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ORIGINAL PAPER

Effect of Dune Sand Incorporation on the Physical and Mechanical Behaviour of Tuff: (Experimental Investigation)

Elhadj Guesmia Daheur · Idriss Goual · Said Taibi · Ratiba Mitiche-Kettab

Abstract The present paper focuses on the effect of the addition of dune sand on the physical and mechanical properties of the tuff. The percentage of sand added to tuff ranged between 0 and 100%. The geotechnical characteristics of sand and tuff as well as those of their different mixtures were first determined. Then, a series of mechanical tests (unconfined compressive strength UCS and triaxial shear test) were performed on compacted samples at modified proctor optimum (MPO). The results showed that the tuff–dune sand mixtures are denser than the basic materials with lower optimum water content at MPO. It was noticeable that the plasticity index decreased with the increasing percentage of sand added, due to the contribution of the fine particles of the sand. However, Californian Bearing Ratio, suction, UCS, maximum deviatory strength and secant modulus increased with the increasing percentage of sand added. They reach their maximum value when the portion of sand incorporated ranged between 25 and 35%. The optimal formulation of 65% tuff and 35% dune sand was selected to meet economic and environmental constraints. This analysis showed that the dune sand incorporation improved the geotechnical characteristics and the mechanical behavior of the tuff. It provided a better elaborated material; satisfying the standards requirements, which could be exploited for the construction of Saharan roads.

Keywords Tuff · Dune sand · Triaxial test · Suction · Secant modulus

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1 Introduction

Algeria has invested billions of dollars in an ambitious program intended for the realization and rehabilitation of several road projects i.e. the trans-Saharan roads; allowing an easy access to the highlands regions and Southern Algeria (Goual 2012). The new partnership for development in Africa (NEPAD) classified the

trans-Saharan roads as a priority; where they represent a big challenge for the neighbouring countries. This huge project crosses the Algerian territory from the Mediterranean coast (north) to the extreme south, with a total length of 2760 km and prolongs across the neighbouring countries like Mali, Niger and Nigeria. The construction started in 1970 and is still ongoing where the Algiers-Tamanrasset segment, of about 2000 km, was finished in 1978.

However, this has faced many difficulties, particularly related to the harsh climate and thermal contrasts. Moreover, most of the Saharan regions are short of standardized road materials (Morsli et al. 2000, 2002). Therefore, to compensate this deficiency, the use and improvement of local materials such as tuff and dune sand can be very interesting and may constitute a positive outcome.

Tuff is a common material in Algeria; with an area of about 300,000 km^2 (Goual et al. 2012). The use of this material for the structure of the Saharan road; in the in base and the foundation layers, has been noticeably enhanced (Fenzy 1966). Once compacted and dried, the material acquires a lasting cohesion force (Morsli et al. 2007). This force is a characteristic of the non-cohesive granular materials, which owe their cohesion to the presence of the capillary forces, or suction during the compaction (Soulié 2008).

Many techniques have been developed in the last 40 years, to improve the mechanical properties of the tuff, using the stabilization and the reinforcement techniques, with a reasonable cost (Dupas and Pecker 1979; Porbaha et al. 1998; Thomé et al. 2005). Recently, many researches on the effect of adding sand to the tuff material have interested. Morsli (2007), Goual, et al. (2012) and Cherrak et al. (2015) studied the mechanical properties of the tuff-sand mixtures. The results revealed that adding sand increases the maximum dry unit weight and reduces the optimum water content; both CBR value and unconfined compressive strength (UCS) of the mixtures are improved. Each author based on the tests performed, has chosen an optimal percentage of added sand; where the values reported are very close and varying from 20 to 25% of added sand.

The Sahara covers about the third of the surface of African. Moreover, the dune sand cover about 30% of the Algerian Sahara, which represents around 80% of the surface of Algeria (Benabed et al. 2014; Fooks and Higginbothman 1968). Therefore, using dune sand for the construction of Saharan roads has great interest. Mixing tuff and desert dune sand for road construction engineering, in extreme climatic conditions such as the Sahara, is a new approach.

