on the dry method as well as some on the wet method provide some answers (Consoli et al., 2009, 2010, 2011; Lee et al., 2010; Shahnazari et al., 2013 ; Hirabayashi et al ., 2009 ; Kido et al., 2009 ; Umesha et al., 2009). However, there is no global parametric study studying both the impact of soil type and quantity of water on the characterization of cemented soil material. In the same way, the workability of the material has not yet been studied. The influence of the sandy part as well as that of the grain size on the ground, are also some of the most relevant questions.

The objective of our research project is, therefore, to improve the dosing methods as well as the sizing methods of the structures in cemented soil. In the same way, the determination of the field of workability of the material for use in wet method is capital for its homogeneity and the continuity of the works, and thereby performing a parametric study on the cemented soil material. A series of direct shear tests were carried out on a sandy soil reinforced by a hydraulic binder (cement). The use of the direct shear apparatus enabled us to study the characteristics of the shear strength and the variation of vertical deformation of cemented sand. The parameters used in this study are mainly: the relative density ($D_r = 80\%$), the normal stress ($\sigma_n = 100, 200$ and 400 kPa), the water content ($\omega = 3, 7$ and 10%), cement content ($C_c = 2.5, 5, 7.5$ and 10%) and curing time (7, 14 and 28 days).

Table 1: Physical characteristics of Chlef sand and cemented sand.

Materials	Cc (%)	γ_s (g/cm ³)	D ₅₀ (mm)	C _{unif} (.)	C _{curv} (.)	e _{min} (.)	e _{max} (.)
Sand	0	2.719	0.44	2.35	1.32	0.588	0.853
sand cemented	2.5	2.735	0.43	2.5	1.4	0.542	0.831
	5	2.765	0.42	2.66	1.5	0.535	0.811
	7.5	2.81	0.41	2.75	1.45	0.529	0.815
	10	2.845	0.4	2.85	1.5	0.517	0.823

2 Experimental program

2.1 Materials

A series of direct shear tests were carried out on the sandy soil of the Chlef area, from the banks of the Chlef Valley. The soil was initially air dried and sieved through a 2 mm sieve, Fig. 3(a). Chlef sand particles are with a reduced grain shape and quartz with some carbonates, and they are usually isometric particles. Figure 1 shows a microscopic view of an electronic scanning of the tested sand. The basic properties of sand are given in Table 1, the grain size distribution curves of this soil with different cement content are shown in Figure 2. Many researches were performed to study the Chlef sand behavior (Arab et al., 2008, 2009, 2014; Djafar et al., 2011, Belkhatir et al., 2013; Benessalah et al. 2019 ; 2018 ; 2017 ; 2016 ; Della et al. 2011; Aouali et al., 2018; Merabet et al. 2019).

The cement used in this study is the cement of Chlef CEM II/A type of 42.5 classes, density 3.1 and a surface area of 3298 cm²/g. The silica fume used in cement is 8%, according to the standard EN 13263-1, having a density of 2.4 and a surface area of 220 000 cm²/g (Figure 3(b)). The chemical and mineralogical characteristics of the cement smoke are shown in Table 2. The mixture of soil and cement is introduced into a kneader for 2 minutes while adding appropriate water content.

2.2 Samples preparation and tests procedures

A series of 117 tests was carried out in a rectangular shear box to study the effect of adding cement on the shear strength of the cemented sand. The shear box had a dimension of 60 x 60 mm horizontal cross section; the height of the test piece was 25 mm. All tests were performed according to the standard ASTM D-3080 (2005) with a constant horizontal shear rate of 1.00 mm/min.

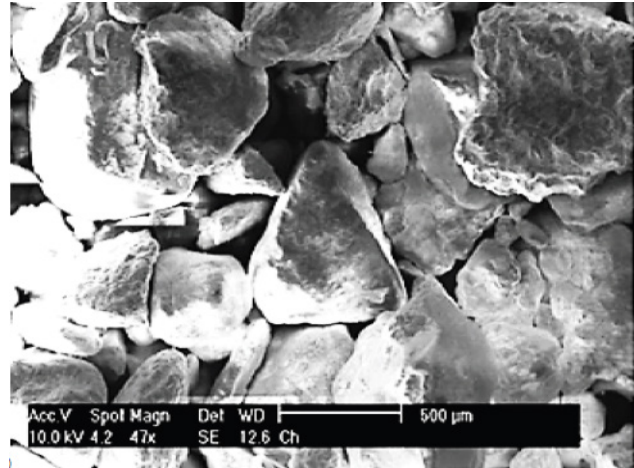


Figure 1: Scanning electron microscope view (SEM) of Chlef sand, Della et al. (2014).

