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ORIGINAL PAPER

THE IMPACT OF FINES CONTENT ON THE SHEAR STRENGTH CHARACTERISTICS OF TUFF

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ABSTRACT

This paper is part of a study examining the effects of silty fines on the physico-mechanical behaviour of limestone tuffs from the Chlef region of Algeria. Our investigation initially focused on determining the optimum compaction parameters (maximum dry density, γ_{dmax}, and optimum water content, ω_{opm}) for Tuff/fines mixtures with low proportions of silty fines, varying from 0 % to 20 %. In the second phase of the tests, we adopted a direct shear test protocol using a high relative density (RD = 90 %). This was performed on samples prepared with a water content fixed at the optimum Proctor level for the different mixtures. The objective was to evaluate the mechanical behaviour of the various Tuff/fines mixtures in terms of shear strength and volume change. The results indicated strong correlations between various physical parameters, particularly showing a polynomial relationship concerning the uniformity coefficient (Cu) and curvature (Cc) as the content of fines increases. Conversely, the grain diameters (D10, D30, D50, and D60) decrease almost linearly once the fines content exceeds 5 %. It was also observed that the presence of silty fines significantly influences the mechanical behaviour of Tuff. The maximum dry density (γdmax) increases with a higher fines content, and the optimum Proctor results reveal a peak at 20 % fines content. In the direct shear test, findings showed a critical fines content threshold at 10 %, where the time taken to attain maximum shear strength improved. Interestingly, for fines content below 10 %, there was a slight reduction in the maximum shear strength. This threshold also contributes to greater resilience against deformation-induced loads by exhibiting a more dilatant behaviour, potentially minimizing the occurrence of expansion and contraction cracks in the specimens.

LIST OF SYMBOLS

φ	Internal friction angle (°),	e	Global void ratio,
C	Interlocking or internal cohesion (kPa),	γ_s	Specific weight of solids [g/cm^3],
RD	Relative density (%),	σ_n	Normal stress [kPa],
D_{50}	Mean grain size (mm),	τ	Shear strength [kPa]
δ_H	Horizontal displacement (mm),	τ_{max}	Peak shear strength [kPa],
δ_V	Vertical displacement (mm),	SEM	Scanning electron microscope,
C_u	Uniformity coefficient,	G_s	Specific gravity of solids [-],
Cc	coefficient of curvature	G_f	Specific gravity of silt [-],
ρ_s	Unit weight of sand particles,	D_{10}	Effective grain size (mm),
ρ_a	Bulk density,	I_p	Plasticity index (%),
e_{max}	Maximum void ratio,	ω	Water content (%),
e_{min}	Minimum void ratio,	Fc	Fine content (%),
n_{max}	maximum porosity	γ_{dmax}	Maximum dry density (g/cm^3),
n_{min}	minimum porosity	ω_{opm}	Optimum water content (%).

INTRODUCTION

Calcareous tuffs are typically carbonate rocks that are soft, friable, porous, and come in light colors. They are widely used in road engineering because they are highly workable when mixed and compacted in a wet state. However, these materials are not suitable for areas with heavy road traffic, which presents a challenge that needs thorough investigation.

In Algeria, calcareous tuffs are widely available and used in large quantities. In regions rich in aggregates, they serve as substitute materials to conserve more valuable resources. The limestone tuffs found in the Chlef region are abundant in the Dahra massif, which extends northward to the Mediterranean Sea and dates back to the Quaternary period (Ben Dhia, 1983). These tuffs are primarily composed of

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calcite ($CaCO3$), with a content exceeding 70 %, as confirmed by X-ray diffraction (XRD) analyses (see Fig. 1). Geographically, Chlef is located approximately 200 km between Algiers and Oran. The climate in this area is classified as semi-arid to arid, with variable winter temperatures averaging around 10 °C and hot, dry summers averaging 40 °C. The average annual precipitation is about 450 mm. The region is also very seismic, as noted in the literature (Ambraseys, 1981).

The composition of tuff is variable and results from a range of dissolution exchanges and precipitation processes. When compacted in a wet state, tuff exhibits increased cohesion which tends to diminish over time, disappearing entirely when the material becomes saturated (Alloul, 1981; Ben Dhia, 1983; Boukezzi, 1997; Guidel, 2001; Loualbia et al., 2020). This observation has been supported by various studies on the static and dynamic behaviour of tuff, including works by Alloul (1981), Ben Dhia (1983), Hachichi et al. (2000), Améraoui (2002), Goual et al. (2005), Morsli et al. (2007), Goual et al. (2011), Daheur et al. (2018), Azaiez et al. (2020) and (Ezziane et al., 2025).

Over the past forty years, numerous techniques have been developed to enhance the properties of tuff for use in pavement applications, particularly in areas subjected to heavy road traffic, such as base layers and foundations. These improvements have been achieved through the treatment of tuff with hydraulic or lime binders or by incorporating other fine materials, including crushed, fluvial, or dune materials (Ben Dhia, 1983; Dupas and Pecker, 1979; Morsli et al., 2005; Morsli, 2007; Goual et al., 2005; Goual et al., 2011; Daheur et al., 2018; Villalobos et al., 2018; Boutouba et al., 2019; Loualbia et al., 2020; Azaiez et al., 2020; Baghdir et al., 2024).

In terms of Tuff improvement, (Daheur et al., 2018; Daheur et al., 2023) demonstrated that mixtures of dune sand and binders on tuff are denser than base materials produced with low optimum moisture content (OMC), and they found that the plasticity index (PI) decreases as the percentage of sand increases. They concluded that the economic and environmental factors favor an optimal formulation of 65 % tuff and 35 % dune sand. In a different study, Goual (2012) investigated the enhancement of limestone tuff properties by adding limestone sand. The results indicated that both compaction and bearing tests show improved performance with reduced OMC and increased density with higher sand-limestone content. An optimal range for sand and limestone content was found to be between 30 % and 40 %, associated with an optimal index, improving over four days of immersion. A formulation of 80 % tuff and 20 % sand was identified as providing the optimal resistance, particularly useful for the design of Saharan road pavements.

Research on tuff has produced conflicting results regarding the hardening process of gypsum-limestone tuff during compaction tests. For instance, Alloul (1981) and Fumet (1959) demonstrated that the hardening of Tuffs is influenced primarily by the rearrangement of grains during the drying process. In contrast, other researchers have linked the hardening of tuff to two main factors: the partial dissolution of calcium carbonate ($CaCO3$) and the recrystallization of grains, which can impart a degree of hardness to the calcareous crust (Ben Dhia, 1983; Peltier, 1959). Additionally, Villalobos et al. (2018) investigated the impact of fine particles (less than 80 μm) on the shear strength of volcanic tuffs and zeolites. Their shear tests indicated that shear stress increases with rising normal stress and relative density, while the contractive/dilative response remains consistent with other materials sourced from various quarries. Considering the limited studies conducted on Tuff/fines mixtures, this research aims to explore the physico-mechanical characteristics of Tuff/fine mixtures, specifically those with silty fines. Such investigations are believed to be valuable for the development of this new material in the fields of road and motorway technology. The study first focuses on determining the optimum compaction parameters (maximum dry density, $\gamma dmax$, and optimum moisture content, ωopm) for Tuff/fines mixtures with silty fines in proportions ranging from 0 % to 20 %. In the second part, we examine the mechanical behaviour in terms of shear strength and volume change, considering a high relative density (RD = 90 %) and water contents set at the Proctor optimum (between 13 % and 14 %). This initial relative density is employed as the majority of treated soils are typically groomed or compacted, in accordance with the Proctor protocol, which establishes optimum conditions at high relative densities.

Loualbia et al. (2022) the study finds that the compaction of limestone tuff specimens on the wet side produces a highly permeable and oriented structure, while compaction on the dry side produces a less permeable structure. The results also show that the material's strength increases with increasing density, but only for high confinement stresses.

The silty fines utilized in this study serve as a reference point for several published works (Belkhatir et al., 2010; Djafar Henni et al., 2013; Benessalah et al., 2021). By examining the undrained resistance of the sand/fines matrix under both monotonic and cyclic conditions at various proportions of fines, the existing literature reveals some controversies. Amini and Qi (2000) and Dezfulian (1982) reported that undrained strength increases with higher fines content. In contrast, Arab et al. (2014), Belkhatir et al. (2010), and Lade and Yamamuro (1997) observed a decrease in strength as fines content increased. Additionally, other studies have indicated a decrease in strength up to a certain threshold of fines, followed by an increase in resistance (Koester, 1994; Polito and Martin, 2001).