The present work aims to valorise the dune sand and the tuff, which are local materials widely abundant in the arid areas in Algeria, in the design of the Saharan roads. The major purpose of this study is to improve the physical properties and the mechanical behaviour of the tuff, using an economical technique. For this intention, different formulations of tuff–dune sand mixtures have been established with dune sand content varying from 0 to 100%. The experimental investigation has been carried out on compacted samples using different tests as CBR, unconfined compressive strength and consolidated drained triaxial.

2 Materials and Methods

2.1 Materials

2.1.1 Material Description

The tuff and the sand studied have been collected in the province of Ouargla, located 800 km to the South of Algiers.

The tuff (T) dates from the Quaternary period (Ben dhia 1983). It consists of light-coloured, tender, friable and porous superficial material, used usually in the paving of low traffic roads in arid regions.

The sand known as desert sand or dune sand (DS), is a common material in the Algerian Sahara; it consists of quartz grains, derived directly from eruptive rocks, especially from sandstones; the grains are spherical, with slight angularities (Gueddouda et al. 2010), where the aeolian erosion has shaped the sand loads, provided by the rivers.

2.1.2 Engineering Properties

The geotechnical identification of the studied material has been performed according to the Algerian and the French standards: "Saharan Road Technology" or SRT (Fenzy 1966), "Catalogue Sizing of New Pavements" (CTTP) (2001) and "Technical guideline on embankment and capping layer construction" (GTR) (1992); they are classified according to the Unified System Classification of Soils USCS (Holtz and

Kovaks [1996]) and GTR standards. The geotechnical characteristics are presented in Table 1.

The tuff is composed principally of sand (about 70%), particles smaller than 80 μm (35%) and particles of 40 mm, considered as maximum diameter (D_{max}). The plasticity characteristics (Liquid limit = 53%, Plasticity Index = 26%) proved that the tuff is slightly clayey; which is also confirmed by the blue value (BV = 0.8).

The grain size distribution is uniformly graded for the DS, with values of uniformity (Cu) and curvature (Cc) coefficients of 1.9 and 1.2 respectively. Its sand equivalent test (E_s = 75%) revealed the absence of any clay traces.

The tuff characteristics did not satisfy some criteria, to be used alone in road engineering, especially fine particles content and Plasticity Index.

2.2 Methods

In order to find the optimal tuff–dune sand (T-DS) mixture, with the best physical and mechanical properties, the following T-DS mixtures: 100%T + 0%DS, 95% T + 5%DS, 85%T + 15%DS, 75%T + 25%DS, 65%T + 35%DS, 50%T + 50%DS and 0%T + 100%DS have been analyzed, using standard tests (Table 2).

Table 1 Soils properties

	Materials		Specifications		
	Tuff (T)	Dune sand (DS)	STR	CTTP	GTR
Grading analysis					
D_{max} (mm)	40	0.4	–	20–40	< 50
% < 0.425 mm	55	100	–	36–52	–
% < 80 μm	35	3.35	< 30	22–32	≤ 35
Uniformity Coefficient: C_u (%)	219	1.9	–	–	–
Hazen Coefficient: C_z (%)	2.6	1.2	–	–	–
Atterberg limits					
Liquid limit: LL (%)	53	N.M	–	< 40	–
Plasticity Limit: PL (%)	27	N.M	–	–	–
Plasticity Index: PI (%)	26	N.M	< 13	< 15	≤ 12
Sand Equivalent					
Es (%)	4.5	75	–	–	–
Blue value test					
VB	0.8	0.05	–	–	< 1.5
Compaction					
Maximum dry unit weight: γ_{dmax} (kN/m³)	18.9	16.7	> 17	–	–
Optimal water content: w_{MPO} (%)	11.75	7.4	–	–	–
Bearing					
Un-soaked C.B.R. index: I CBR I (%)	52	6	> 40	–	–
Soaked C.B.R. index: CBR I (4 h) (%)	42	5	–	–	–
Unconfined Compressive strength				–	–
UCS at 95% of γ_{dmax} (MPa)	1.7	00	> 1.5		
Chemical analysis					
Insoluble (%)	32.4	95.4	–	–	–
$CaCO_3$ (%)	29	00	–	≥ 45	–
$CaSO_4,2H_2O$ (%)	25	1	–	–	–
Classification					
USCS	SC	Sm			
GTR	B6	B1			

