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Influence of Silt Content on the Mechanical Behavior of Tuff Mixtures in Unsaturated Condition

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ABSTRACT**:** The objective of this study is to examine the impact of silt content on the unsaturated behavior of tuff-silt mixtures. The study encompasses silt proportions ranging from 0% to 20%.
Testing involved standard compaction (NF P 94-093) and direct shear tests using a Casagrande apparatus (NF P 94-071-1). Shear test specimens were prepared at three relative densities: 20% (loose), 50% (medium-dense), and 90% (dense).
Results indicate that silt content significantly enhances compaction characteristics in unsaturated specimens (prepared at 93% degree of saturation). Maximum dry density increases with silt content, peaking at 20% fines.
Shear tests reveal that fines content markedly increases apparent cohesion, reaching a maximum of 37.77 kPa at 10% fines. The internal friction angle (ϕ) varied across density states, with a maximum value of 37° observed under dense conditions.

KEYWORDS: Tuff, silt content, Proctor, relative densities, direct shear test

1 INTRODUCTION

Limestone tuffs are generally carbonate rocks that are soft, friable, porous and light in colour. They are widely used in road construction because they are easy to mix and compact when wet. However, these materials are not used for heavy road traffic and represent a problem that needed to be studied rigorously.

The constituents of tuff are variable and result from a certain number of exchanges by dissolution or precipitation. Their compaction in a wet state favours an increase in cohesion, which lasts over time but disappears when the material becomes saturated (Alloul, 1981; Ben Dhia, 198; Ben Dhia et al.1984). This has been confirmed by several studies carried out on the static and dynamic behaviour of tuff, including: (Goual et al. 2012). The various techniques developed over more than forty years with the aim of improving tuffs for use in road bases with heavy traffic (base and sub-base layers) have been based either on treatment with hydraulic binders or lime or by incorporating other fine materials of a crushed, fluvial, or dune nature (Loualbia et al. 2021).

As for tuff improvement, Daheur et al. (2019) showed that dune sand-tuff mixtures are denser than base materials obtained with low OPM water contents and the plasticity index (Ip) decreases with increasing sand percentage. They deduced that the economic and environmental criteria are more favorable for an optimal formulation of the type: 65% Tuff + 35% Dune Sand.

The objective of this work is to study the influence of silty fines on the unsaturated behavior of tuffs in the Chlef region (Algeria). The results are based on shear tests under different conditions.

2 MATERIALS AND METHODS

2.1 *Materials*

The physico-chemical characteristics of the materials used in this study are given in Tables 1

Table 1. Physico-chemical characteristics of the Thaalba Tuff (Oued Sly -Chlef) and Silt.

Parameter	Symbol	Tuff	Silt	Unit
specific gravity	Gs	2.67	2.70	-
maximum partical size	D_{max}	5	0.08	mm
effective partical diameter	D_{10}	0.19	0.0017	mm
effective partical diameter	D_{30}	0.45	0.022	mm
effective partical diameter	D_{50}	1	0.035	mm
effective partical diameter	D_{60}	1.3	0.04	mm
coefficient of uniformity	C_u	9	40	-
coefficient of curvature	Cc	0.82	7.12	-
maximum Porosity	n_{max}	0.53	-	-
minimum Porosity	n_{min}	0.42	-	-
maximum void ratio	e_{max}	0.53	1.137	-
minimum void ratio	e_{min}	0.42	0.72	-
plasticity index	Ip	1.96	5	%
methylene blue	MB	0.23	-	g/100g
GTR	-	B6	A1	-
Shape	-	Sub-rounded	rounded	-
Carbonate calcium	C	91.68	24.71	(%)
Iron oxide	Fe	1.3	-	(%)
Silica	Si	-	72.16	(%)

Table 1 shows the main physical properties of the soils used in this study. The calcareous tuff is quite rough, with a maximum grain size of 5 mm, while the silt is much smoother (maximum grain size = 0.08 mm). This is also shown by how easily they can change shape, with numbers of 1.96 and 5 for the calcareous tuff and fine silt, respectively. These results clearly show the different physical characteristics of the two materials.