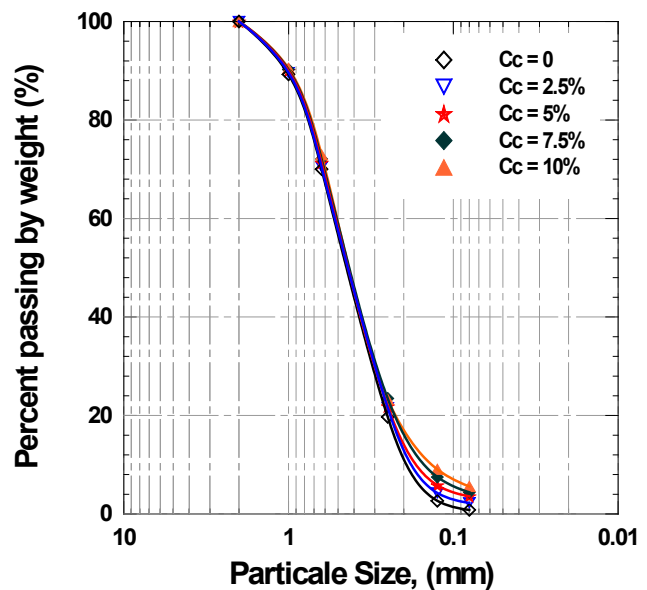


Figure 2: Grain size distribution curve of Chlef sand and cemented sand.



Figure 3: Materials used in this study: (a) Sand, (b) Cement, (c) Sample preparation.

Shear stress was recorded as a function of horizontal displacement to an average shear strain of 13%.

The first series in this laboratory study concerned shear tests on unreinforced Chlef sand with different water contents $\omega = 3, 7$ and 10%, the second series carried out involved 108 tests on a mixture of sand-cement with a cement content $C_c = 2.5, 5, 7.5$ and 10%. The dense relative density (Dr) used was 80%. Samples were sheared under normal stresses $sn = 100, 200$ and 400 kPa. The sample preparation time was approximately one hour for setting the cement; then they are placed in a room at a temperature of $26^\circ \pm 2$ for a duration of 7, 14 and 28 days with a humidity of 90%. The average cement concentration is defined as a percentage of the dry weight of sand, according to the following equation:

$$C_c = \frac{W_c}{W_s} \times 100 \text{ [%]} \quad (1)$$

With: W_c the cement weight and W_s the sand weight.

Each sample was prepared in three layers (Figure 3(c)). The mass of each layer was determined according to the value of the initial relative density (Dr). Each layer was poured into the mold and then compacted manually; the number of strokes was 25 until obtaining the desired height for the dense tests. Table 3 shows all the parameters considered in the test program.

3 Results and discussion

3.1 Unreinforced sand

Figure 4(a) illustrates the results of the shear box tests on the unreinforced sand samples with water contents of 3,

Table 2: Chemical and mineralogical compositions of the cement.

CEM II/A			
Chemical compositions (%)		Mineralogical compositions (%)	
SiO ₂	20.58	C ₃ S	57.79
Al ₂ O ₃	4.90	C ₂ S	20.47
Fe ₂ O ₃	4.70	C ₃ A	7.20
CaO	62.8	C ₄ AF	11.49
SO ₃	2.28		
MgO	0.53		
K ₂ O	0.42		
Na ₂ O	0.12		
Free lime	2.17		

7 and 10%, relative density $Dr = 80\%$ and sheared under a normal stress of 100 kPa. The results clearly show that an increase in water content has a significant impact on the soil shear strength. Soil resistance decreases with increasing moisture content. Figure 4(b) illustrates the variation of the vertical displacement as a function of the horizontal displacement. It is noted here that an increase in the water content leads to an increase in the vertical displacement, and therefore, the contractiveness of the sample increases, these results are consistent with those found by Benessalah et al. (2015).

3.2 Shear response of the cemented sand samples

Several researchers (Eathcote et al. 1994; Walker et al. 1995; Huang et al, 1998; Schnaid et al, 2001) showed the contribution of cement content in the evolution of soil resistance. Figure 5 illustrates the results of the direct shear

Table 3: Parameters of the experimental program.

Type of Samples	Vertical stress (kPa)	Water content (%)	Cement content (%)	Relative density (%)	Time of cure (days)	Number of tests
Uncemented samples	100	3	0	80	0	9
	200	7				
	400	10				
Cemented samples	100	3	2.5	80	7	108
	200	7	5		14	
	400	10	7.5		28	
			10			