Recent research by Ezziane et al. (2025) investigates how silt fines affect the mechanical behavior of calcareous soils, specifically limestone

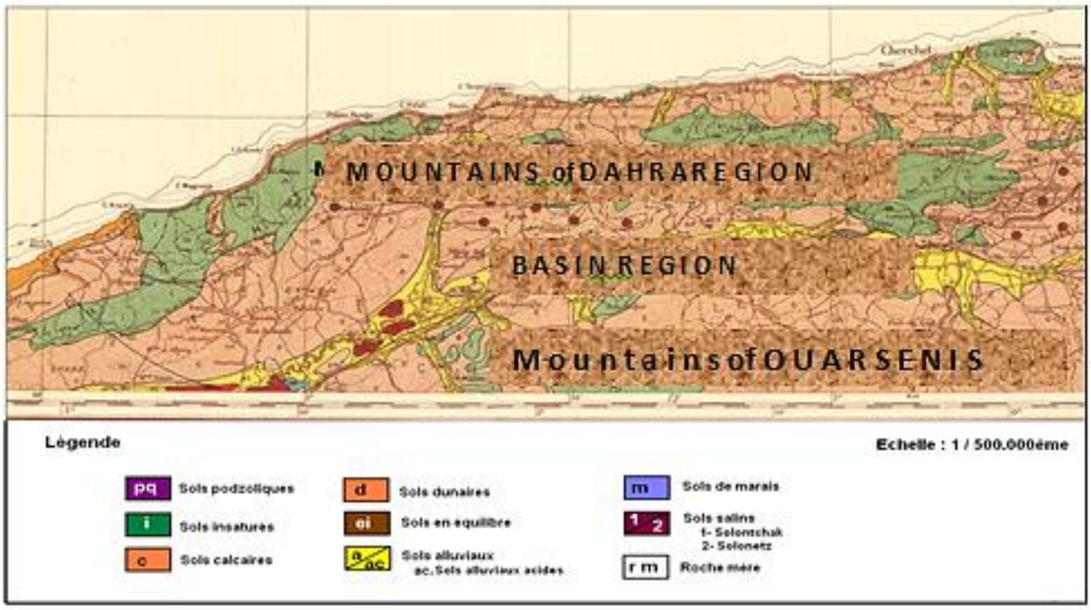

Fig. 1 Structural distribution of limestone encrustation in the Chlef region (Algeria) (Durand, 1959).

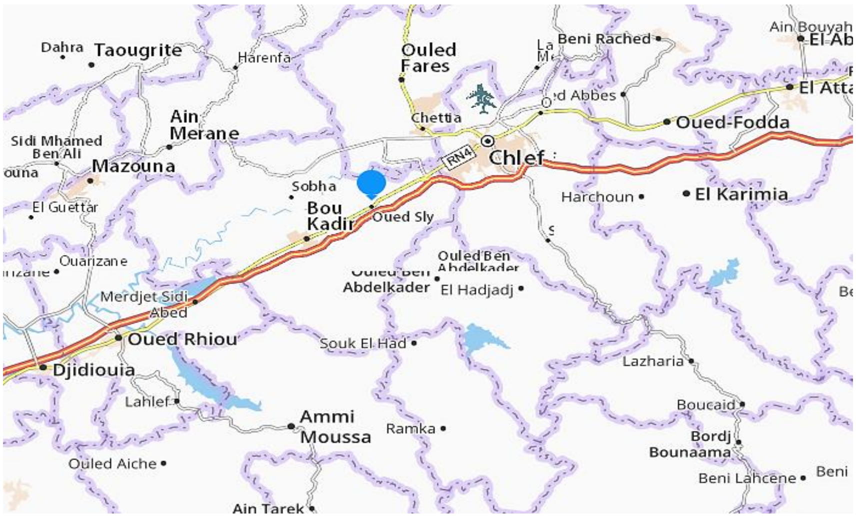

Fig. 2 Location map showing studied material (36°.09,1°.24).

tuff. Through a series of undrained triaxial tests, the study reveals that adding silt fines can significantly enhance the strength and overall performance of the soil.

GEOLOGICAL CONTEXT OF THE CHLEF REGION (EX EL-ASNAM)

The Chlef region is represented on the geological map created at a scale of 1:500,000 (Fig.1). This area is bounded to the north by the Dahra massif, which extends to the Mediterranean Sea, and to the south by the Ouarsenis massif. Geologically, the Cheliff basin has existed since the Tertiary era, formed on a previously folded and dislocated substrate. It has behaved like a subsidizing basin, as indicated by several thick accumulations of marine, lagoon, and continental deposits, reaching up to 3,000 meters in thickness. Subsequently, large quantities of Quaternary alluvium have filled these depressions (Amokrane et al., 1981).

The limestone tuffs in the Chlef region, shown in Figures.1 and 2, illustrate the extensive band of the Dahra Mountain, which is rich in limestone tuff and located approximately 10 kilometers west of the town of Chlef, adjacent to National Road N° 4.

MATERIALS AND LABORATORY PROCEDURES

MATERIALS USED

We utilized two types of materials sourced from different quarries. The first material, a carbonate known as Tuff, was obtained from the Oued Sly quarry (Thaalba), located approximately 10 km west of Chlef city. The second material, silty fines, was collected from the bottom of a sieve measuring 0.08 mm,

Table 1 Geographical coordinates of the Thaalba quarry (Oued Sly-Chlef).

Latitude	Longitude	Altitude (m)
36°09’	1°24’	101

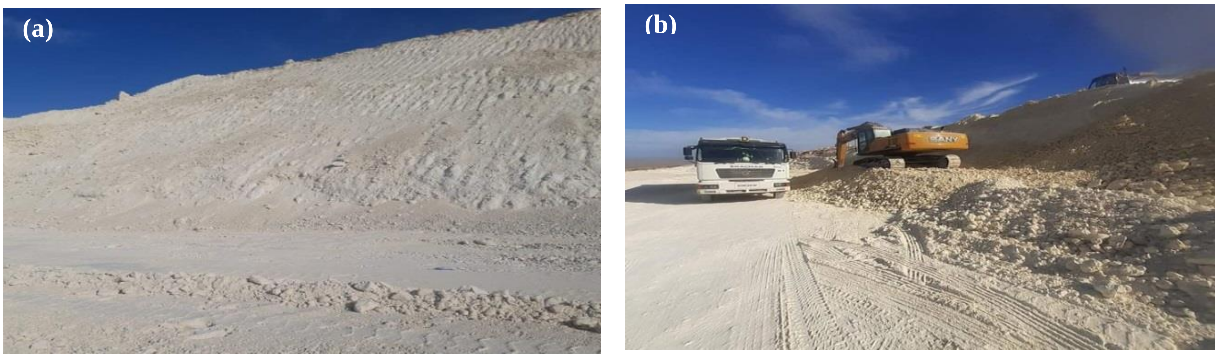

Fig. 3 Overview of Tuff quarry “Thaalba” Oued Sly (Chlef): (a) Frontal facies of the "Thaalba" quarry; (b) Quarry in exploitation of Tuff.

Table 2 The physical characteristics of the analyzed Tuff.

Properties	**Value**	**Properties**	**Value**
< 0.08 [%]	0.86	e_{max} [--]	0.53
γ_s [-]	2.67	e_{min} [--]	0.42
D_{max} [mm]	5	$\gamma_{d\,max}$ [kN/m^3]	15.43
D_{10} [mm]	0.19	$\gamma_{d\,min}$ [kN/m3]	12.53
D_{30} [mm]	0.45	Ip [%]	1.96
D_{50} [mm]	1	VBS [%]	0.23
D_{60} [mm]	1.3	USCS	GW
C_u [--]	9	GTR	B6
C_c [--]	0.82	Shape	Sub-rounding

derived from Chlef silty sand. These fine particles are characterized by low plasticity (Ip = 5 %) and come from highly siliceous material (with % SiO2 greater than 70 %). This sand was sampled from the Cheliff Valley, which runs along the northern fringe of Algeria for at least 100 km, passing through the Chlef region (see Fig.1).

TUFF (FROM OUED SLY-CHLEF QUARRY)

The Tuff used in this study is beige in color (Fig. 3) and is sourced from the Thaalba quarry, located 10 km west of Chlef's center. The geographic coordinates for the quarry are provided in Table 1.

Figure 3a presents an overview of the Thaalba quarry located in the Chlef region, while Figure 3b illustrates its operational aspects, specifically relating to its application in road pavements. Additionally, Table 2 outlines the physical characteristics of the analyzed tuff.

The material used has a D_{max} of 5 mm with a low percentage of fines (Fc = 0.86 %) of porosity n between 0.42 and 0.53, low plasticity (Ip = 1.96 %), classified B6 in the GTR and of sub-rounded shape. The chemical characteristics of the tuff were analyzed from the tests carried out by X-ray diffractions, is illustrated in Figure 4. The material analyzed by X-ray diffraction in Figure 4a shows a predominance of a high rate of calcite (% $CaCO_3$=91.68 %), confirmed by an intensity varying between 650 ($2\theta = 30°$) to an intensity 180 for $25° < 2\theta < 65°$. The other constituents represent small amounts such as iron oxide (% Fe_2O_3 =1.3 %), molybdenum and strontium, 7.02 %.