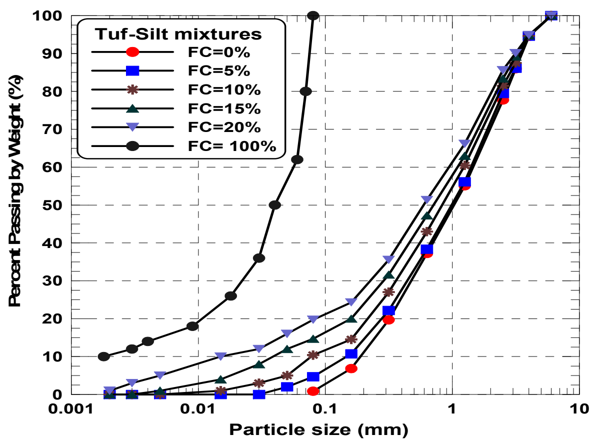

Figure 1. Grain size distribution of tuff with silt

Figure 1 shows the particle size distribution of calcareous tuff-silt mixtures with different fines content (FC = 0–100%) as determined by sieve analysis. An increase in fines content shifts the grading curves towards the finer fraction, indicating a higher proportion of small particles. Natural soil (tuff) has a predominantly granular structure; however, the addition of fines results in smoother, more continuous gradation, reflecting improved particle packing. The sample with 100% fines exhibits typical fine-grained soil behaviour. Overall, the incorporation of fines significantly alters the soil's granulometric composition and is expected to affect its mechanical response.

Tuff-silt mixtures were prepared with silt contents of 0, 5, 10, 15, and 20%, followed by imbibition at the optimum water content (Wopt). The samples were subjected to compaction tests (NF P 94 093) and Casagrande box shear tests (NF P 94 071-1), which were prepared according to three relative density states (Dr=20%, 50%, 90%) and then sheared at a constant displacement rate of 1 mm/min. The relative density of a material is given by the following equation (1):

$$Dr\ (\%) = \frac{e\max - e}{e\max - e\ min} \times 100 \qquad (1)$$

Where: e_{max}, e_{min}, and e are the maximum and minimum void ratio, and overall void indices of the material under study, respectively.

3 RESULTS AND DISCUSSIONS

the results obtained during our investigations have enabled us to draw the following conclusions

3.1 *Compaction*

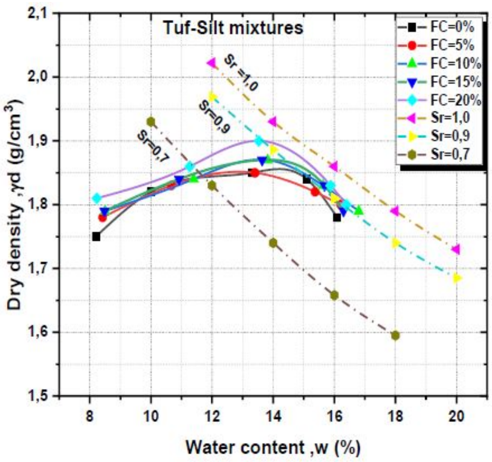

Figure 2. Compaction curves for tuff with the addition of silty fines.

Figure 2 illustrates the variation of dry density γd as a function of water content (W%) in tuff-fine mixtures. Dry density increases with the addition of fines content. A fines content of 20% densifies the tuff to reach a peak optimal density at γdopm = 18.8 kN/m³, corresponding to a water content of W = 13.53%, This represents the optimum moisture content (OMC) condition for this mixture.

The density enhancement occurs because silt particles migrate into void spaces between coarser tuff grains during compaction at sub-optimal moisture conditions. This particle rearrangement mechanism—consistent with observations by Goual et al. (2012)—improves packing efficiency and reduces overall void ratio.

3.2 *Relative compactness*

Relative compactness (RC) is used to determine the degree of in-situ compaction in relation to that determined in the laboratory (γdopm). This value is expressed by equation (2) (Razouki and Kuttah, 2020).

$$RC = \frac{\gamma d\ in{-}situ}{\gamma d\ max} \times 100 \qquad (2)$$

With:

γd in-situ: Dry density corresponding to different in- situ water contents.

γdmax: Dry density corresponding to the Proctor optimum.

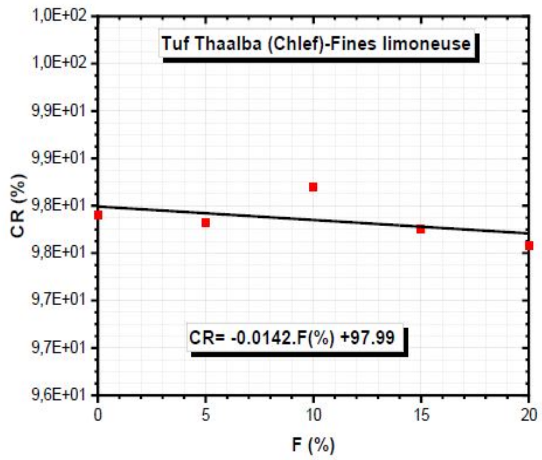

Figure 3. Variation in relative compactness as a function of fines content

Figure 3 presents the relationship between relative compactness (RC%) and silty fines content (F%). The data exhibit a linear trend with a slight negative slope, observed at a constant degree of saturation (Sr = 93%). This relationship is expressed by Equation (3) :

$$RC = -0.0142.\ F\ (\%) + 97.99\ \% \qquad (3)$$

However, this relative compactness fluctuates around 98%, which characterises good performance adopted in accordance with the recommendations of the GTR (1992).

