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Application of the hypoplastic model for validating direct shear tests to investigate the impact of fines on the behavior of chlef sand.

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Abstract

This study was carried out to describe the mechanical behavior of different materials in terms of shear strength, cohesion and friction. For this purpose, an experimental shear tests were carried out. The soils used for the preparation of the samples were the Chlef sand, Chlef silt and M'zilla clay and a mixture composed of 50% of silt and 50% of clay. The soils were prepared by mixing Chlef sand with fines content of silt, clay or clay silt ranging from 0, 10, 20, 30 and 40%. The tests were conducted on sand samples prepared at a relative density of 20% representing a loose state and subjected to three normal stresses of 100, 200 and 400 kPa. All the tests were conducted at constant displacement rate of 1.00 mm/min. From the obtained results, it can be seen that the clean sand showed the highest shear strength at a small strains. At large strains, sands with 30% clay rather than 30% clay silt showed the highest shear strengths respectively. More contracted sands have the greatest increased maximum shear strengths. The sand with clayey silt, at a fine content of 20%, develops the most increased cohesion, among the other silty-clayey sands, together with the most reduced shear strength in elastic behavior. The sand with 40% of silt content develops a greater internal friction angle, however, the other silty sands, showed reduced shear strength, at the same behavior. To validate these findings, numerical simulations were performed on sand-silt mixtures using the hypoplastic model. The results indicated that the hypoplastic model accurately predicts the shear behavior of sand-silt mixtures in direct shear test, providing realistic insights into the effects of fines on the mechanical properties of the soil.

Keywords: Sand, Silt, Clay, Fines Content, Shear Strength, Friction, Cohesion.

Notation

G_S	Specific gravity of solids
γ_S	Unit weight of the solid grain
D_{10}	Effective grain diameter
D_{50}	Average grain diameter
C_U	Uniformity coefficient
C_C	Coefficient of curvature
C	Cohesion
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
RD	Relative density
σ_n	Normal stress
τ_{max}	Maximum shear strength
τ	Shear strength
φ	Friction angle at the peak of shear stress
ΔH	Horizontal displacement
ΔV	Vertical displacement
IP	Plasticity index
Fc	Fine content
R^2	Coefficient of determination

1. Introduction

The shear strength of soils is mainly considered to be the source of prediction of soil instability. In this study, the shear strength is defined, from the stress-strain curves, as being the maximum shear stress developed. The mechanical behavior has piqued the interest of numerous researchers. Several researchers have been interested to study the mechanical behavior of sand using different approaches leading to results specifying the materials tested. [1, 2] found that at the low fines content in the sand, they remain contained freely in the spaces provided by the coarse grains of the sand which are in contact. They give compressibility during the shear, which leads to a collapse and a reduction in the shear strength. However, the mechanical behavior becomes dominated by the fines contacts when the fines content exceeds 5%. This, in turn, leads to an increase in the shear strength.

Some authors, [2, 3, 4, 5, 6] showed that the shear strength reduces with fines added. Other researchers [7, 8] have shown that the shear strength of sand increases with the increase of the fines content. However, some [9, 10] have concluded that the shear strength decreases until certain fines content then it tends to grow again. [3, 11, 12] found that the add fines in the granular materials increases the cohesion and reduces the internal friction angle. For the silty samples sands, [13] depending on the increase in silt content, have found that the shear strength and the internal friction angle decrease, but the cohesion increases. But, for the silty-clayey sand samples, they found that the shear strength and the internal friction angle decrease until reaching minimum values of the fines content then increase beyond these fines contents while the cohesion increases and reduces. [14] Found that the susceptibility to the deformability of silty and clayey sands increases with the increase of the clay content rather than the silt content. [15] Found that the grow in the shear strength of silty sands is implied by the grow in their permeability. Several studies show that the shear strength of sand reduces with the increases of fines content in the soil [16, 17, 18, 19, 20, 21, 22, 23, 24, and 25].

The utilization of numerical analysis in geotechnical engineering is increasingly gaining popularity and becoming a standard practice for enhancing engineering projects [26, 27, and 28] first introduced the initial hypoplastic model, incorporating the current stress and void ratio into their constitutive relations for granular materials. The hypoplastic model proposed by [29] stands out as the most widely recognized model for simulating the behavior of granular soils. This model necessitates the specification of eight material parameters (φ_c, n, hs, ei0, ed0, ec0, α, and β). It has been extensively employed by various researchers as a constitutive model for granular soils, including studies by [30, 31, 32, and 33].

The study concerns shear tests carried out on Chlef sand mixed with fines content of silt, clay and clayey silt ranging from 0, 10, 20, 30 and 40%, at a relative density of 20% and a normal stress of 100, 200 and 400 kPa. After that, several hypoplastic model parameters (Hs, n, α, β, e_{i0}, e_{c0}, e_{d0}, and φ_c) were employed to estimate the mechanical behavior of various mixtures.