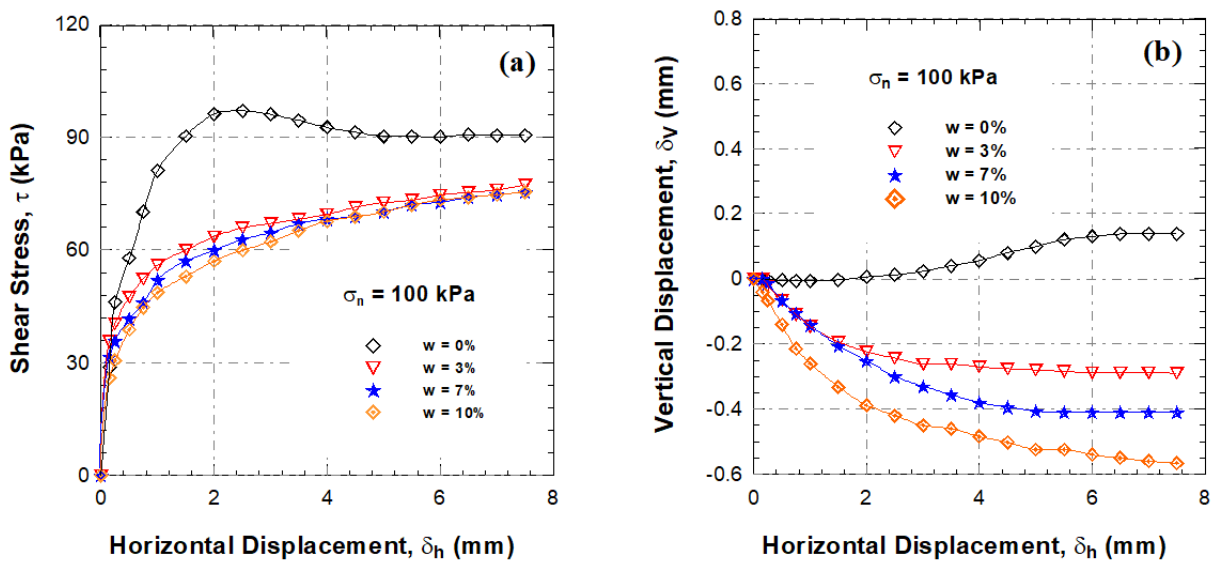


Figure 4: Influence of water content on the behavior of Chlef sand ($\sigma_n = 100$ kPa, $D_r = 80\%$), (a): Shear stress as a function of horizontal displacement, (b): Vertical displacement as a function of horizontal displacement.

tests on cemented sand samples with a cement content $C_c = 2.5, 5, 7.5$ and 10% with a water content $\omega = 3, 7$ and 10% emphasizing with comparison between them and the results of the unreinforced sand. These tests were sheared under a normal stress of 100 kPa. The results show that the shear strength of the unreinforced samples increases with increasing horizontal displacement without a peak appearance, while for samples reinforced with cement, it is found that the resistance increases significantly with the increase of the cement content up to a resistance peak of 80, 90, 100 and 110 kPa for C_c equal to 2.5, 5, 7.5 and 10%, respectively; then the resistance drops followed by a residual resistance to the shear end for samples with water content of 3% (Figure 5(a)). The results of the tests of the samples made with a water content ω of 7 and 10% are illustrated in Figures 5(b) and 5(c); a very significant increase in the strength of the mixture is observed with the increase in the cement content where the shear strength

reaches values of 106, 181 and 189 for water contents of 3, 7 and 10% for the samples mixed with 10% cement. Figures 6(a), 6(b) and 6(c) illustrate the variations of the vertical deformation as a function of the horizontal deformation; the results of these tests show a contractiveness phase for the small horizontal displacements followed by a phase of dilatancy, which reduces the deformability of the grounds against the external forces; on the other hand, the unreinforced sand showed only a contractiveness phase of deformation, which represents the vulnerability of unreinforced sand that will be represented by cracking during external loading.

Figure 7 shows the evolution of the maximum shear strength as a function of the cement content. Note that increasing the normal stress increases the shear strength considerably. It can also be seen that the shear strength of the sand-cement mixture increases with an increase of the cement content according to a quasi-linear growth