N.M not measurable

Table 2 Tests carried out and standards

	Tests	Standards
Physico-mechanical characteristics	Grading analysis test	ASTM D422
	Atterberg limits test	ASTM D4318
	Compaction test	ASTM D1557
	California Bearing ratio test	ASTM D1883
Mechanical behaviour	Unconfined compressive strength test	ASTM D2166
	Suction measurement	ASTM D5298-94
	Consolidated drained triaxial test	ASTM D7181-11

2.2.1 Physico-Mechanical Characteristics

The physico-mechanical properties i.e. grading curve, Atterberg limits, maximum dry unit weight, optimum water content, Unsoaked and Soaked CBR index have been assessed following the ASTM standards. The tuff has been sieved to 20 mm, for the tests of Modified Proctor and the Californian Bearing Ratio (CBR), and to 0.4 mm for Atterberg limits.

2.2.2 Mechanical Behaviour

The different mixtures studied have been subjected to the unconfined compressive strength (UCS) test and the consolidated-drained (CD) triaxial test, to evaluate their mechanical behaviour.

The samples have been prepared on three steps:

1. Natural soils have been air-dried; then the tuff has been passed on a 4 mm sieve to eliminate the gross particles. Then, the different tuff and dune sand were fractions have been mixed to obtain different T-DS mixtures.
2. The required quantity of water, corresponding to the optimum water content has been added to the T-DS mixtures, with careful hand mixing and sieving to have a homogeneous mixture. The soil–water mixture was then stored in a sealed plastic bag, for at least 24 h to achieve uniform moisture conditions.
3. The material has been statically compacted to the corresponding dry density of MPO in mould with double piston, at a rate of 1.14 mm/min. This compaction method leads to a homogeneous repartition of the compaction stress (Romero 1999; Ghembaza et al. 2007; Gueddouda et al. 2010).

(a) Unconfined compressive strength test (UCS)

The unconfined compression test is, widely used in the applications of pavement and soil stabilization to evaluate the cohesion of compacted materials (Morsli et al. 2007; Ben Dhia et al. 1984; Alloul 1981; Fumet 1959; Fenzy 1966; Peltier 1959).

The UCS tests have been performed on samples compacted at MPO; with two initial states:

1. Wet samples: immediately after being compacted with a saturation degree ranging between 70 and 80%;
2. Dried samples: after compaction, samples have been dried in the oven and to achieve saturation degree of about 0%.

Two sets of cylindrical samples with 50 mm diameter and 100 mm height have been prepared for the UCS test.: the first one has been tested directly after compaction (less than 1 h), and the other one after being dried at 55 °C, for 2 days, according to the Saharan Road Technology (SRT) standard.

The tests have been performed in triplicate for an optimal reproducibility.

(b) Suction measurement

The initial suction of the compacted samples has been determined using the filter paper method, according to the standard ASTM D 5298-94: a specific amount of soil was poured into the compacting mould in order to obtain around 60 mm of compacted soil, then a Whatmann 42 filter paper was placed on the soil between two filter papers. Finally, an amount of soil, corresponding to 15 mm of compacted soil, was poured and compacted. The samples were then wrapped and stored. After equilibrium, the filter paper was extracted from the sample and its water content

was determined. The suction is then deduced from filter paper calibration curve; following the ASTM standard. The suction range accessible by this technique is between 50 and 30,000 kPa.

(c)   Consolidated drained (CD) triaxial test

Cylindrical samples with 38 mm diameter and 76 mm height have prepared for this test. The experimental device consists of a triaxial cell of about 1700 kPa of maximum cell pressure, equipped with an internal load transducer and related to two pressure–volume controllers (GDS); the first one to control the confining pressure and the second one to measure the volume change of the sample. The CD test has been done on saturated samples, with three effective confining pressures of 150, 300 and 450 kPa respectively.