2. Laboratory test program

2.1 Tested materials

The tested materials used in this study are composed of clean Chlef sand, which has an estimated specific gravity of 2.67 [34], silt and M'zilla clay. The silt's plasticity index is Ip = 5.02 and M'zilla clay is Ip = 79%. Figure 1 represents the maximum void ratio (e_{max}) [35], minimum (e_{min}) [36] and that of the void ratio corresponding to the density state (e_{RD}). The mixtures' particle size curves shown in Figure 2 were obtained using to the standard methods [37].
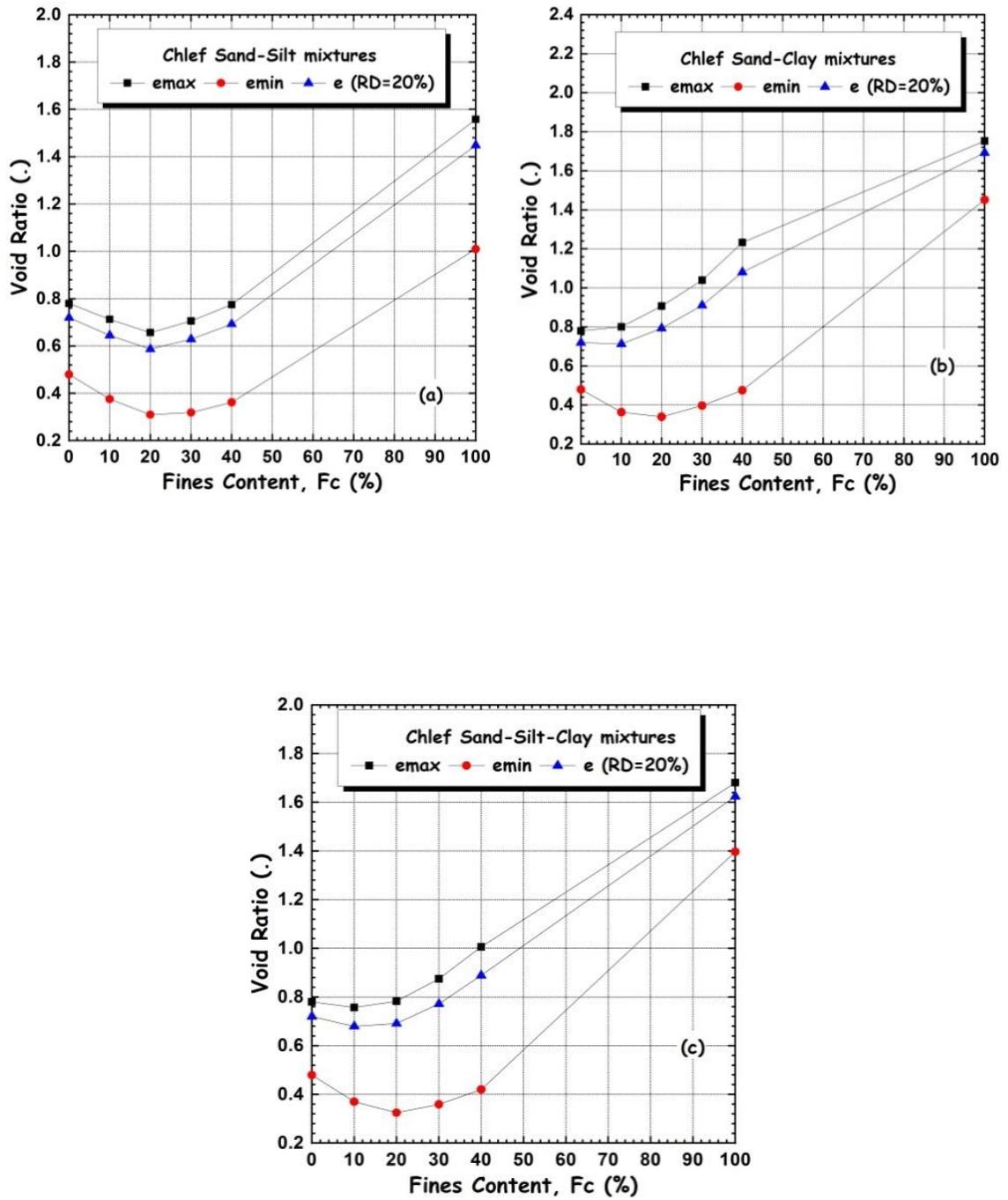
Figure 1- (a) void ratio of sand as a function of silts content, (b) void ratio of sand as a function of clays content, (c) void ratio as a function of silt-clay content.
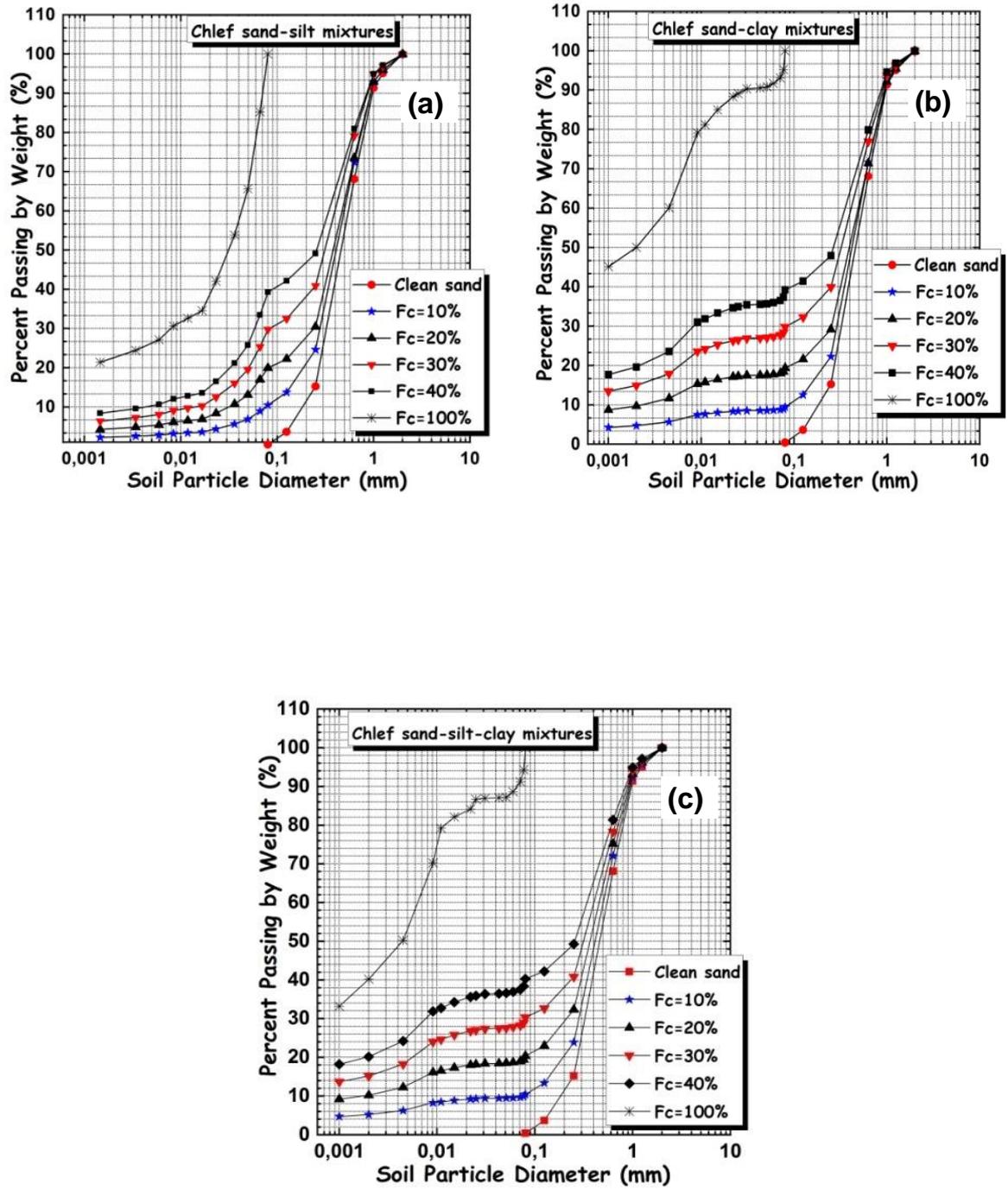
Figure 2 - Grain size distribution curves of tested materials: sand with silt mixtures, (b) sand with clay mixtures, (c) sand-silt-clay mixtures.

Table 1 summarizes the different physical and particle size characteristics of the mixtures.