Figure 4b shows a magnification at 500 µm, carried out under an electron microscope showing a sub-rounded shape of the various aggregates composing the tuff, of relatively beige color showing a relatively apparent porosity between the solid particles.

SILTY FINES

The silty fines used in this study were obtained by sieving Oued Chlef sand, which was collected from the banks of the Cheliff Valley, using an 80 µm sieve. It is important to note that the sand from Oued Cheliff has served as a significant reference database for various published articles and has been instrumental in addressing the liquefaction phenomenon that occurred at the confluences of the Cheliff Valley during the earthquake on October 10, 1980. This sand has been cited in several studies, including those by Belkhatir et al. (2010), Djafar Henni et al. (2013), Arab et al. (2014), Bouaricha et al. (2017), and Merabet et al. (2020).

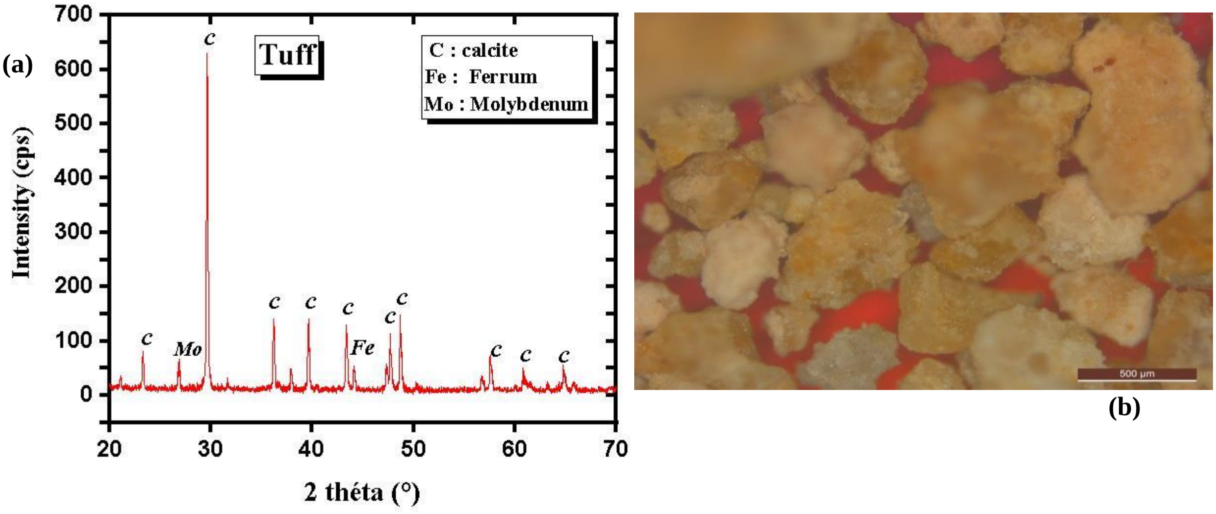

Fig. 4 (a) XRD analysis of Tuff; (b) 500 µm magnification microscope.

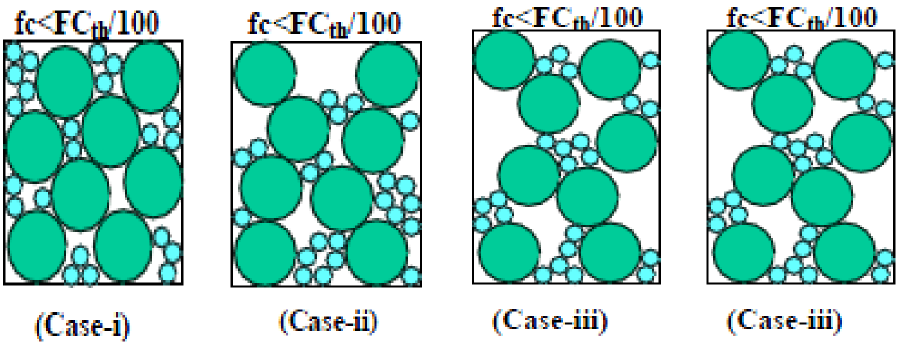

Fig. 5 Microstructure and intergranular matrix phase diagram (Thevanayagam, 2000).

The use of silty fines in this study is motivated by the concept of void ratios affecting the compaction parameters in this case the water content as well as the compaction energy to improve the dry density by the decreasing effect of void ratio. This has been mentioned in the study reported in detail by Thevanayagam (2002). The diagram is explained by taking different cases of microstructural matrices and inter-granular contact (Fig. 5).

Indeed, Thevanayagam (2002) explained that the behaviour of the matrix composed of (soil + fines) is affected by coarse-grained contacts (diameter D) with fines contents (Fc <Fcth / 100) (case-i), the finer grains (diameters d) can move from one pore space to another without significantly contributing to the mechanical response of the soil. For this to work effectively, the particle size of the finer grains must be significantly smaller than the pore size between the coarse grains, and the intergranular pore space should not be entirely filled with these finer grains. In scenarios ii and iii, the microstructure is characterized by a separation of partial grains by finer grains, as well as finer grains occupying the voids between the coarser grains. In scenario iv, the content of fine grains exceeds that of coarse grains (Fc > Fcth), indicating that the finer grains begin to play a more critical role, while the presence of coarse grains diminishes. Finer grains can withstand contact and shear forces, while coarse grains serve as reinforcing elements embedded within a matrix of finer grains.

The physical characteristics of the finer grains are summarized in Table 3. The material analyzed is siliceous and silty in nature, predominantly very fine, with a size of less than 0.08 mm (100 % of the sample). It is low in plasticity (Ip = 5 %), rounded in shape, and classified as ML according to the Unified Soil Classification System (USCS) and A1 according to GTR (1992).

A study carried out by magnification with a scanning electron microscope (SEM) showed a rounded shape of the particulate grains of the alluvial fines (Fig. 6.a) and the chemical composition showed a predominance of silica, SiO_2 (72.16 %) on carbonates $CaCO_3$ (24.71 %), and small quantities of magnesium, Mg (1.85 %) (see Fig. 6b). Figure 6c shows that the study carried out by X-ray diffraction (XRD), locating a threshold of silica particles (Si), oxygen atoms (0) to form the carbonates $CaCO_3$ and small amounts of magnesium (Mg).

Table 3 Physical characteristics of the silty fines.

Physical properties	Value	Physical properties	Value
< 0.08 mm (%)	100	e_{max} [-]	1.137
Gs [--]	2.70	e_{min} [-]	0.72
D_{max} (mm)	0.08	γ_{dmax} [g/cm^3]	15.70
D_{10} (mm)	0.0017	γ_{dmin} [g/cm^3]	12.63
D_{30} (mm)	0.022	Ip [%]	5
D_{50} (mm)	0.035	Form	Rounded
D_{60} (mm)	0.04	USCS	ML
Cu [-]	40	GTR	A1
Cc [-]	7.12		