The saturation of the samples has been done in two steps: first, using de-aired water, under a confining pressure of 50 kPa and a pore pressure gradient of 20 kPa, between the bottom and the top of the sample; then, the back pressure and confining stress have been gradually elevated to 550 kPa and 600 kPa respectively. The corresponding Skempton's parameter B was about 0.97 referring to saturated (Goual et al. 2012; Taïbi 1994; Gueddouda et al. 2011).

The axial strain has been measured using an external displacement sensor and the volume change of the sample has been assessed using a volume-pressure controller, maintaining a constant pore pressure. The deviatoric loading has also been performed at a rate of 0.05 mm per minute, using an electromechanical press, where low rate prevents the appearance of excess pore pressure within the sample. The triaxial test is controlled via a data acquisition system connected to a computer.

3 Results and Discussion

3.1 Physico-Mechanical Characteristics

3.1.1 Grading Curves

The particle size distribution of the tuff (T), the dune sand (DS) and the different T-DS mixtures are presented in the Fig. 1. We note that the percentage of fine elements (< 80 μm) decreases with the addition of sand; when the sand represents 50% of the mixture, the fine elements' percentage is 15%, which presents a reduction of about 60% compared to the case of pure tuff. According to SRT, CTTP and GTR standards, adding 15% of sand satisfies the recommendation for the fine elements (Table 3). Our findings are in agreement with those reported by Morsli (2007) and Cherrak et al. (2015).
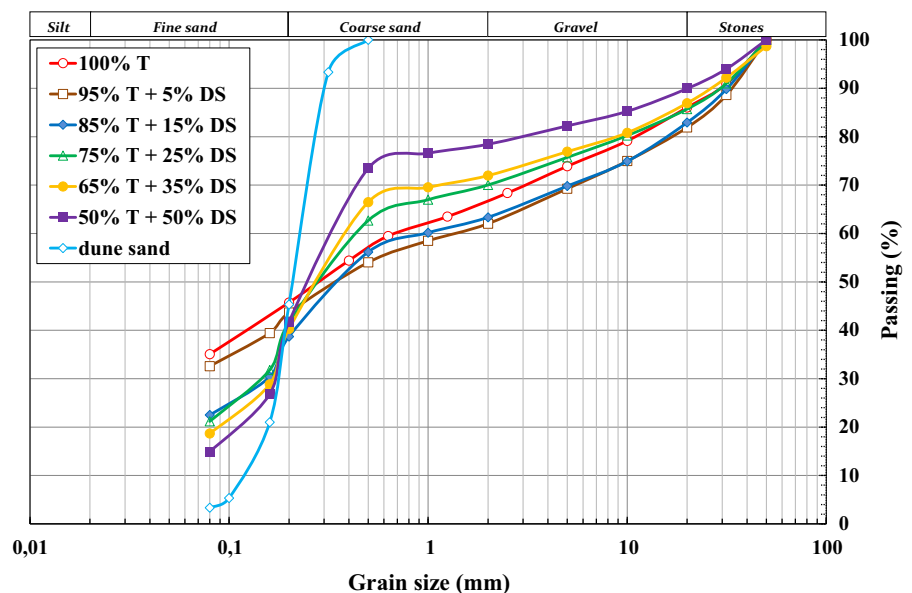

Fig. 1 Grading curves of T-DS mixtures

Table 3 Mechanical characteristics of different mixtures

	Mixtures						
	100%T + 0%DS	95%T + 5%DS	85%T + 15%DS	75%T + 25%DS	65%T + 35%DS	50%T + 50%DS	0%T + 100%DS
UCS of dried samples (MPa)	**2**	1.84	1.72	1.71	1.5	0.55	00
UCS of wet samples (MPa)	0.31	0.33	0.35	0.38	**0.39**	0.32	00
Initial suction (MPa)	0.15	0.20	0.26	0.28	**0.33**	0.29	0.06
Effective cohesion c' (kPa)	102	100	128	**165**	159	141	00
Effective internal friction angle φ' (°)	36.6	36.9	36.9	36.8	**37.5**	36.7	33.9
Maximum deviatoric stress q_{max} (MPa)　150 kPa	0.82	0.85	0.96	1.06	**1.11**	1.01	0.4
300 kPa	1.29	1.25	1.37	1.55	**1.56**	1.48	0.78
450 kPa	1.74	1.75	1.86	2	**2.04**	1.9	1.18
Secant modulus E_{50} (MPa)　150 kPa	0.37	0.35	0.37	**0.45**	0.42	0.34	0.34
300 kPa	0.5	0.51	0.53	0.66	**0.69**	0.53	0.57
450 kPa	0.74	0.71	0.74	**0.95**	0.89	0.86	0.74