Table 1- Index characteristics of sand with silt, sand with clay and sand-silt-clay mixtures.

| Materials	Fc (%)	Gs	D₁₀ (mm)	D₅₀ (mm)	Cu	Cc
Clean sand	0	2.670	0.194	0.50	2.955	1.146
Sand-silt	10	2.673	0.0756	0.451	7.025	2.133
Sand-silt	20	2.676	0.032	0,422	15.959	3.612
Sand-silt	30	2.679	0.0142	0.34	31.02	1.129
Sand-silt	40	2.682	0.0044	0.261	86.79	2.07
Silt	100	2.700	-	0.03	-	-
Sand-clay	10	2.658	0.088	0.464	6.161	2.019
Sand-clay	20	2.646	0.002	0.437	221	52.61
Sand-clay	30	2.634	-	0.353	-	-
Sand-clay	40	2.622	-	0.275	-	-
Sand-silt-clay	10	2.665	0.0775	0.456	6.9032	2.148
Sand-silt-clay	20	2.661	0.0110	0.406	45.041	8.798
Sand-silt-clay	30	2.656	-	0.343	-	-
Sand-silt-clay	40	2.652	-	0.258	-	-
Clay	100	2.550	-	0.002	-	-
50% silt and 50% clay	100	2.583				

2.2 Experimental Procedures

This paper presents an experimental study carrying out box shear tests on different dry soil samples also an analysis of the results found and their interpretation. The materials constituting the mixtures presented in Figure 3, are a clean Chlef sand, Chlef silt, M'Zilla clay and a mixture of clay silt with 50% of silt and 50% of the clay. A series of direct shear tests were carried out for a relative density of RD = 20% for different fines content (Fc = 0, 10, 20, 30 and 40% under three normal stresses 100, 200 and 400 kPa. The tests were performed using a square direct shear box 60 x 60 mm². The initial thickness of samples was 30 mm. The mass (ms) of the soil to be placed in the box is given according to the equation 1 where VT is the total volume of the sample. Each sample was dumped dry three times in equal quantities by mass. These tests were conducted according to standards [38].

$$m_s = \frac{V_T . \gamma_s}{\left(1 - e_{max}\left(1 - RD\right) + RD . e_{min}\right)} \quad \text{……………………..} \tag{1}$$

Figure 3 - Materials employed in this investigation: (a) Clean sand, (b) clay, (c) silt, (d) Silt-clay mixtures.

Figure 4 shows the reliability tests performed on Chlef sand at a loose density (RD=20%) and under a normal stress of 200 kPa. These two tests show similar results.
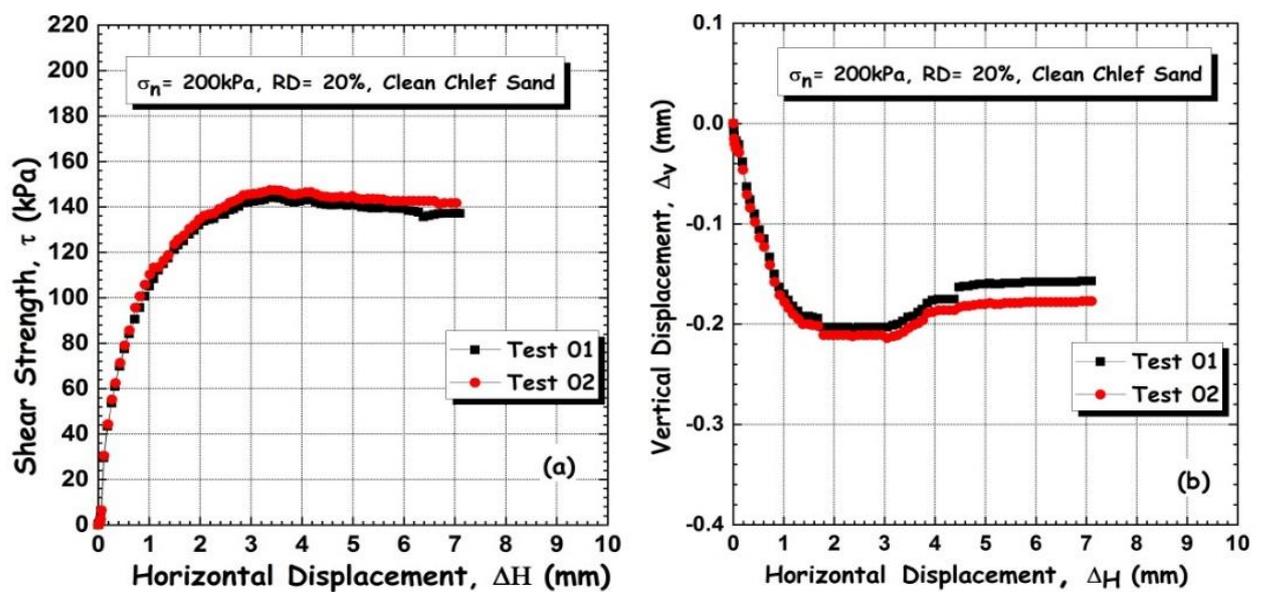
Figure 4 - Repeatability tests (σ_n = 200 kPa and RD = 20%): (a) Shear stress (τ) as a function of horizontal displacement (ΔH), (b) Vertical displacement (ΔV) as a function of horizontal displacement (ΔH).

2.3 Numerical procedure
2.3.1 Sand hypoplasticity

Numerical simulations employing the hypoplastic model for granular materials were executed using the Plaxis finite element software. This model relies on eight parameters: α, β, h_s, p_s, n, e_{i0}, e_{d0}, and e_{c0} (as detailed in Table 2). In a study conducted by [39], numerical simulations were carried out to validate the results of triaxial and oedometer tests on mixtures of sand-silt from Chlef, with varying percentages (0%, 10%, 20%, 30%, and 40%). The parameters of sand-silt mixtures utilized in these simulations are outlined in Table 2. The parameters α, β, h_s, p_s, n from [39]. Specifically, the analysis focused on shear strength versus deformation data obtained from direct shear tests (see Fig. 3). The implementation of the hypoplastic model for granular materials was accomplished through a user-defined subroutine named user mod.