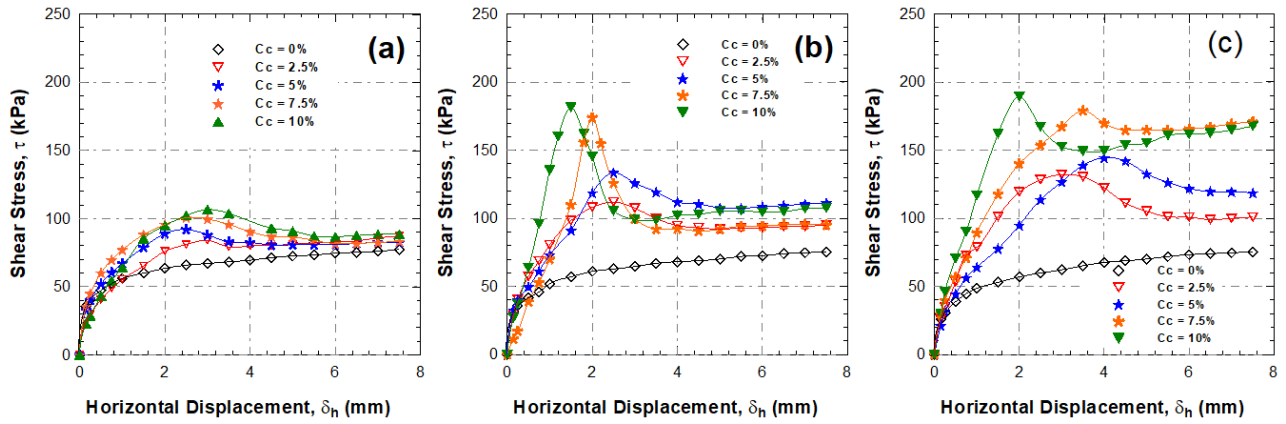


Figure 5: Cement content influence on the shear strength of cemented sand ($\sigma_n = 100$ kPa), (a) $\omega = 3\%$, (b) $\omega = 7\%$, (c) $\omega = 10\%$.

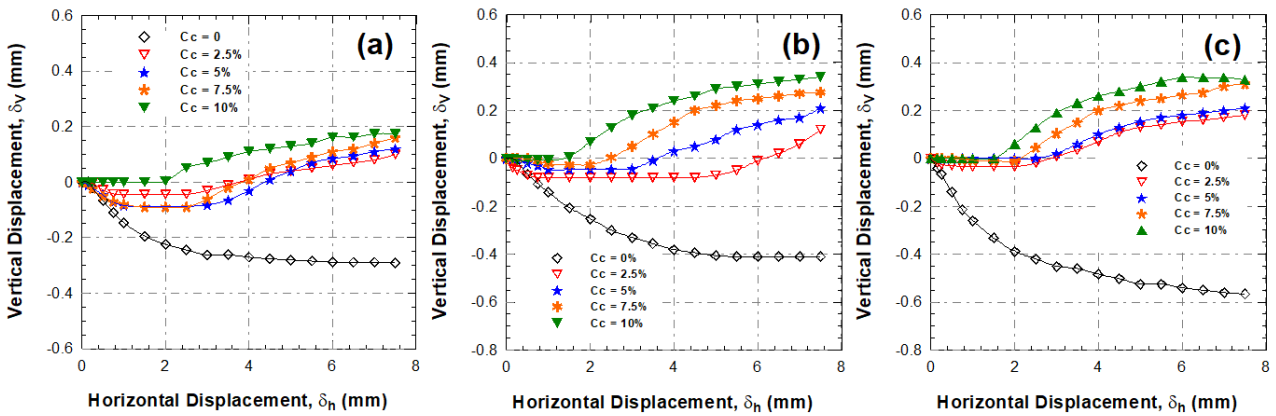


Figure 6: Cement content influence on the vertical displacement of cemented sand ($\sigma_n = 100$ kPa), (a) $\omega = 3\%$, (b) $\omega = 7\%$, (c) $\omega = 10\%$.

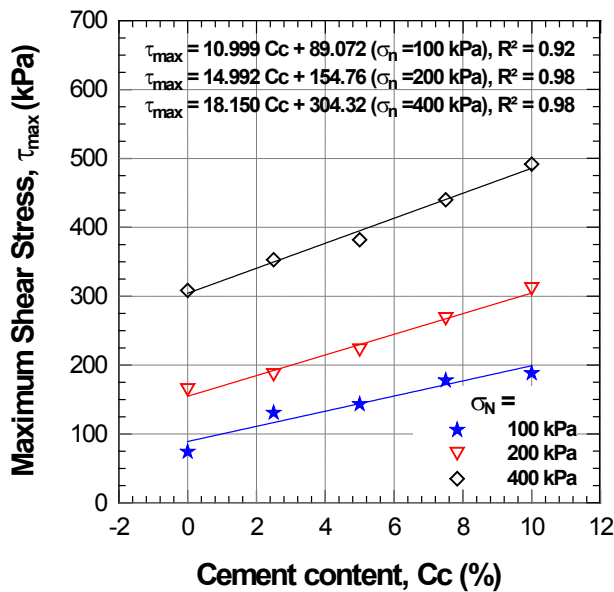


Figure 7: Evolution of the maximum shear strength of cemented reinforced sand as function of cement content (case of a water content $\omega = 10\%$).

(coefficient of determination $R^2 = 0.92, 0.98$ and 0.98 for the three normal stresses $\sigma_n = 100, 200$ and 400 kPa, respectively).