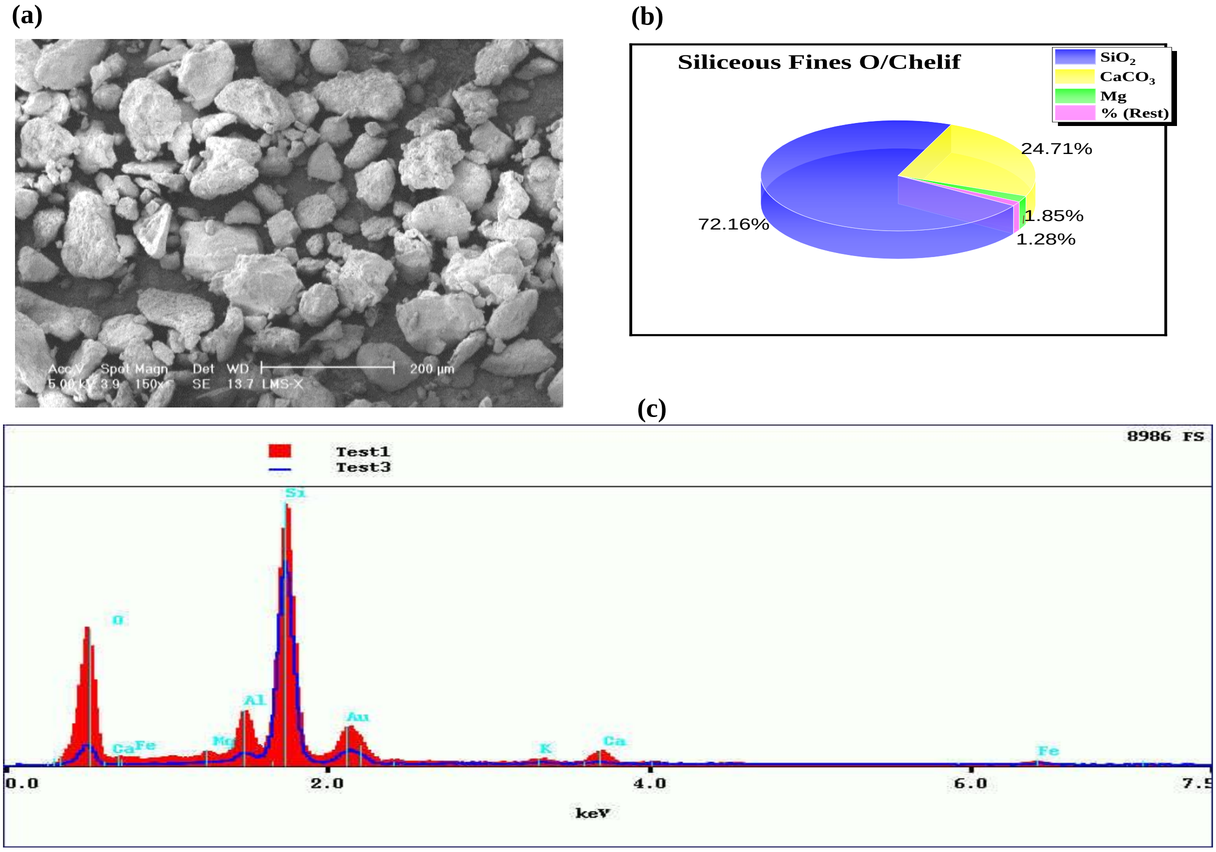

Fig. 6 The silty fines used: (a) Microscopic view of the silty; (b) Chemical composition of fines; (c) XRD analysis of the silty fines.

SAMPLE’S PREPARATION

The samples were prepared by starting with the dry state of the Tuff mixtures, with variable proportions of silty fines ranging from 0 to 20 %. The absorption of a measured amount of water and the efficacy of the mixture are subject to a chemical process that is associated with the phenomenon of the dissolution of carbonates by carbon dioxide in the presence of water. The reaction is governed by the relationship given by equation (1):

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons CaH_2(CO_3)_2 \qquad (1)$$

Indeed, the CO_2 dissolved in the water causes in particular the formation of HCO_3^- and H^+ ions; these H^+ ions react with the CO_3^{--} ions of the limestone defined by the relation (2):

$$CO_3^- + H^+ \rightleftharpoons HCO_3 \qquad (2)$$

The first phase of the experimental program involved performing Proctor compaction tests following the NF P 94-093 standard. For this purpose, dry-prepared samples were moistened to various water contents ranging from 8 % to 20 %. Subsequently, continuous and homogeneous manual mixing was carried out to ensure uniform coating of the Tuff and fine particles. The corresponding Proctor optimum parameters, namely the maximum dry density (γ_{dmax}) and the optimum water content (w_{opt}), are presented in Table 6.

The second phase of the investigation focused on direct shear tests using the Casagrande shear box, conducted by the NF P 94-071-1 standard. The dry mass of the samples (ms) was determined based on

Fig. 7 Materials used for mixtures preparation: (a) Silty fines; (b) Dry Tuff sample; (c) Moisturized Tuff/fines mixtures.

Table 4 Physical characteristics of Tuff/Fines mixtures.

Properties	Tuff/fines mixtures			
Fc (%)	5	10	15	20
G_S	2.668	2.667	2.665	2.664
D_{10} (mm)	0.17	0.08	0.04	0.015
D_{30} (mm)	0.42	0.35	0.28	0.22
D_{50} (mm)	1	0.8	0.7	0.53
D_{60} (mm)	1.3	1.2	1.0	0.88
Cu (--)	10	18.75	30	53.33
Cc (--)	0.8	1.27	1.96	3.66
e_{max} (--)	1.03	0.95	0.99	1
e_{min} (--)	0.66	0.65	0.63	0.60
n_{max} (--)	0.507	0.487	0.497	0.5
n_{min} (--)	0.397	0.394	0.386	0.375

a relative density (RD) of 90 %, representing dense soil conditions approximating in-situ compaction. The value of ms was calculated using Equation (3) provided below:

$$ms = (V_T * \gamma s)/(1+e_{max}(1 - RD) + RD * e_{min}) \qquad (3)$$

With: V_T Volume of the shear box , γs : Unitweight of the solid grains , emax, emin : Maximum and minimum void ratios , RD : Relative density and e : Global void ratio.

The physical characteristics of the mixtures are included in Table 4.

Figure 7 shows a view of the two materials used during our study namely: Silty fines (Fig. 7a). Figure 7b and Figure 7c shows a sample of Tuff/fines mixtures using wet deposition, respectively.

Table 4 presents the physical characteristics of Tuff/fines mixtures with fines contents ranging from 0 % to 20 %. The particle size distribution curves for the silty fine sand and the corresponding Tuff/fines mixtures are depicted in Figure 8.

SHEAR BOX TEST RELIABILITY

In order to ensure the reliability of our results obtained during our various laboratory tests, we carried out shear tests in the laboratory for a relative density RD=50 % and at a normal stress σn =200 kPa (TEST N °1). This test was compared to TEST N°2 carried out under the same conditions in another laboratory (example of test taken from the technical sheet of the reference laboratory). Figure 9a and Figure 9b clearly show the reliability of the rectilinear shear device used where we see the superposition of the two curves of tests 1 and 2. These repeatability tests were also used by Nougar et al. (2021).

PHYSICAL CHARACTERIZATION OF TUFF/FINES MIXTURES

Figure 10a shows that there is a correlation between the coefficients of uniformity (Cu) and curvature (Cc) as a function of the fines content in the mixtures. Their evolutions are given according to a polynomial function of equation for a fines content varying from 0 to 20 % as:

$$Cu = 0.134 * (Fc)^2 - 0.5216 * (Fc) + 9.22 \quad R^2= 0.998 \qquad (4)$$

$$Cc = 0.0104 * (Fc)^2 -0.0723 *(Fc)+ 0.856 \quad R^2= 0.992 \qquad (5)$$

Figure 10b represents the variation of the diameters of the grains D_{10}, D_{30}, D_{50} and D_{60} according to the fines content Fc (%). It appears that the diameters have relatively constant values between 0 and 5 % fines. Beyond 5 % of fines, the diameters of the particles decrease in an almost linear way up to 20 % of fines.

Figure 11 represents the variation of plasticity index Ip and the maximum dry density as a function of the fines content containing in the mixtures. The value of Ip increases significantly from 2 % to 5 % to stabilize slightly when the fines content reaches 15 %. At the same time, the dry density indicates a decrease between 0 and 5 % (minimum value of 1.85 g/cm^3) of

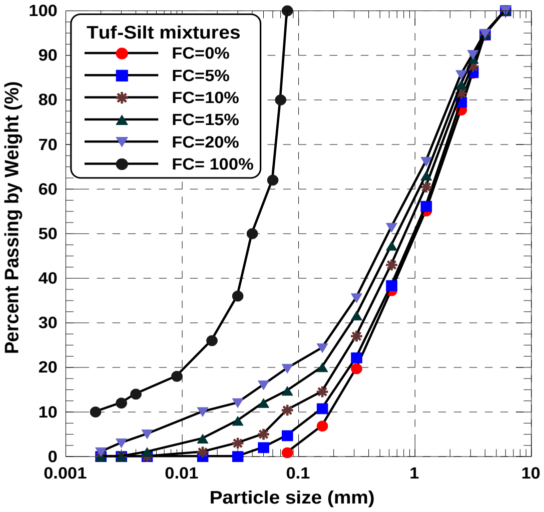

Fig. 8 Particle size curves of 100 % fines as well as Tuff/fines mixtures with different fines contents, Fc = 0, 5, 10, 15 and 20 %.

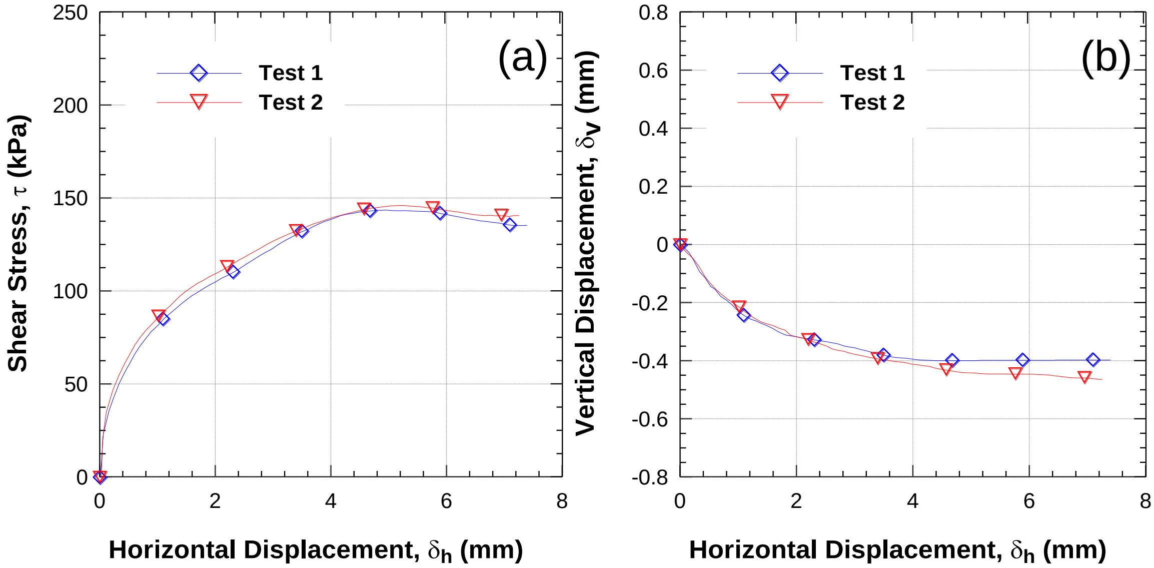

Fig. 9 Repeatability test with σ_N = 200 kPa and RD = 50 % (Nougar et al., 2021): (a) Variation of shear stress versus shear displacement (ΔH); (b) Variation of vertical displacements (Δv) versus shear displacement (ΔH).