Table 2 - Parameters of sand-silt mixtures used into the model.

| Materials	Fc (%)	φ_c (°)	n	h_s (GPa)	e_{c0}	e_{d0}	e_{i0}	α	β	e
Clean sand	0	36.55	0.420	0.35	0.650	0.480	0.780	0.210	3.50	0.742
	10	35.23	0.435	0.25	0.594	0.376	0.713	0.170	3.10	0.648
Sand-silt mixtures	20	34.97	0.460	0.24	0.547	0.310	0.657	0.125	2.15	0.600
	30	33.13	0.472	0.18	0.588	0.319	0.706	0.100	1.54	0.641
	40	28.33	0.482	0.20	0.630	0.362	0.755	0.070	1.34	0.687

3. Results and Discussion

3.1 Impact of clay, silt, and silt-clay contents on the shear strength of Chlef sand

Figures 5a, 5b and 5c show the variation of shear strength as a function of horizontal displacement of silty, clayey and silty-clayey sands, respectively. It can be seen that the shear stress of all sand increases with the horizontal displacement until a maximum value. The clean sand develops small peak shear strength at 3 mm of horizontal displacement for the absence of fines which have the effect of separating the grains of the sand. However, for the sand with fines content, no more apparent peak shear strength was developed due to the non-shearing of the sand grains at their contact points. Even an insignificant content such as 10% in any addition seems to fill the intergranular porosity by no longer leaving contact between the grains of different sands. At small deformations, when the initial structure is sufficiently maintained; the shear strength of clean sand was the highest everywhere, it was observed at 2 mm approximately of the horizontal displacement because sand without addition offers a friction performance which aims to develop high shear strength.

However, at the same strain condition, sands with 40% of silt or clay (Fig.5a, 5b) had the most reduced shear strength, unlike clean sand; at this content and a little less, the shear strength is managed by the spacing that the additions in quality of silt and clay cause among the sand grains. But when the addition is clayey silt (Fig. 5c), it is the sand containing 20% of this addition which had the most reduced shear strength; this phenomenon calls into question the fact that 20% of clayey silt presents a quantity of clay intended to separate the pore space among the silt present in an equivalent quantity. Explicitly, at 20% clayey silt content and a little less, the reduced shear strength is the result of the separation of the sand grains by the silt particles which are themselves separated by the clay particles. The separation of such grains or particles obeys to the phenomenon of dry segregation. This phenomenon is driven by the specific surfaces of the soils constituting the silty-clay sand, indicated by plasticity indices. In the long term of strain, the sands with 30% of fines content recorded the most increased maximum shear strength; these are bordered by slightly lower maximum shear strength of the sands with 40% of silt (Fig. 5a) and 20% of the clay (Fig. 5b). The sand with 40% of clayey silt (Fig. 5c), the mixture mobilizes a maximum shear strength slightly

reduced compared to that of the clayey silt content of 30%. Sands with 30% and a little more silt or clayey silt and those with 30% and a little less clay, each have the grains initially arranged via a described structure of lower initial stiffness compared to that of clean sand; then they had a new grain arrangement that allowed them to manifest high maximum shear strength; this new beneficial arrangement with respect to the gain in maximum shear strength is governed by the contracting behavior.
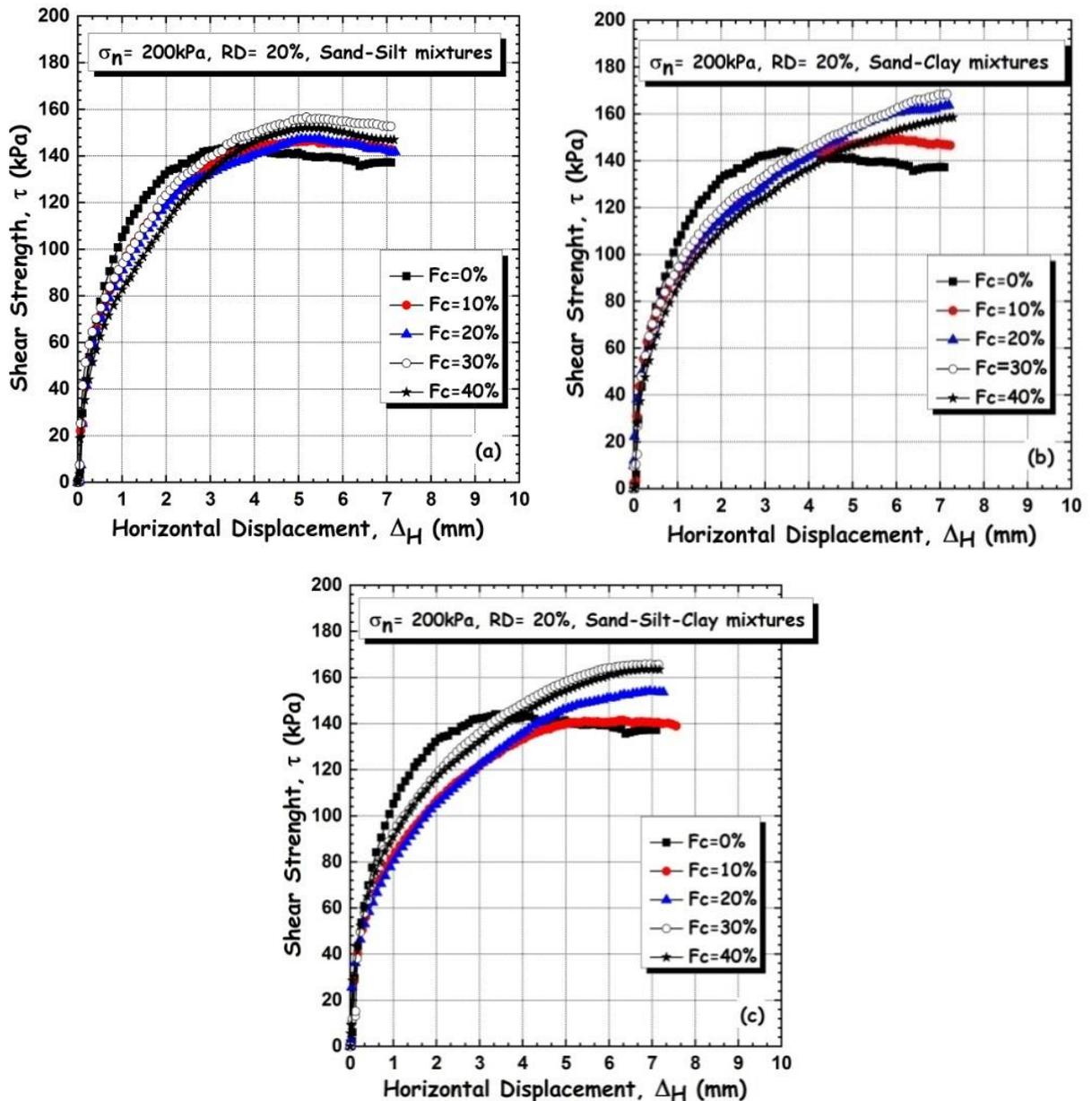
Figure 5 - Effect of different type of fines content on the shear strength of loose Chlef sand (RD = 20%): (a) sand with silt mixtures, (b) sand with clay mixtures, (c) sand-silt-clay mixtures.