3.3 Cement content effect on the mechanical characteristics

Although a curved rupture envelope is expected for the sand-cement mixtures under study, by a linear regression between the shear stresses and the normal stresses applied to the samples at a given shear displacement; to determine the shear strength parameters including friction angle and the interlocking between the particles or the intercept cohesion. Variations in internal friction angle and intercept cohesion versus cement content are shown in Figure 8. Here, the interception of cohesion and the friction angle increase as the cement content increases. In particular; Figure 8(a) illustrates the evolution of the interlocking that has been presented in the figure as an intercept cohesion

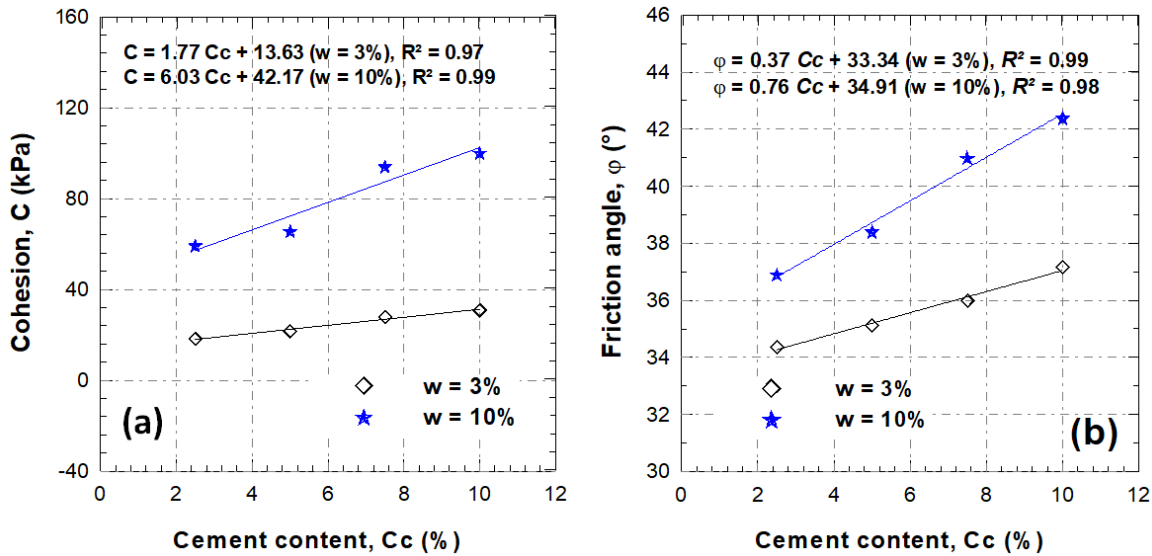


Figure 8: Influence of the cement content on the mechanical properties of cemented sand: (a) variation of the interlocking or intercept cohesion; (b) Variation of the friction angle.

of the mixture versus the cement content for water contents $\omega = 3$ and 10%. The results clearly show that the intercept cohesion (C) of the soil increases linearly with the increase of the cement content and also with the water content ($\omega = 10\%$ has greater values of intercept cohesions of all the samples under study, approximately the double of the values obtained with $\omega = 3\%$). Figure 8(b) illustrates the evolution of the friction angle with the increase in the cement content (Cc); here, we find that the friction angle (φ) increases significantly and with a linear manner with an increase in the cement content (Cc) for all the mixtures under study. Water content decreases immediately due to cement hydration and long-term pozzolanic reactions as water is absorbed and converted to cement-based products (Bergado et al., 1996, Bennert et al., 2000; Chew et al., 2004). So, the increase in curing time increases the shear strength, and consequently, also increases on the cohesion and the angle of friction because of continuous cementing reactions. Our results are in good agreement with those found by (Consoli et al., 2009; Amini et al., 2013; Asghari et al., 2003). These results show in addition the positive role of the water content in the improvement of the mechanical behavior of cemented reinforced sand and also indicate that the optimum water content is not yet reached taking into account the two values used in this study. Consoli et al. (1998) used the brittleness index as an indicator of the brittle behavior of soil as follows:

$$I_B = \frac{q_{\max}}{q_{\text{res}}} - 1 \quad (2)$$

where: I_B is the brittleness index, and q_{\max} and q_{res} are the peak and residual deviatoric stresses, respectively. They indicated that the addition of cement in the composite material leads to an increase in stiffness, brittleness and peak resistance. However, they noted that the inclusion of fibers increases both the peak and residual triaxial strength and reduces stiffness, which makes it possible to change the brittle behavior to a more ductile one.