fines then increases beyond 5 % up to 20 % of fines, recording a maximum value of 1.88 g/cm^3. This can be explained by the fact that the intergranular contacts play an important role in increasing the maximum dry density. In fact, the filling of the voids between coarse grains by the fines inducing intergranular contact forces, therefore an increase in the max dry density, (case i, ii, iii) of Figure 5 (Thevanayagam ,2002).

RESULTS AND DISCUSSION

COMPACTION TEST (PROCTOR TEST)

Compaction tests are commonly utilized in road engineering to increase the dry density of soil while reducing its optimum water content. This process aims to minimize the void ratio of the compacted soil, ensuring that the soil particles are tightly interlocked (Al-Khafaji, 1993; Goual, 2012; Ören, 2014; Azaiez, 2020).

The preparation of the Tuff/silty fines mixtures was made by incorporating the silty fines to the Tuff in proportions varying between 0 and 20 % fines content, kneaded manually with additions of quantities of initial water contents varying between 8 and 14 %.

The Proctor molds used in this study have the following specifications: a diameter of 101.6 mm and a height of 117 mm, in accordance with NF P 94-093 standards. The characteristics of the Proctor compaction hammer are a diameter of 50.8 mm, a height of 114.3 mm, and a weight of 2.4 kg. The Tuff/Fines mixtures were placed in the Proctor mold in three layers and compacted with 25 strokes per layer, achieving a total height of 30.5 cm. This corresponds to a stored energy of approximately 587 kJ/m^3. Figure 12 illustrates how the dry density (γ_d) varies with water content (ω, %), specifically for the Tuff/Fines mixtures. It is evident that the dry

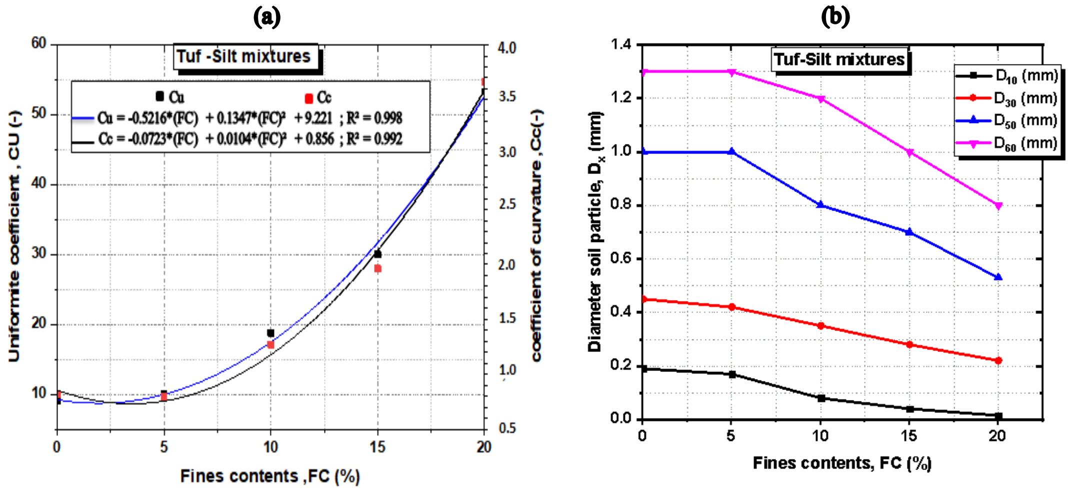

Fig. 10 Variation of physical characteristics (Cu, Cc) and grain diameters Dx depending on fines content.

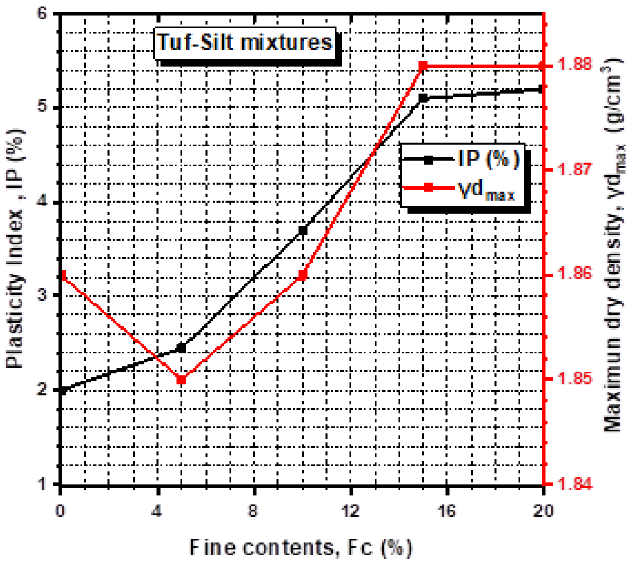

Fig. 11 Variation of plasticity index IP and dry density (γ_{dmax}) as a function of fines content (Fc).

density increases with the addition of finer materials. A fines content of 20 % densifies the tuff, resulting in an optimum dry density (γ_{dopm}) of 1.9 g/cm³, corresponding to a water content (ω) of 13.53 %. This increase in density can be attributed to the rearrangement of grains during high-energy compaction, which was achieved with 55 strokes per layer (Goual et al., 2012), or it could be explained by the dissolution of limestone tuff and, CO_2 in the presence of high water content (Ben Dhia, 1983).

DIRECT SHEAR TEST

To evaluate the mechanical behaviour of Tuff/fines mixtures with fines content ranging from 0 % to 20 %, we conducted a series of conventional direct shear tests on the different mixtures. The preparation of the samples, including water content, was based on the results of the optimum Proctor parameters (maximum dry density γ_{dmax} and optimum moisture content ωopt), as reported in Table 6. The degree of saturation was also considered.

$$Sr\ (\%) = \frac{\gamma s.w\%}{\gamma w.e};$$

With: γ_s and γ_w: Unit weight of solid grains and water, respectively; w %: Water content and e: global Void ratio.

The samples of Tuff and fines mixtures were moisturized to the optimum Proctor water content and placed in shear molds with dimensions of 60 x 60 x 25 mm. The procedure for placing and compacting the layers was conducted based on the initial relative density of the mixtures, set at RD = 90 %. This initial relative density was chosen because most treated soils are typically groomed or compacted. Additionally, it aligns with the Proctor protocol, which determines optimum values at a high relative density.

The procedures involved tamping the various layers until the desired initial relative density and appropriate soil weight were achieved. All samples were then consolidated and subjected to shear tests under normal stresses of σn = 100, 200, and 300 kPa, with the normal stress remaining constant throughout

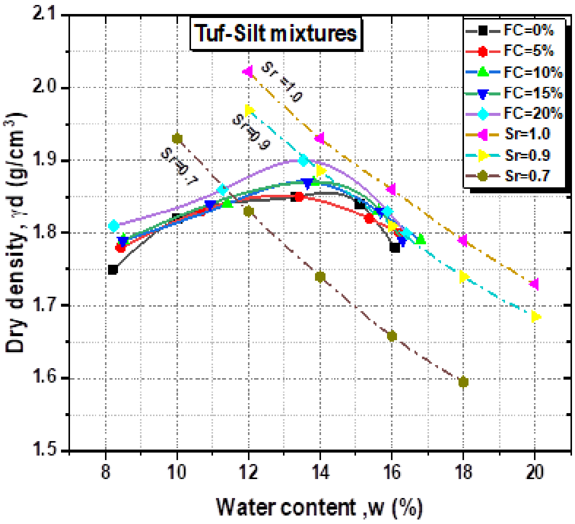

Fig. 12 Compaction curves for Proctor test for the different mixtures: Fc = 0, 5, 10, 15 and 20 %.

Table 6 Optimum characteristics of Proctor tests on the different Tuff/Fines mixtures.