3.2 Effect of silt content, clay content, silt-clay content on contracting and dilating phase

The sand at 0% of fines content presents a contracting behavior until 3 mm of horizontal displacement then it behaves in dilating without returning to its initial state of density (Fig. 6). The contracting phase developed is due to the presence of the pore space under the effect of the applied vertical stress which further acts as densifying agent. When the relative density reached becomes much higher, the contracting behavior is converted into a dilating behavior. Sands with silt content (Fig. 6a) are all contracting, their contracting increases with the increase of the silt content.
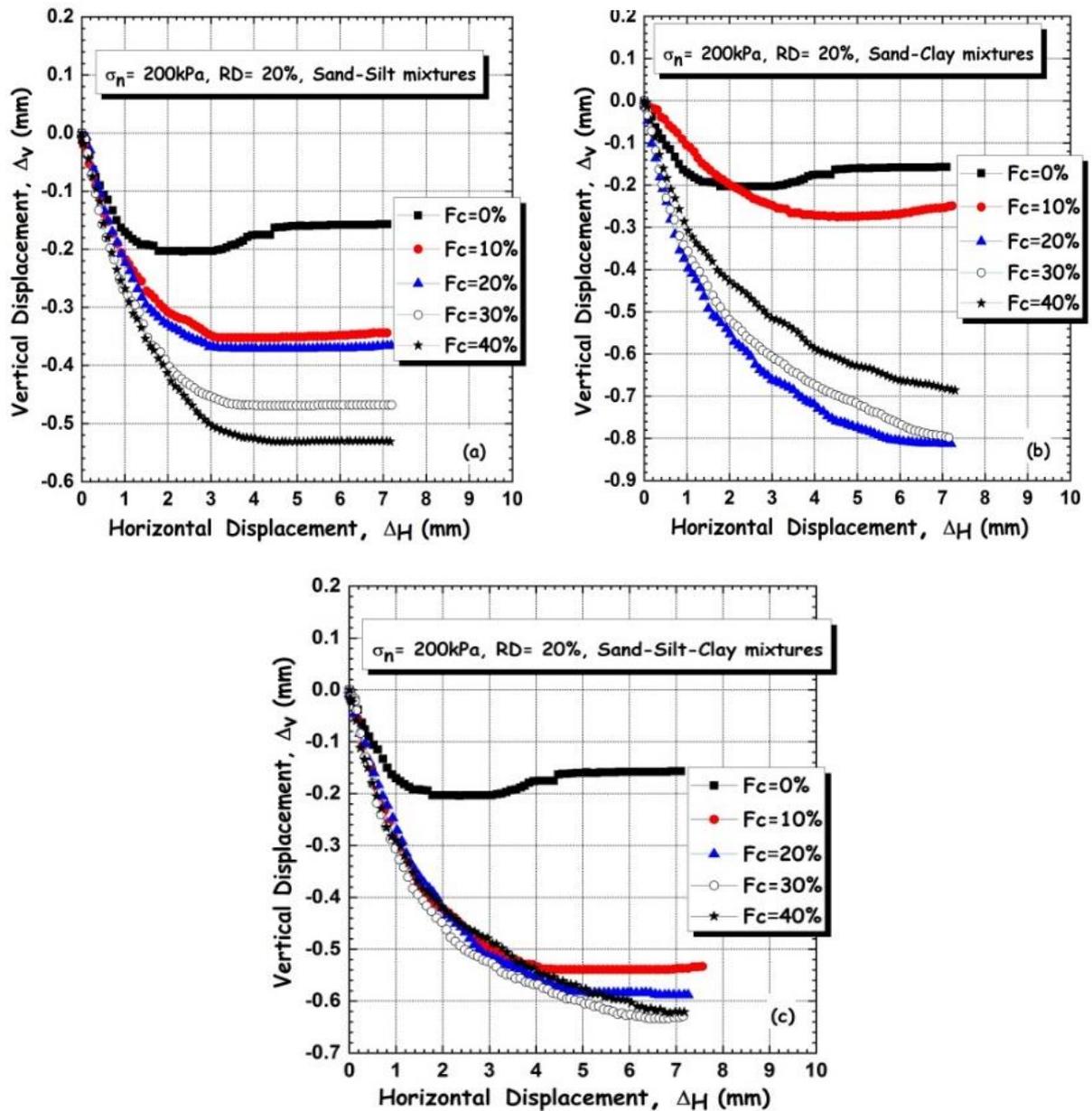
Figure 6 - Impact of different type of fines content on the contracting and dilating phase of loose Chlef sand (RD = 20%): (a) sand with silt mixtures, (b) sand with clay mixtures, (c) sand-silt-clay mixtures.

The sand with 10% of clay content (Fig. 6b) seems contracting until 4.5mm of horizontal displacement; then, it behaves slightly to the dilating. This phase change, from contracting to dilating, is due to the shrinkage of the pore space. However, two contacting phases were induced, the first which is due to densification of the sand and the second is due to the reduction in porosity in the clay fines. For this reason, sand with 10% clay content shows a failure behavior. However, other clay sands are all perfectly contracting and the most contracted; their contracting increases with the decrease of clay content. The sands with 20% and 30% of clay content show a contracting behavior.

The sands with clay-silt content (Fig. 6c) are all contracting; their contracting increases with the increase of the clay content; the difference in contracting is more expressed beyond 4mm of horizontal displacement. The sands with 30% and 40% of clay silt content are respectively the most

contracted and have had, in the same order, the highest maximum shear strength in long-term horizontal displacement behavior. The sands with 10% and 20% of clay silt content are the least contracted and had, in the same order, shear strength, slightly varied between them, the most reduced, at small deformations. There, 10 and 20% silt content together with the corresponding sand fractions satisfied the partial embrittlement of the considered silty-clay sands at small strain, hence reduced shear strengths were developed. On the other hand, the sands with 30% and 40% of clayey silt satisfied a condition of partial stiffening of silty-clayey sands considered at large deformations, from where high shear stresses were developed. However, clean sand and sand with 10% of clay, shows a contracting behavior. This justifies that the contracting pronounced by any sand containing an addition of any nature is not only the result of densification due to the entanglement of grains, but it also comes from the shrinkage of the space between the particles of the addition which governs plastic behavior. This explanation is in agreement with the fact that the most contracted silt-containing sands had the highest shear strengths.

3.3 Impact of silt, clay and silt-clay contents on the Mohr-Colomb failure line
Figures 6a, 6b and 6c show the intrinsic Mohr-Coulomb shear lines defined by equation (22):

$$\tau = \sigma.tg\phi + c ....(22)$$

These curves lead to determine of mechanical characteristics of material like the internal friction angle (φ) and the cohesion (c). They develop an envelope separating between the state of the strengths acting in the stable zone and the state of the strengths acting in the unstable zone.