The values in bold are the maximum values that help to choose the optimal formulation

3.1.2 Atterberg Limits

The T-DS mixtures have been analyzed to determine the effect of adding sand on the Atterberg limits of the tuff. The Atterberg limits decreased with the addition of sand. Likewise, the increase in sand content from 0 to 50% was accompanied by a decrease in the plasticity index, from 26 to 7%.

The grading curves of the mixtures proved that the Atterberg limits follow the variation of the fine particles content; as a result the workability increases (Baran et al. 2001; Mallela et al. 2004; Morsli 2007).

The Algerian and the French standards (SRT, CTTP and GTR), recommend to add an amount of sand more or equal to 25% (Table 3).

3.1.3 Compaction Characteristics and Bearing

The values of the grain density Gs measured for the tuff, dune sand and different mixtures, showed that Gs ranges between 2.68 and 2.7. Given this small variation, this value of Gs (2.7) is used for the calculation of the saturation curve of different mixtures. Adding sand moves the curves to the left while improving the optimal characteristics. This behaviour is similar to that of compacted materials at different energies (Holtz and Kovaks 1996).

The optimum water content decreased with the increase in the as sand content. In contrast, the maximum unit weight increased, to achieve a maximum value of about 1.96 g/cm³ for mixtures with 25% and 35% of sand content, then decreased to 1.91 g/cm³ while remaining higher than the dry unit weight of the tuff.

When replacing tuff by sand, the fine elements content decreased, which explains the decrease in water content. The shape and the size of sand grains has an impact on the rearrangement of the tuff particles, which decreases the void ratio, giving then higher soil density. However, beyond a certain percentage of sand (35%), there is an excess in sand particles to fill the voids, therefore void ratio increases, giving lower density. Beyond this percentage, the sand replaces the tuff and imposes its own characteristics.

After being compacted at MPO, the T-DS samples initially soaked or unsoaked have been subjected to the CBR tests. The results reveal that adding sand until 25% leads to a significant increase in the CBR value, for both soaked and unsoaked samples. A gain of about
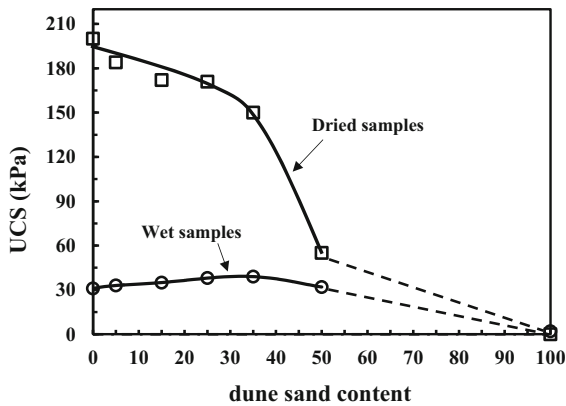
Fig. 2 UCS function of dune sand content

90% and 60% was recorded for unsoaked and soaked samples respectively. For mixtures with 50% of sand content, the CBR values decrease, while remaining higher than the CBR value of tuff alone. The soaked samples present CBR values lower than those of

unsoaked. This is due to the sensitivity of the tuff to the increase in moisture. Other authors (Goual et al. 2012; Cherrak et al. 2015; Daheur et al. 2012, 2015) have been obtained similar results. For example, Goual et al.(2012) reported that adding 50% of calcareous sand to the tuff leads to a decrease in the optimum water content from 11.4 to 9% and an increase in dry unit weight at MPO from 1.95 to 2.04 g/cm³. Regarding the CBR Index, the assays have been performed on soaked and unsoaked samples prepared at MPO. The results obtained revealed an optimal content of calcareous sand of 30% for soaked samples (a gain of 42% compared to pure tuff) and 40% for unsoaked samples (a gain of 47%).