3.3 *Direct shear*

Direct shear tests were performed on tuff-silt mixtures with silt contents ranging from 0% to 20%, prepared at relative densities of Dr = 20%, 50%, and 90%. Figure 4 presents the shear stress (τ) versus horizontal displacement (ΔH) relationships.

The soil samples were prepared at three distinct density levels : 90%, 50%, and 20%. The high density (90%) was achieved by compacting the soil in three equal layers, with each layer receiving 25 blows of the standard compaction hammer. For the medium density (50%), the soil was also placed in three layers but without any application of compaction energy. The low density (20%) was obtained by gently pouring the soil through a plastic funnel to ensure a uniform and very loose state with minimal compaction.

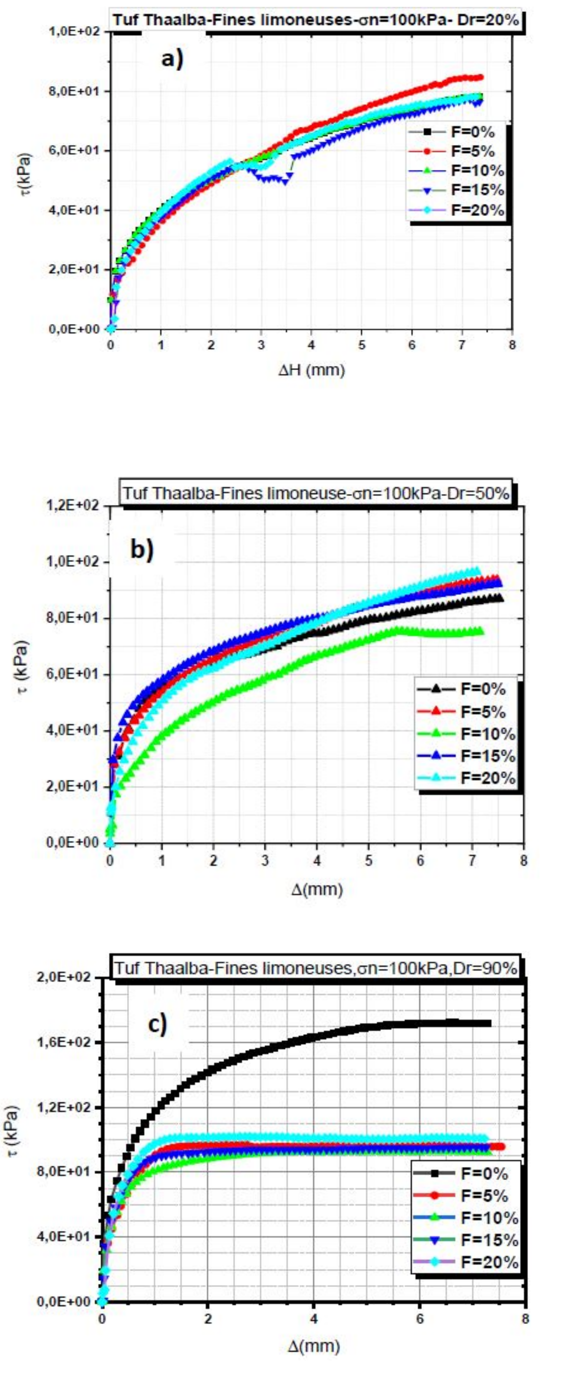

Figure 4. Evolution of shear stress as a function of horizontal displacement at σn= 100 kPa. (a) Dr= 20% (b) Dr = 50% (c) Dr= 90%)

In Figures 4a, b, and c, it can be seen that fines play a dominant role in the mixtures.

Figure 4a (Dr=20%) shows an initial rapid increase in shear stress followed by a short relaxation zone between approximately 2.5 mm and 4 mm for the specimens containing 15% and 20% fines. This temporary decrease in shear stress is attributed to a transient build-up of excess pore water pressure and local particle rearrangement under undrained conditions. which momentarily reduces beyond this interval, the shear stress increases again with displacement, and the 15% and 20% mixtures develop the highest shear resistance, indicating that this fines content range improves particle packing and contact efficiency within the granular skeleton. Shear testing reveals density-dependent responses to silt content: specimens at medium density (Dr = 50%, Figure 4b) exhibit significantly enhanced shear strength, reaching approximately 100 kPa with increasing silt content due to optimal particle packing. In contrast, both loose (Dr = 20%, Figure 4a) and dense (Dr = 90%, Figure 4c) specimens illustrate diminished strength gains. This behavior is attributable to the particle rearrangement efficiency at optimum moisture content. At Dr = 50%, silt particles occupy intergranular voids to improve stress transfer. At Dr = 20%, insufficient confinement limits particle interlocking. At Dr = 90%, restricted pore space hinders silt redistribution. The unsaturated condition (Sr < 100%) further influences this response through suction-dependent stiffness effects.