For any fines content, the shear strength increases with the increase in the normal stress (σ_n). The difference between the shear strengths, given the same vertical stress, is less pronounced at the normal stress of 100 kPa, and is more or less obvious at 200 kPa, but is more noticeable at 400 kPa, more particularly for clayey silty sands. This is explained by the fact that the effect of the addition content on the shear strength is expressed consequently at large normal stresses. This difference is expressed, even more, when the addition is clayey silt (Fig. 7c); when the addition is clay this difference in resistance is less pronounced (Fig. 7b); and it is significantly small when the addition is silt (Fig. 7a). This comes down to the variation ranges of friction angle and cohesion for each range of materials, based on the three additions considered as shown in table (3).

The intervals mentioned in this table indicate that the shears strength of sands with clayey silt, at the same normal stress is the furthest apart. In addition, for all two sands whose one of the two has an internal friction angle and cohesion, both more increased than those of the other, the one whose characteristics are higher gives the higher shear strength. For any two sands of which one has a smaller cohesion than that of the other and has a greater internal friction angle than that of the other, the one whose angle of internal friction angle is small gives the greater shear strength, until to a term coinciding with a transient normal stress, after this term it is the one whose friction angle is large which records the highest shear strength.
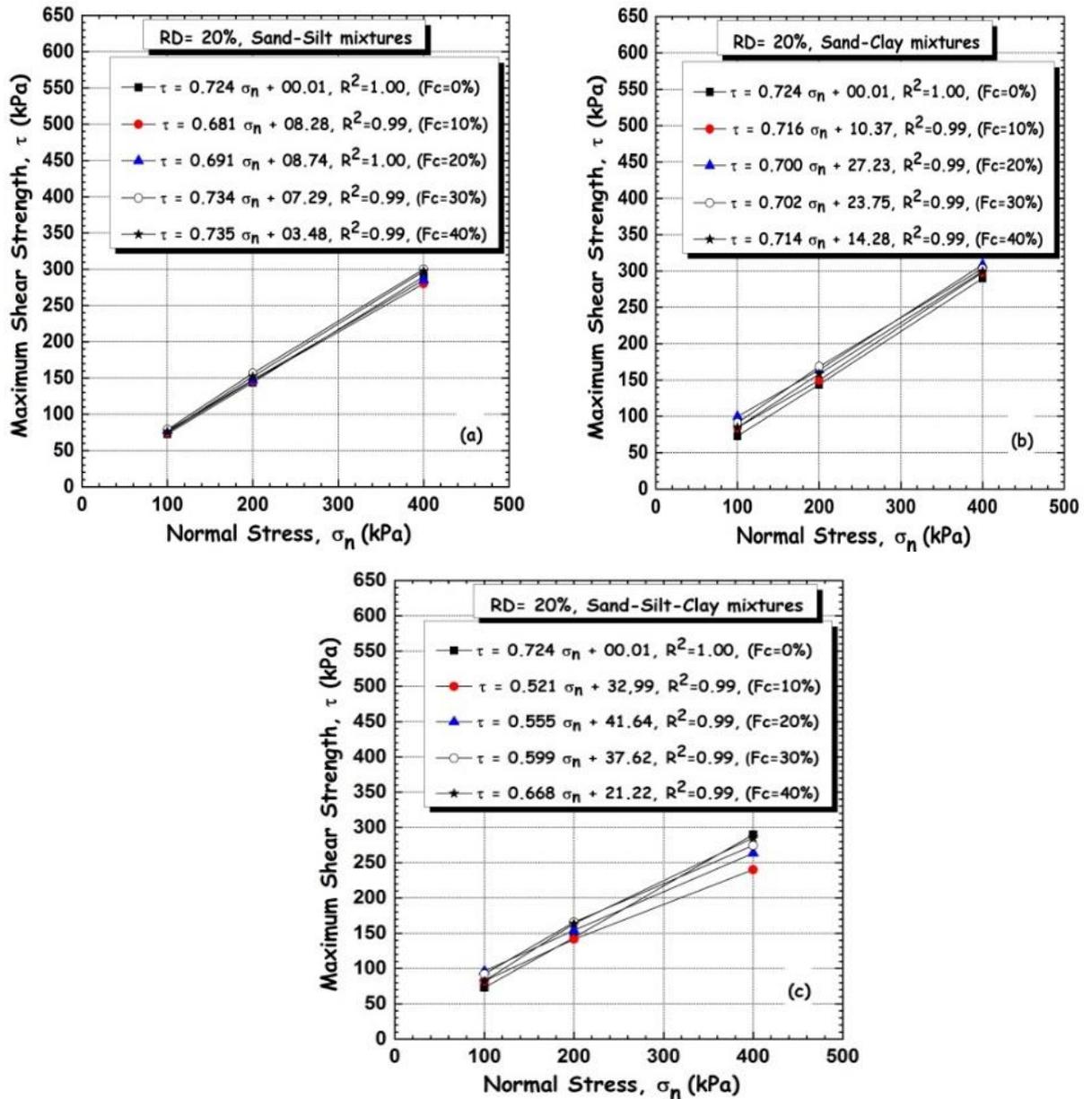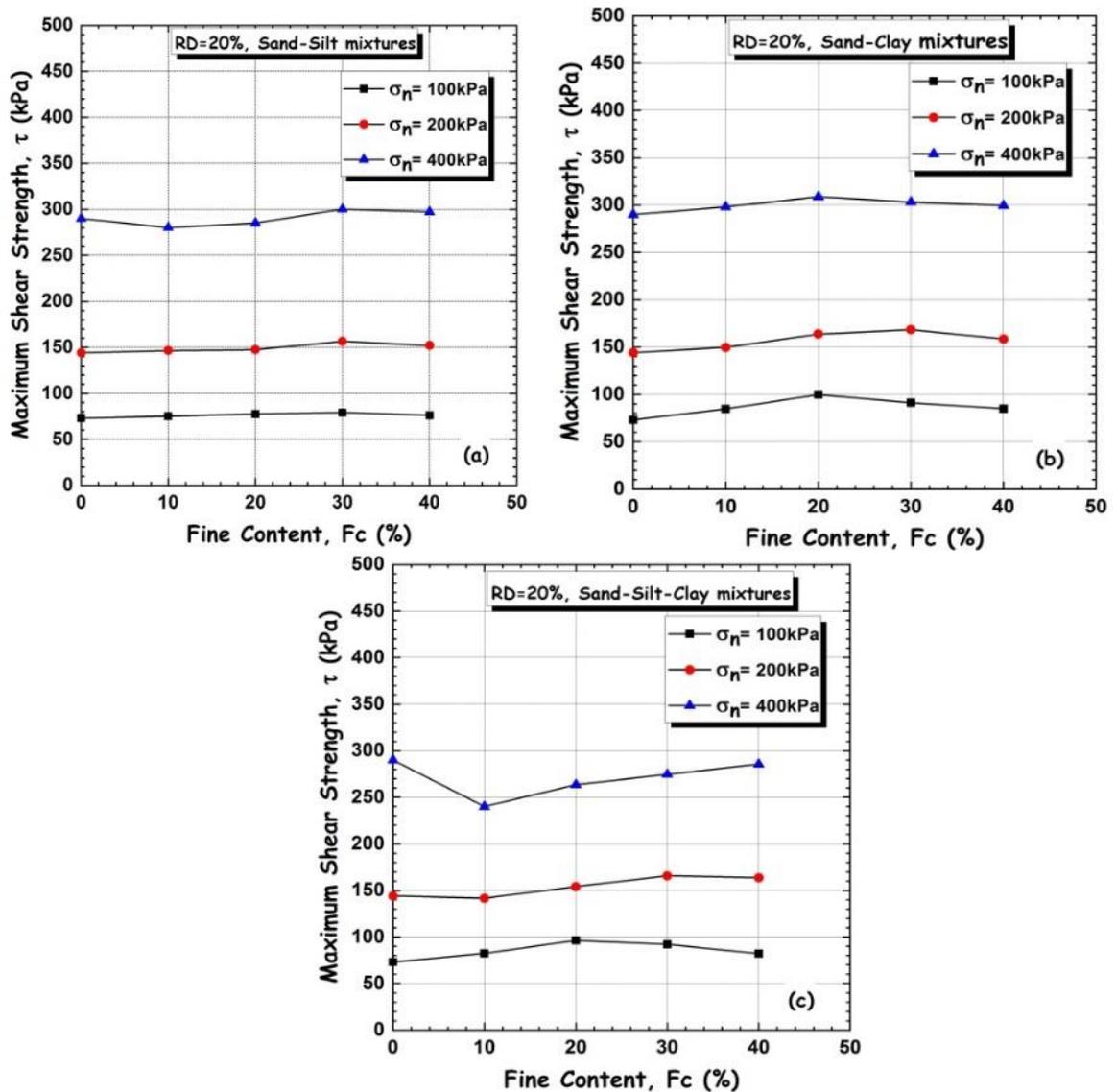
Figure 7 - Maximum shear strength versus normal stress (RD = 20%): (a) sand with silt mixtures, (b) sand with clay mixtures, (c) sand-silt-clay mixtures.