Fc (%)	W_{opt} (%)	γ_{dmax} (g/cm^3)
0	13.3	1.86
5	13.41	1.85
10	13.82	1.86
15	13.64	1.88
20	13.53	1.88

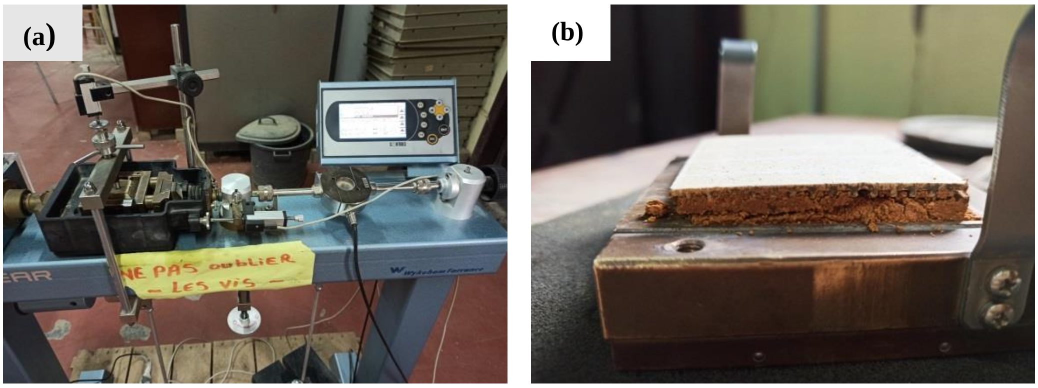

Fig. 13 Experimental device: (a) The "Autoshear" apparatus used; (b) Mixture sheared presented at the end of the test.

all test stages. The shear rate was set at 1 mm/min, a rate used by several researchers, including Bouaricha et al. (2017), Boutouba et al. (2019), and Azaiz et al. (2020). Figure 13 illustrates the shear device used during the test and shows the sample after it was sheared at the end of the test.

A series of direct shear tests were conducted on Tuff samples with varying silty fines content between 0 % and 20 %. The samples were imbibed with optimum water content, determined by the Proctor test, ranging from 13.3 % to 13.82 % (refer to Table 6). All samples were placed in the box with a high relative density (RD) of 90 %. The normal stresses applied during these tests were σN = 100, 200, and 300 kPa. The behaviour of the different mixtures is analyzed in the following sections, which discuss the effects of: (a) normal stress levels (σn = 100, 200, and 300 kPa) on the shear behaviour of both untreated samples and those treated with silty fines; and (b) the influence of fines on the shear behaviour of Tuff/Fines mixtures under varying normal stresses.

EFFECT OF NORMAL STRESS ON THE MIXTURES' SHEAR RESPONSE

Figure 14a and Figure 15a illustrate the variations of the shear stress τ [kPa], as a function of the horizontal displacement δH (mm) of the untreated samples and samples with Fc = 20 % fines content, respectively. The samples of both soils have been consolidated and sheared under three normal stresses σ_N = 100, 200, and 300 kPa. From the figures, there is a progressive increase in the shear stress (τ) when the

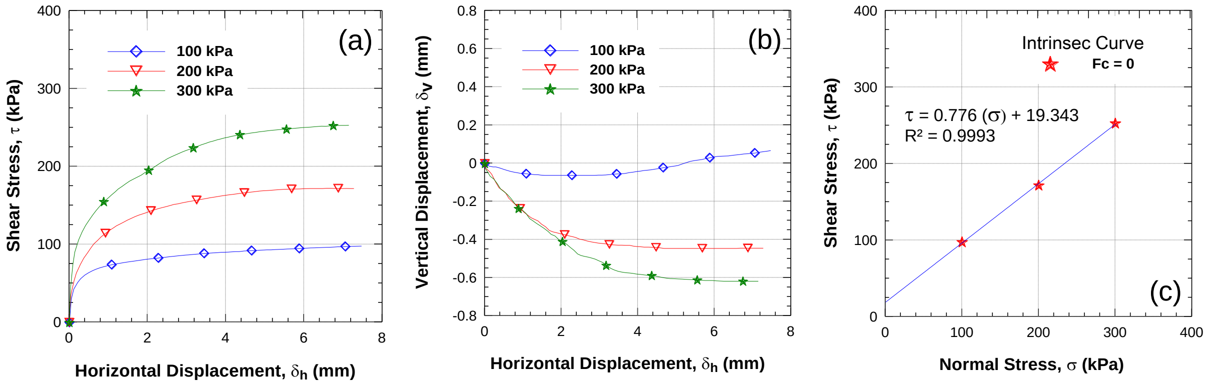

Fig. 14 Shear strength behaviour of the Tuff/Fines mixtures (Fc = 0 %): (a) Variation of the shear stress (**τ**) vs horizontal displacement (ΔH); (b) Variation of vertical displacement (ΔV) vs horizontal displacement (ΔH); (c) intrinsic curve.

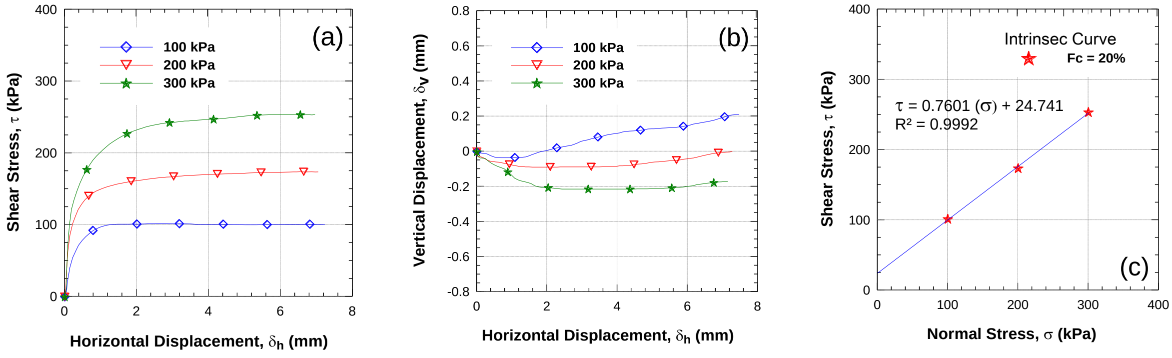

Fig. 15 Shear strength behaviour of the Tuff/Fines mixtures (Fc = 20%): (a) Variation of the shear stress (**τ**) vs horizontal displacement (ΔH); (b) Variation of vertical displacement (ΔV) vs horizontal displacement (ΔH); (c) Intrinsic curve.

vertical stress increases from 100 kPa to 300 kPa. This linear correlation represents the Mohr-Coulomb lines or failure lines, which are represented in Figures 14c and 15c.

It is therefore noted that the curves do not show a clear peak for the samples consolidated under the two normal stresses σ_v = 200 kPa and σ_v = 300 kPa; and the shear deformability appears from 2 mm of horizontal displacement. For example, the samples containing 20 % fines content get his peak shear strength 254 kPa (at σ_N = 300 kPa) in comparison with a weak peak of the order of 174 kPa (at σ_N = 200 kPa).

Figures 14b and 15b illustrate the variation of vertical displacements, ΔV (mm) versus horizontal displacements, ΔH (mm). All the sheared samples behave with a contractiveness phase at the beginning of the test until a maximum settlement corresponding to the peak shear strength is achieved due to the rearrangement of the soil particles at the beginning of the test. After that point, a dilatant phase is generally reported at which the soil is already at its peak strength. The composite material, Tuff +20 % fines content, has low contractiveness deformations compared to the untreated material (Fc = 0 %), which means that the introduction of 20 % fines content improves the dilatant character.

Silty fines significantly influence the time it takes to reach peak shear stress (τmax). For example, samples containing 20 % silty fines achieve a maximum shear stress of τmax = 102 kPa (under a normal stress σ_N = 100 kPa) in approximately 1 to 2 minutes. In contrast, untrained samples reach a maximum shear stress of τmax = 98 kPa (also consolidated and sheared under the same normal stress of σ_N = 100 kPa) only at the end of the test. It is important to note the effective transmission of intergranular forces and the interlocking of particles of varying sizes when they are saturated with optimal water content. However, a detailed study is needed to examine the effects of different proportions of fines, which will be addressed in the next section.

EFFECT OF THE SILTY FINES CONTENT ON THE MIXTURES' SHEAR RESPONSE

Figures 16, 17, and 18 show the results of straight shear tests on Tuff/fines mixtures with different fines content values. These results clearly indicate that the fines content has a significant impact on the soil's behaviour.