3.4 Influence of curing time on the shear strength

It is known that cure temperature plays a very important role in the evolution of resistance; a high temperature of the environment generates a faster development of the resistance against a low temperature will slow down the setting process. Several studies have been developed in this direction, such as Hashimoto et al. (2009), Ahnberg et al. (2003), and Umesha and Val (2009). For temperatures below zero, the process will not be triggered by the freezing of water molecules. Figure 9 illustrates the results of stress-strain shear tests for cement-treated samples that were cured at 7, 14 and 28 days. It can be seen from the results that the shear strength increases significantly with increasing curing time, for example, the sample with 10% cement for a curing time of 7 days, has a resistance of 190 kPa; after 14 days, the resistance increases to 270 kPa and continues to increase to reach the value of 290 kPa after 28 days. This increase in resistance is due to curing time

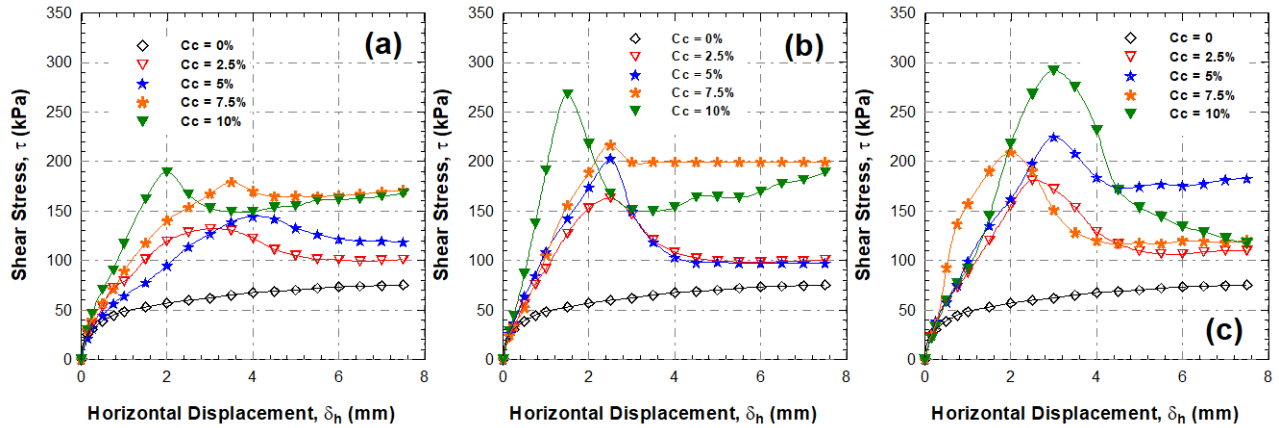


Figure 9: Influence of curing time on shear strength of cemented sand ($\sigma_n = 100$ kPa), (a) after 7 days, (b) 14 days, (c) 28 days.

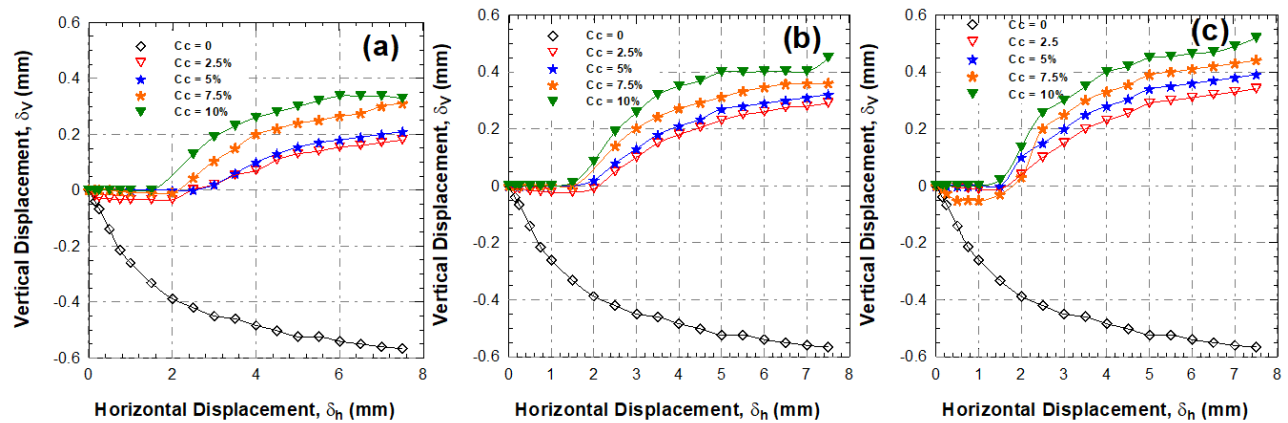


Figure 10: Influence of curing time on deformability of cemented sand ($\sigma_n = 100$ kPa), (a) after 7 days, (b) 14 days, (c) 28 days.

on increasing the rigidity of the soil. Figure 10 illustrates the evolution of vertical deformations as the functions of horizontal deformations. It is noted that the increase in the cement content and the cure time considerably reduces the deformability of the mixtures that is represented by reducing the contractiveness character, and having a dilatant character after around 2 mm of horizontal displacement. These results are in perfect agreement with those found by Zillur Rabbi et al. (2011).