Table 3 - Range of variation of internal friction angle and cohesion.

Sand mixtures	Range of variation of internal friction angle ($\phi°$)	Range of variation of cohesion C (kPa)
Sand- silt	0.681 - 0.735	0.01 - 8.74
Sand-clay	0.700 - 0.724	0.01 - 27.23
Sand-clayey silt	0.521 - 0.724	0.01 - 41.74

3.4 Impact of clay, silt, and silt-clay contents on the peak shear strength

Figure 8a, 8b and 8c show the variation of the maximum shear strength (τmax) as a function of silt, clay and clay-silt content respectively for the three applied normal stresses of 100, 200 and 400 kPa. It can be seen that the maximum shear strength (τmax) increases with the increase in normal stress for the same fines content. The maximum shear stress of the sand silt mixtures under a normal stress of 100 and 200 kPa, increases with the increases of silt content, however for 30% of silt content, the maximum shear strength (τmax) is very pronounced for the high normal stress, after this content, the maximum shear strength decreases (Fig. 8a).

Figure 8 - Maximum shear strength versus fines content (RD = 20%):(a) sand with silt mixtures, (b) sand with clay mixtures, (c) sand-silt-clay mixtures.

Figure 8b shows the variation of the maximum shear strength (τmax) versus the clay content. It can be seen from this Figure that the maximum shear strength (τmax) increases with the increase of the fines content. The highest maximum shear strength coincides with 20% of clay content. Beyond this fines content, the maximum shear strength decreases. The sands under 200 kPa have maximum shear strength that increase with the increase of the clay content. The sand with 30% of clay content clay had the higher maximum shear strength; beyond this fine content, this maximum shear strength decreases.

The variation of the maximum shear strength of sands with clayey silt evolves in a clear manner (Fig.8c). For the normal stress of 100 kPa, the maximum shear strength (τmax) increases with the increase of the clay-silt content until reaching a maximum value at 20% of clay-silt content, beyond this fines content, it decreases. The maximum shear strength of the sands under 200 kPa increases with the increase in the clay-silt content until reaching a high value at 30% of clay-silt content; then it decreases. At 10% of silt clay content, the maximum shear strength is the lowest value under 400 kPa; then this shear strength increases; but the maximum shear stress is expressed at 0% of silt clay content.

3.5 Influence of silt, clay and silt-clay contents on the mechanical characteristics

Figure 9a and 9b show the variation of the cohesion and the internal friction angle as a function of silt content, clay or clayey silt content of loose sand from 0 to 40%. From Figure 9a, it can be seen for all sands with silt, clay or clayey silt that the cohesion increases with the increase of the fines content until a maximum value corresponding to 20% of fines content, then it decreases. Also, it can be seen that the rate of variation was observed more in the sand silt-clay mixtures to the sand clay mixtures and from sand clay mixtures to the sand silt mixtures. At the same fines content of 20%, the sand silt mixtures records a cohesion of 8.74 kPa, in contrast, the sand silt-clay mixtures records a cohesion of 41.64 kPa for the sand clay mixtures the cohesion is 27.23kPa.

The cohesion is created in the sand by the presence of fines content. However, the sand silt-clay mixture is more cohesive; this cohesion is due to the presence of clayey-silt in the sand which the results show to be more cohesive than the clay. It can be seen that the addition of 50% of silt among the clay increases the cohesion of the mixtures. The material is dry, so this cohesion is far from being favored by humidity. But this is a cohesion is due to the attractive electrostatic interaction between the positively charged particles and those negatively charged for the rapprochement between them under the action of the state of the stresses exerting. From Figure 9b, the internal friction angle of the silty sand at 10% of silt content is 34.25°. Then, this internal friction angle increases with the increase of silt content until reaching a maximum value of around 36.31° coinciding with the content of 40%. This maximum value exceeds that of clean sand which is 35.9°.