The shear strength of Tuff/silt mixtures tested shows a slight decrease with an increase in fines content up to 10 %. Beyond this point, shear strength

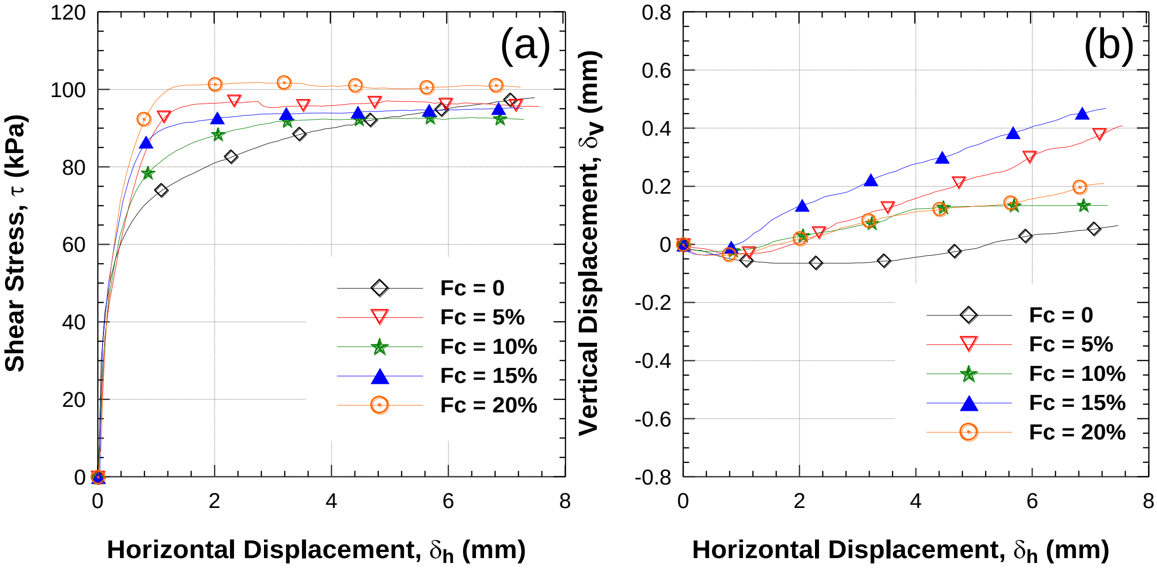

Fig. 16 Shear strength response (σ_V = 100 kPa): (a) Variation of the shear stress ($\boldsymbol{\tau}$) vs horizontal displacement (ΔH); (b) Variation of vertical displacement (ΔV) vs horizontal displacement (ΔH).

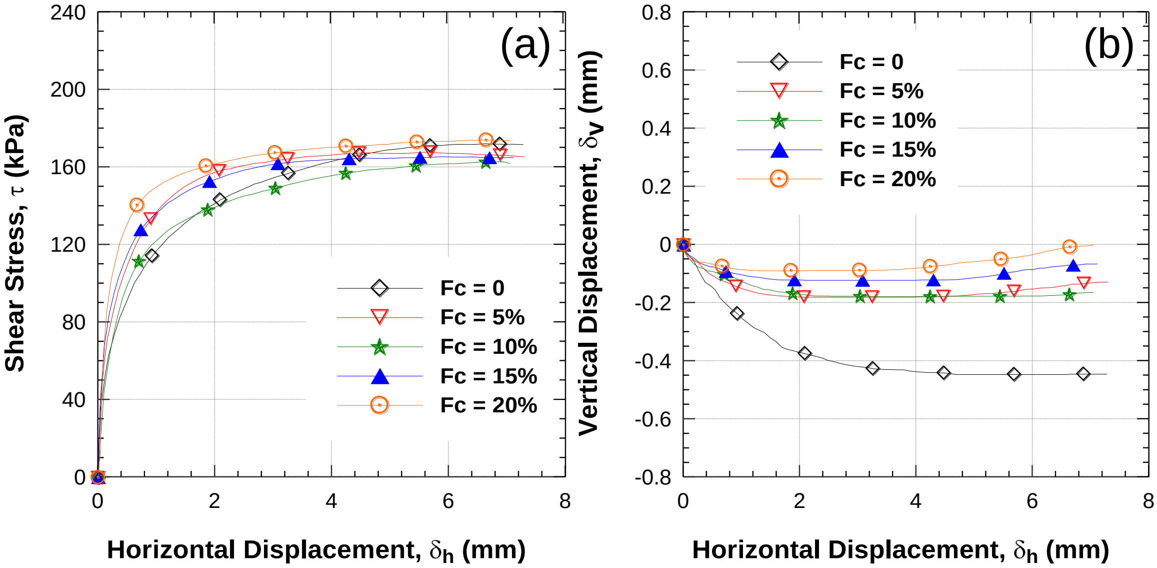

Fig. 17 Shear strength response (σ_V = 200 kPa): (a) Variation of the shear stress ($\boldsymbol{\tau}$) vs horizontal displacement (ΔH); (b) Variation of vertical displacement (ΔV) vs horizontal displacement (ΔH).

begins to increase. Numerous researchers have investigated the impact of fines content on soil strength. Shen et al. (1977) demonstrated that the presence of fines enhances soil strength. Ishihara et al. (1980) observed that the undrained strength of soil remains constant when the plasticity index is below 10. However, beyond this threshold, the undrained strength significantly increases with a rising plasticity index. Seed et al. (1985) supported this finding.

Georgiannou et al. (1990) indicated that the presence of fines in soil creates a more compressible soil fabric, which can lead to a notable reduction in soil resistance to liquefaction. Arab et al. (2014) and Benessalah et al. (2021) corroborated this observation for fines contents ranging from 0 % to 40 % and from 0 % to 50 %, respectively. The results of the current study seem to align with earlier findings from undrained monotonic and cyclic tests conducted on sand/silt mixtures, which indicate a reduction in resistance up to a certain threshold of fines content, followed by an increase in resistance when the fines content exceeds this threshold (Porcino et al., 2019; Bouferra and Shahrour, 2004; Koester, 1994).

Despite the decrease in shear strength caused by the introduction of fines to the Tuff (with Fc <10 %), it is important to note that these fines actually help improve the time it takes for the mixtures to reach their maximum shear strength. In Figures 16a, 17a, and 18a, we observe that the maximum shear strength of the Tuff alone is achieved at the end of the test. In contrast,

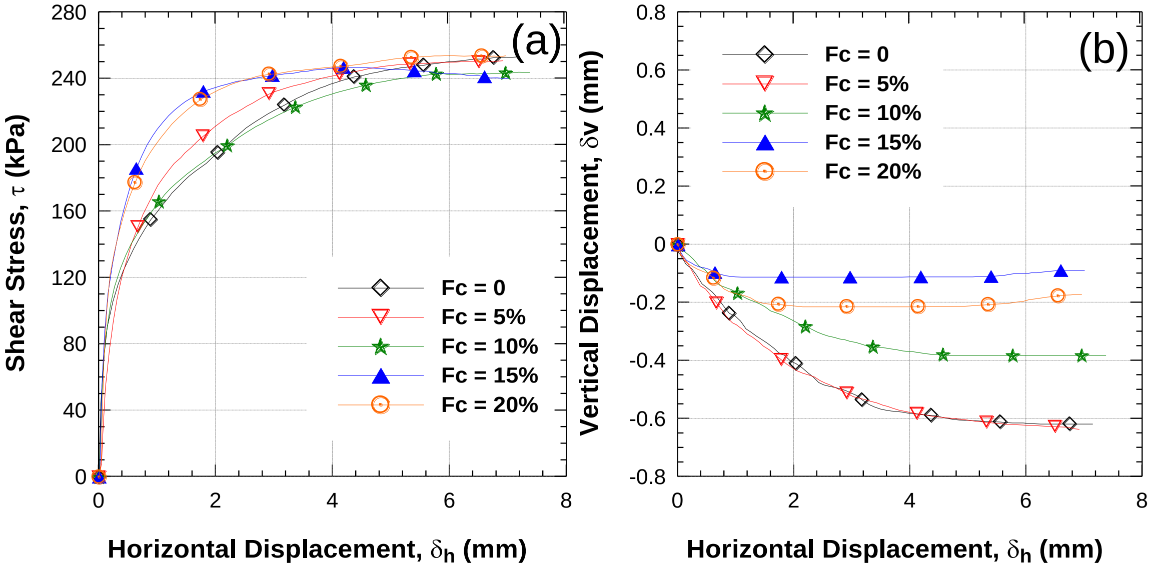

Fig. 18 Shear strength response (σ_V= 300kPa): (a) Variation of the shear stress (**τ**) vs horizontal displacement (ΔH); (b) Variation of vertical displacement (ΔV) vs horizontal displacement (ΔH).

Table 7 Values corresponding to internal friction angle (φ°) and cohesion (C kPa) at different mixtures Fc = 0, 5, 10, 15, 20 %

Fc (%)	0	5	10	15	20
Friction angle, φ (°)	37.81	37.65	37.08	37.16	37.24
Cohesion, c (kPa)	19.34	18.32	15.53	17.73	24.73

mixtures containing fines reach their maximum strength within 1 to 3 minutes (or after 1 to 3 mm of shear displacement, since the shear rate is set at 1 mm/min). This advantageous effect is accompanied by a significant improvement in the dilatant behaviour of all mixtures with fines compared to the Tuff alone, as illustrated in Figures 16b, 17b, and 18b.