Figure 11 shows the evolution of maximum shear strength as a function of cement content and curing time. The results of the samples show that maximum shear strength increases almost linearly with increasing cement content and also with increasing cure time. These results are attributed to the interaction and also to the cement bonding of the sand particles, and consequently, the resistance and the improvement of the mechanical behavior increases. These results are close concordances with those found by Consoli et al. (1998) and Schnaid et al. (2001).

The intercept cohesion values obtained with deferent cement content for the three curing times namely 7, 14 and 28 days for the samples of high relative density ($D_r = 80\%$), are presented in Figure 12a. It is noted that the intercept cohesion (C) increases very significantly with the increase in cement content according to almost linear growth ($R^2 = 0.952$, $R^2 = 0.918$, $R^2 = 0.882$, for 7, 14 and 28 days, respectively). It is also noted that shear strength increases with an increasing curing time. Figure 12(b) illustrates the evolution of the angle of friction as a function of the cement content. The results clearly show that the angle of internal friction also increases linearly with an increase in the cement content and also with an increase in curing time ($R^2 = 0.986$, $R^2 = 0.934$, $R^2 = 0.874$, for 7, 14 and 28 days).

Table 4 illustrates a summary of our results with those found in the literature, particularly those of Amini et al. (2013), Asghari et al. (2003) and Consoli et al. (2009). Comparing our results with those of Amini et al., (2013), we find that the addition of cement in the sand is

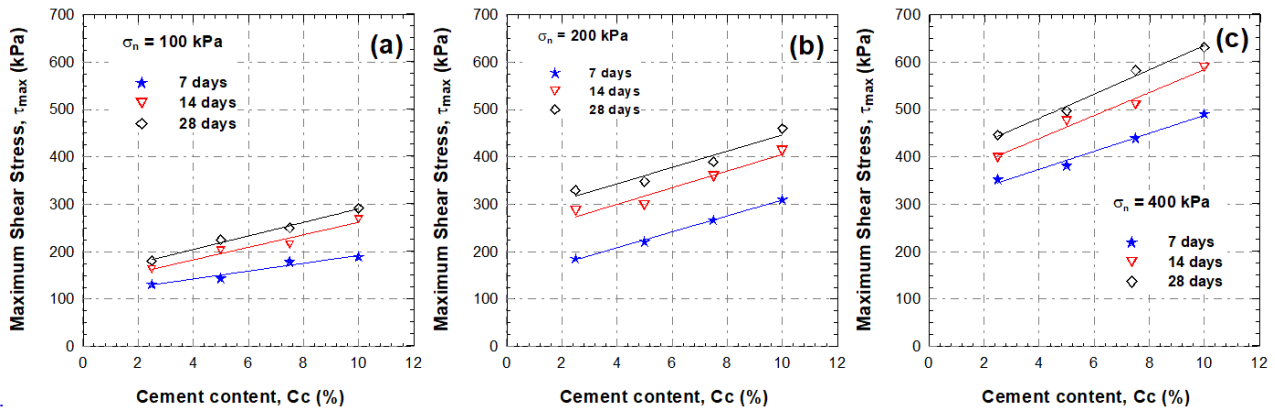


Figure 11: Influence of cure time on the maximum shear strength of cemented sand, (a) Normal stress of 100 kPa, (b) Normal stress of 200 kPa, (c) Normal stress of 400 kPa,.