The internal friction angle of clay sand reduces with the increase in the clay content, until reaching its most minimal value of around 34.99° coinciding with 30% of clay content. Then, it reaches its maximum value of around 35.52° at 40% of clay content. This seems less compared to that of clean sand. For the sand silt-clay mixtures, the internal friction angle of around 27.51°, at 10% of clay silt content; beyond this fines content, this internal friction angle increases with the increase in the fines content to reach the maximum value of around 33.74° coinciding with 40% of clay content; this value seems less compared to those of clean sand and sands containing 40% of silt or clay. The silt, clay and clayey silt have the effect, when included among the sand, of reducing or increasing friction, if their present quantities, indicated by the percentage of inclusion.
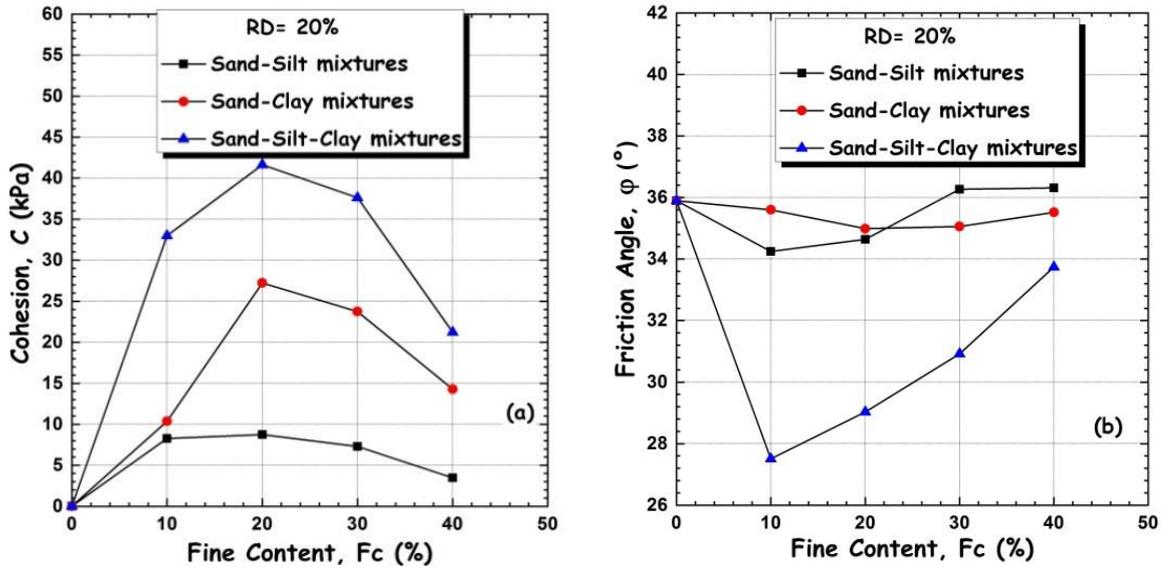
Figure 9 - Effect different fines content on the mechanical characteristics of Chlef sand (RD = 20%): (a) cohesion as a function of fines content, (b) internal friction angle as a function of fines content.

3.6 Numerical results

The outcomes of numerical simulation demonstrated a favorable correspondence with the experimental data presented in Figure 10. The Figure illustrates the comparison of numerical and laboratory direct shear test outcomes. The plotted curve for the suggested α and β values exhibits a commendable alignment with the experimental curves. Notably, a higher α corresponds to an elevated initial deviator stress, with a discernible trend showing that an increment in the α parameter augments the dilatancy of the curves. This observation resonates with findings from previous studies by [33, 39, and 40]. The alignment of curves depicting shear strength against horizontal displacement in both laboratory test results and numerical findings exhibited a strong correlation, affirming the efficacy of this study.
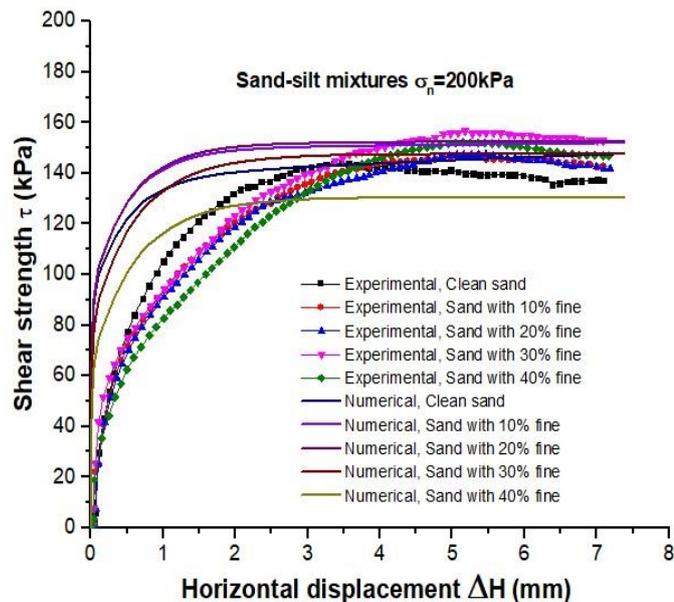
Figure 10 - Comparison of laboratory test with the numerical analysis.

4. Conclusion

At the limit of the experimental conditions provided in this study and the identity of the materials, it can be concluded:

1. There is no possibility of shearing of the grains of sand at their points of contact, this justifies that 10% and more of the content of any addition, taking into account the loose state, systematically separates the grains of sand, in relation to each other, this is done the proof of the plastic behavior of the materials, herein.

2. At large strains, clay rather than clayey silt, included among the sand considered, become renewal factors of the equivalent void ratio, which can have a lower or increased value, associated with a new rearrangement of the grains which manages the most increased shear resistance, compared to the decreased ones.

3. After consolidation and during shearing there is no need to distinguish one density from the other, but the manner of arrangement of the grains in relation to each other remains in relation to their arrangement in the initial stated before consolidation. This justifies the more or less significant shear stresses of loose sands.

4. The change of phase of contracting to dilating, during shearing, is inherent to the fact that the material has reached the major term of densification. The recovery or not of the initial state of density of the sands contacting then dilating is inseparable from the initial density adopted.

5. If a condition of improved shear strength is expected after this sand, in loose deposit, with small strains, it is better not to add silt or clay or half-combined clay silt.

6. The addition of clay loam composed of 50% silt and 50% clay and the insertion of clay especially, among the sand, assume high shear resistances. Therefore, the clayey silt and clay present in this study could be adopted for the stabilization of sands against long-term shear deformation.

7. The quantity by mass of clay or clay silt to be added to the sand is relative to such a condition of shear resistance sought, the results obtained meet this condition, in terms of the content of such addition and the vertical stress equivalent to the stress real exercise exerted in the ground at a given depth.

8. If we find ourselves in front of sand, silt or clay which does not provide the above-mentioned identification, we should look for, according to their own identifications, the fractions of the binary or ideal ternary, except for silt alone, which provide the desired shear resistance.

9. Numerical simulation using finite element method and hypoplastic model for granular materials have a good estimation well to get mechanical behavior for a real geotechnical project.

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