EFFECT OF THE SILTY FINES CONTENT ON THE MECHANICAL CHARACTERISTICS

As previously discussed, Figures 14c and 15c illustrate the variation in the Mohr-Coulomb plane (τ, σn), explicitly showing the rupture envelope for normal stresses of σn = 100, 200, and 300 kPa. The intrinsic Mohr-Coulomb lines, represented by the equation; τ (kPa) = σn * tan(φ) + C (kPa)

Are derived from the peak shear strength values of different mixtures (refer to Fig. 19a). The cohesion values (C) range from 15.53 kPa for 10 % fine content (Fc) to 24.73 kPa for 20 % fine content. Moreover, the intergranular friction angle (φ°) decreases from 37.81° at 0 % fine content (Fc) to a minimum of 37.08° at 10 % fine content before increasing linearly to 37.24° at 20 % fine content. The initial conditions can explain this behaviour during the shear tests, where fine particles fill the voids between the larger grains in the solid skeleton of the tuff. Once a certain threshold is reached (Fc = 10 %), the coarse particles begin to contact the fine particles, enabling the effective transmission of forces among the larger particles.

The intrinsic properties of cohesion (C in kPa) and the angle of friction (φ°) are presented in Table 7 and illustrated in Figure 19.

Figures 19b and 19c illustrate how cohesion (C, in kPa) and friction angles (φ, in degrees) vary with the content of fines (FC, in percentage). It is evident from these figures that the presence of fines significantly influences the strength of Tuff-Fines mixtures. Notably, a threshold of 10 % fines marks a transition in the distribution of voids, which is crucial for evaluating the mechanical parameters (C and φ). At this threshold (FC = 10 %), cohesion increases from 15.53 kPa to 24.73 kPa when the fines content rises to 20 %. Similarly, the friction angle shows a slight increase from 37.08° at 10 % fines to 37.24° at 20 % fines.

CORRELATION BETWEEN THE PARAMETERS OF THE COMPACTION TEST AND THE DIRECT SHEAR TEST

Figure 20 illustrates the variation of maximum shear strength as a function of maximum dry density and optimum water content for different mixtures, specifically with fines content (Fc) of 0 %, 5 %, 10 %, 15 %, and 20 %. These mixtures were consolidated and sheared under three normal stresses: σN = 100 kPa, 200 kPa, and 300 kPa.

This figure consolidates the effects of adding silty fines to Tuff in both the Proctor compaction test and the direct shear test. For instance, Figures 20a and

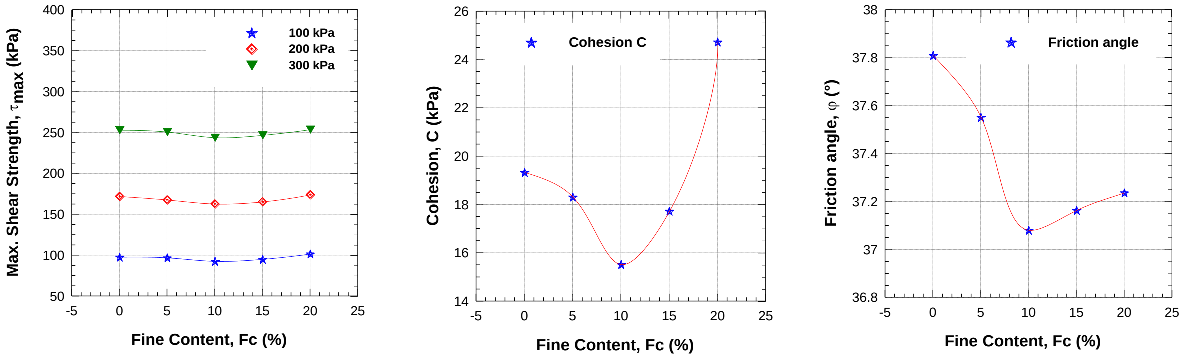

Fig. 19 Variation of the mechanical characteristics versus fines content: (a) Shear strength at the peak; (b) Cohesion (c) Friction angle.

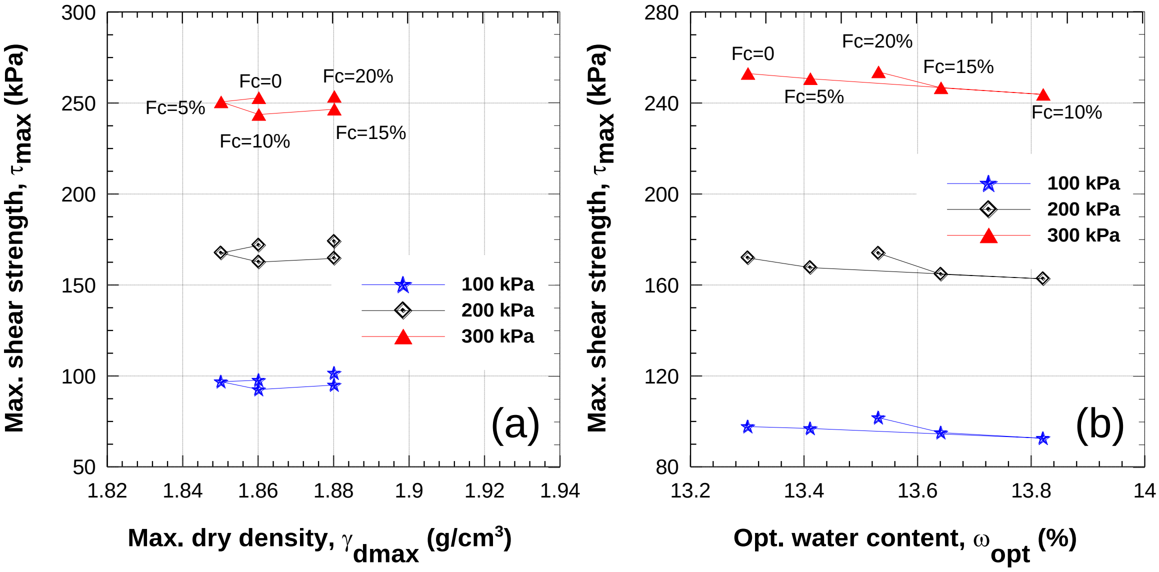

Fig. 20 Variation of maximum shear strength (τ_{max}): (a) versus maximum dry density (γd_{max}); (b) Optimum water content (w_{opm}).

20b demonstrate that the shear strength decreases slightly as the fines content increases up to a threshold of Fc = 10 %. Beyond this point, the shear strength begins to increase for mixtures with fines content higher than Fc = 10 %. Additionally, Figure 20a shows that the mixture consisting of 95 % tuff and 5 % fines has the lowest maximum dry density (γdmax) compared to the other mixtures. Meanwhile, Figure 20b indicates that the optimum water content (ωopt) decreases with increasing fines content until Fc = 10 %. After this threshold, ωopt increases again for the higher fines content mixtures.

CONCLUSION

The silty fines extracted from alluvial sands play a significant role in enhancing the mechanical characteristics of Tuff, particularly given the weak mechanical properties of the Tuff from the Chlef region, which is used in road pavement bedding. The tuff was mixed with variable amounts of fines, specifically 0 %, 5 %, 10 %, 15 %, and 20 %. These mixtures underwent Proctor compaction tests to determine the Proctor optimal values (maximum dry density, γdmax, and optimum water content, ωopt). Following this, a Casagrande box rectilinear shear test was conducted, using samples that were consolidated and sheared under three normal stresses: σN =100 kPa, 200 kPa, and 300 kPa. The samples were prepared while adhering to the optimum parameters established during the compaction tests, which utilized the optimum water content and achieved a relative density (RD) of 90 %. The main findings of the study are summarized below:

- The addition of 20% fine content from Tuff slightly impacted the dry density of the mixtures, resulting in an estimated degree of saturation Sr of 94 %;
- The intrinsic parameters of the particle size distribution, including the effective diameters (D10, D30, D50, and D60), show a quasi-linear decrease as the fines content increases. In contrast, the coefficients of uniformity (CU) and curvature (Cc) are adjusted according to a polynomial pattern;
- The optimal dry density of the mixtures decreases slightly as the fines content (Fc) increases from

0 % to 5 %. However, beyond this point, a slight increase in dry density is observed with further increases in fines content. The highest dry density recorded is 1.88 g/cm³ at a fines content of 20 %;

- The direct shear tests carried out on the various tuff samples with the addition of fines, allowed us to collect the mechanical parameters of the Tuff/fines composite materials in terms of shear strength at the peak, dilatant character, internal friction angles φ° and the cohesion C (kPa). On the face of analysing the variation of each parameter, we can nevertheless think that the mechanical behaviour has been improved.
- The results obtained provide a valuable database for the development and validation of numerical models. It would be beneficial to initially test existing models to identify the parameters that significantly influence the behaviour of Tuff/fines mixtures. Subsequently, discrete element codes could be employed for a more in-depth study of the material's behaviour.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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