Moreover, our results proved that, to obtain the best compaction characteristics, the sand content must be adjusted to a fraction between 25 and 35%.
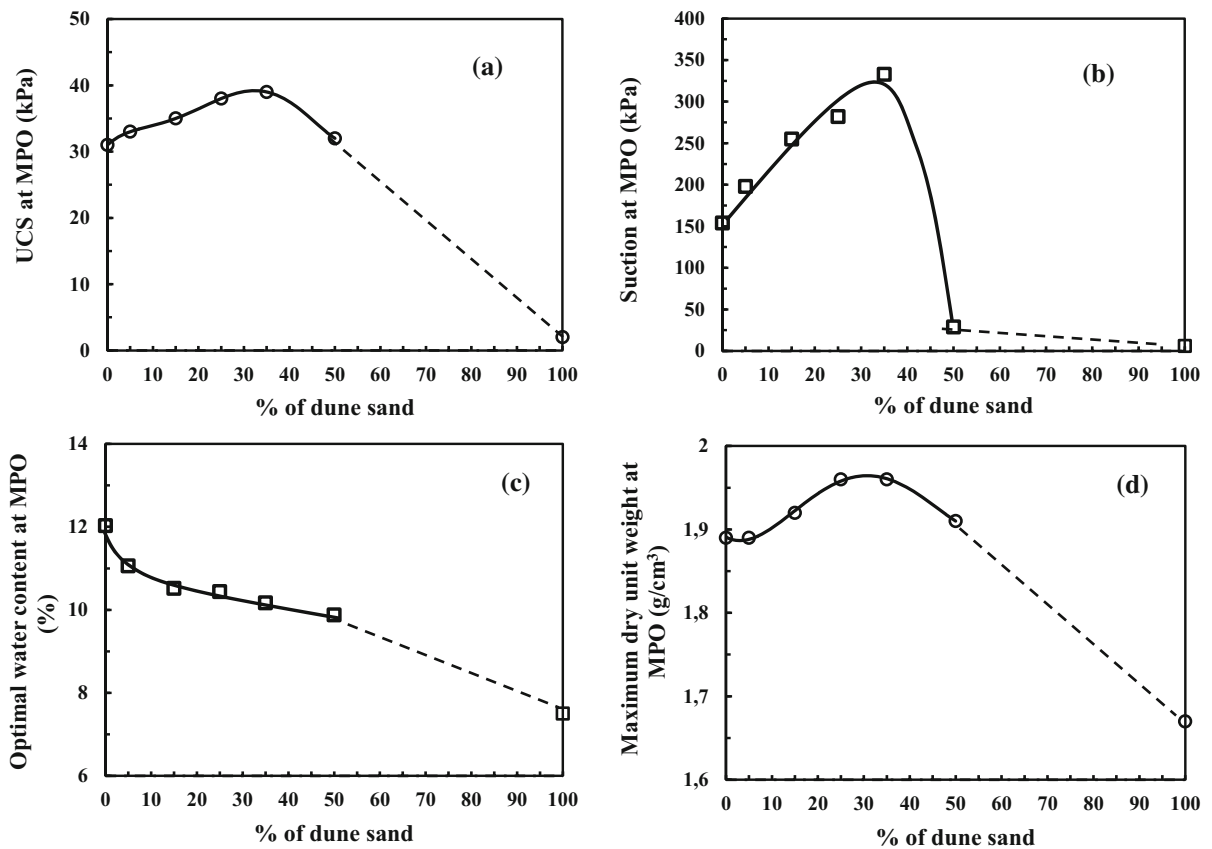