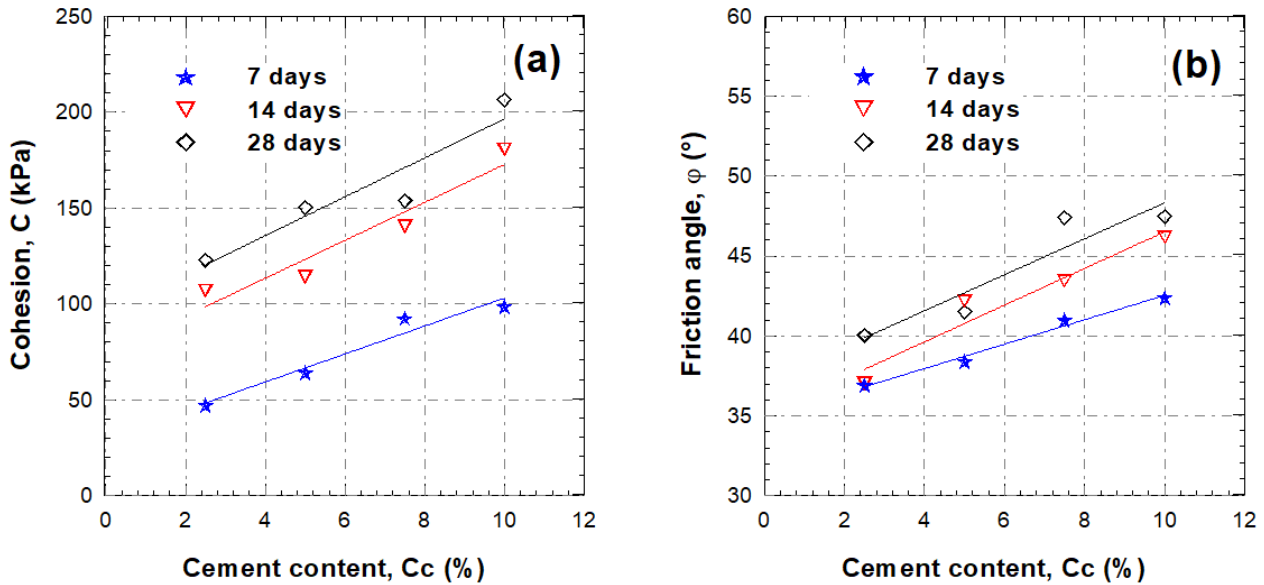


Figure 12: Influence of curing time on the mechanical characteristics of cemented sand.

characterized by a certain efficiency because the cohesion value reaches 94 kPa for a cement content of 2% (Amini et al 2013), while Chlef sand needs 10% cement to reach this value for the same relative density (80% and 85%) and with the same cure time of 7 days. According to the results of Asghari et al, (2003); cohesion reaches a value of 375 kPa for a cement content of 4.5%.

4 Conclusions

In this paper, we present the laboratory results of a series of direct shear tests carried out on unreinforced and cement-reinforced Chlef sand, the reinforced sand samples

prepared with cement contents of 2.5, 5, 7.5, 10% and with different water content ($\omega = 3, 7$ and 10%) in order to study the mechanical behavior of a sand-cement mixture and their influence on the mechanical characteristics, that is, maximum shear strength, intercept cohesion and friction angle. All the samples were consolidated and sheared under normal stresses of 100, 200 and 400 kPa, which considered constant in all the test steps. The following conclusions were drawn:

- The shear strength and the deformability of cemented reinforced sand under study are strongly affected by water content, cement content and curing time.
- The increase in the water content significantly increases the shear strength of the sand-cement

Table 4: Summary of our results with those found in the literature.

Cc (%)	7 days		14 days		28 days	
	C (kPa)	φ (°)	C (kPa)	φ (°)	C (kPa)	φ (°)
0	12.92	36.54	12.92	36.54	12.92	36.54
2.5	47.29	36.9	107.04	37.03	122.97	40.05
5	64.31	38.41	114.22	42.19	150.38	41.51
7.5	92.47	41	140.58	43.46	153.72	47.4
10	98.76	42.39	180.69	46.17	206.54	47.47
Amini et al (2013)			Asghari et al (2003)		Consoli et al (2009)	
Cc (%)	C (kPa)	φ (°)	Cc (%)	C (kPa)	Cc (%)	C (kPa)
0	0	38.74	0	0	0	0
1	58.15	42.28	1.5	200	1	19.5
2	94	43.13	3	250	4	84
			4.5	375	7	146.5
					10	328

mixture due to the hydration of the cement, and reduces the deformability of the sand-cement mixtures (by increasing the dilatant character).

- The addition of cement in the sand increases the shear strength considerably; it not only improves the shear strength of the soil, but also provides diversity in the resistance against the deformations imposed loads, which can result in a minimization of expansion-contraction cracks of the specimens.
- Both internal friction angle and intercept cohesion increased when cement was added. The peak friction angle increased in the mixture with 10% of cement content comparing with samples reinforced with 2.5 cement content; from 34.2° to 37.4° for 3% water content and from 36.8° to 42.3° for 10% water content. It can be concluded that the cement content has a great effect on the shear strength of cemented soil, but in addition to the effect of water content, which decreases immediately due to cement hydration. So, the increase of the curing time makes increasing the shear strength and consequently also increases on the cohesion and the angle of friction because continuous cementing reactions. We must note here that it is recommended to test specimens with greater values of water content to better establish its optimum contribution. Another parameter can affect the mechanical characteristics of cemented soils; curing time has a great effect on the shear strength, and thus, the intercept cohesion and friction angle, where we

found that the mechanical characteristics increased with increasing the values of curing time under study.

As recommendations, cemented reinforced sand would be an interesting solution to obtain a synthetic material against the falls of the resistance and to treat well the problem of the instability and the deformability of the sand. In this case, our research is progress with drained and undrained monotonic and triaxial tests and even cyclic tests on cemented sand to confirm the conclusions and observations presented in this study. Another program on fiber reinforced cemented sand and modeling by Flac3D software are in the program of our research.

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