This can probably be explained by the partial occupation of the fines in the mixtures during preparation and deposition of the material in the shear box at optimum water content. A degree of saturation Sr < 100% therefore favors the phenomenon of vulnerability of the rigidity of the Tuff-Fines material.

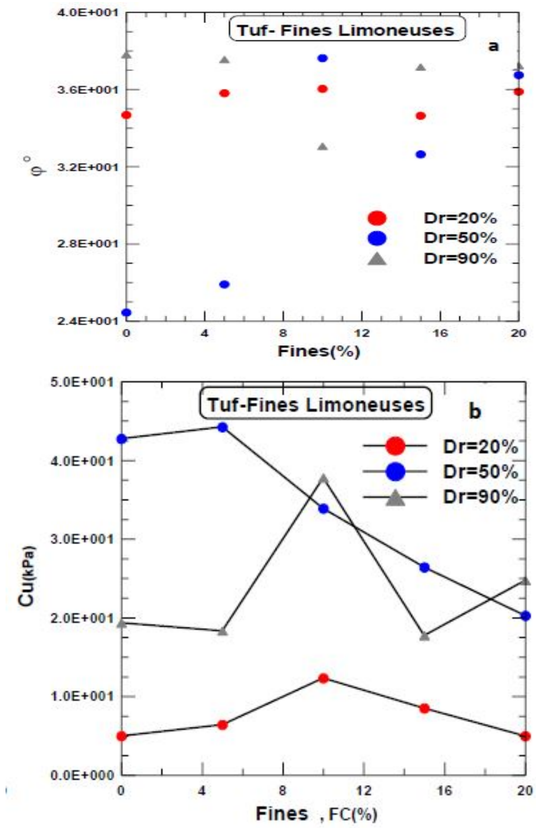

Figure 5. Effect of relative density on the mechanical characteristics of tuff-limon: (a) angle of friction—fine; (b) cohesion—fine.

Figure 5a and 4b depict the variation in friction angle (φ°) and cohesion (C) with increasing fine content in tuff-limestone mixtures at different relative densities (Dr = 20%, 50%, and 90%).

The friction angle (Figure 5a) exhibits a nonlinear relationship, peaking at approximately 37° for a fine content of 10% in moderately dense soil (Dr = 50%). This initial increase suggests that limited fines enhance shear resistance by filling voids and promoting interlocking within the coarse tuff skeleton. However, beyond this threshold, φ° decreases as excessive fines disrupt granular contacts, acting as a lubricant rather than a reinforcing agent.

In contrast, cohesion (Figure 5b) reaches its maximum value of 37.77 kPa at just 5% fines, likely due to physicochemical interactions such as cation exchange (Ca^{2+}, SiO_2, H_2O) and particle bridging, which temporarily strengthen the matrix. Further increases in fine content dilute the load-bearing coarse fraction, reducing cohesion. Notably, while higher relative densities (Dr = 90%) consistently improve φ° through denser packing, their effect on cohesion is less pronounced, underscoring the latter's dependence on electrochemical bonds rather than mechanical compaction (Daheur et al. (2019)). Together, these trends reveal an optimal fine content range of 5–10%, where the balance between granular friction and cohesive binding maximizes shear strength. Beyond 15% fines, the material transitions toward fine-dominated behavior, losing the structural advantages of its coarse skeleton—a critical consideration for geotechnical applications such as slope stabilization or foundation design in tuffaceous soils.

4 CONCLUSION

Based on the results of our investigations, the following points emerge:

- The addition of 20% silty fines combined with tuff significantly improves the dry density of the mixes, with a degree of saturation Sr of the material estimated at 93%.
- Cationic exchanges between calcium ions (Ca++), water (H2O) and silica (SiO2) in the sand (fines) increase the rigidity of the mixtures by arranging and interweaving the fine particles between the pores in the coarse solid skeleton of the tuff.
- The relative compactness CR (%) characterising the state of compactness of the soil in place is a function of the fine content at variable water content and increases with the increase in fine content. A maximum value of the order of 98% was obtained for 10% fines.
- Shear strength decreases with increasing fines content. The peak is localised only for a relative density corresponding to a dense state, Dr = 90%.
- The friction angle φ°max of the order of 37° at 10% of the mixes for a relative density corresponding to Dr = 90% and a maximum cohesion of the order of 37.77 kPa at 5% fines corresponding to a relative density of 50%.

5 ACKNOWLEDGEMENTS

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