Fig. 3 Variation at MPO of **a** UCS, **b** suction, **c** water content and **d** maximum dry unit weight versus dune sand content
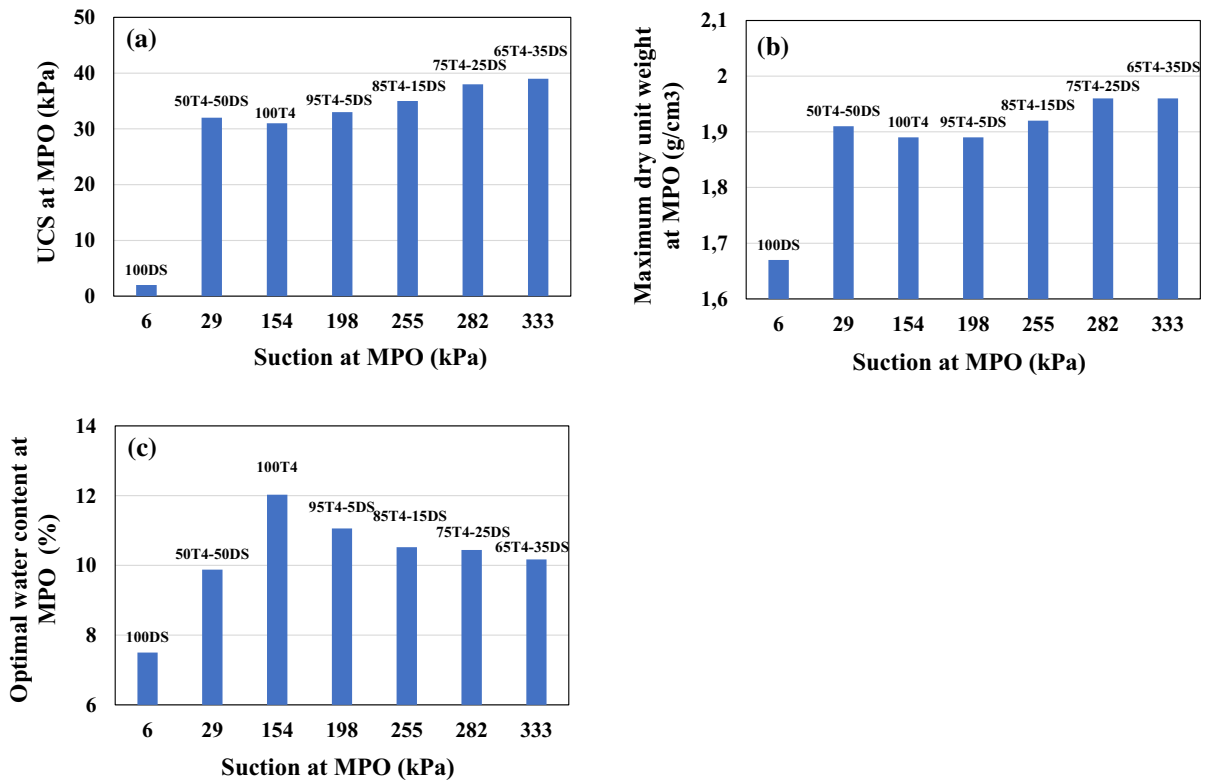
Fig. 4 Variation at MPO of **a** UCS, **b** maximum dry unit weight and **c** water content versus suction at MPO

3.2 Mechanical Behaviour

3.2.1 Unconfined Compressive Strength

The variation in the UCS, related to the sand content is presented in Fig. 2. Regardless of the sand content, the dried samples present higher UCS; the latter decreases with the sand content. It decreases slightly until 25% of sand content and lose 15% of its strength, compared to the tuff. The UCS drops rapidly from 150 kPa to 55 kPa for sand content between 35 and 50%. Furthermore, the samples with 100% of sand present a very weak value (around 2 kPa).

The UCS increases slightly with the percentage of sand added, in wet samples and reaches a maximum value for sand content of 35%. The maximum value corresponds to a strength gain of about 25%, compared to tuff. This increase can be explained by the capillary suction developed during the compaction.

The Fig. 3 presents the variation in UCS, suction at MPO, optimal water content and dry unit weight of wet samples, related sand content. We can notice that

UCS increases while suction and dry unit weight increase, and water content decreases. As well, the maximum value of UCS is reached for 35% of sand content, corresponding to a maximum suction and dry unit weight of about 333 kPa and 1.96 g/cm^3 respectively and optimum water content of about 10%. The UCS, the maximum dry unit weight and the suction increase proportionally with the sand content until an optimum value, and then they decrease. Otherwise, the sand content does not affect the water content, but has an important impact on the suction and the maximum dry unit weight, reflected by the UCS.

Our results prove clearly that beyond 35% of sand content, the amount of sand is in excess of what is needed to fill the voids of the compacted soil matrix. Consequently, there is no variation in the suction at MPO or in the UCS.

When the UCS, the maximum dry unit weight and the optimum water content are plotted versus the suction at MPO (Fig. 4), it can be noted that these parameters do not change in a monotonic way as a function of suction, i.e. the properties increase and
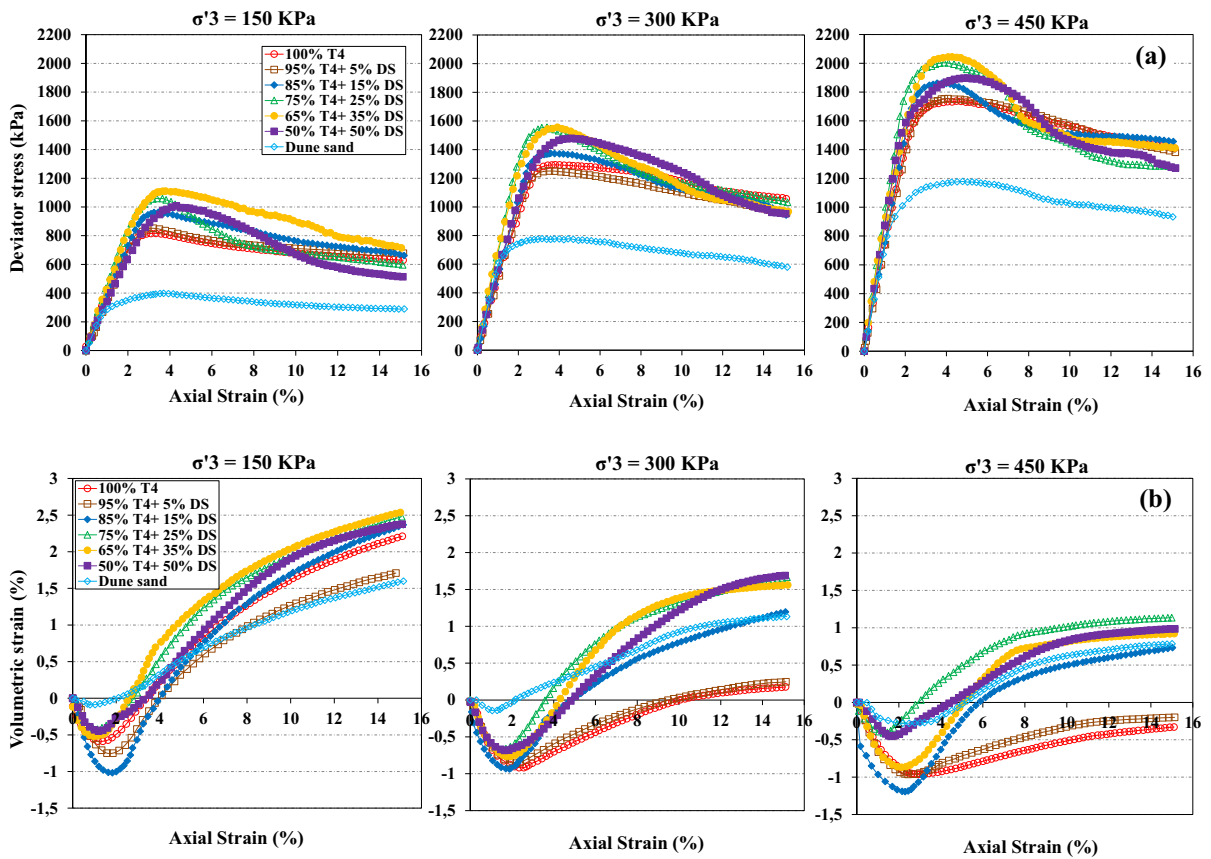
Fig. 5 Consolidated Drained Triaxial tests record under effective confining stresses 150, 300 and 450 kPa: **a** Stress–strain and **b** volume–strain

decrease while the suction increases. Which means that suction cannot explain the properties variation because of the differences in grading curves between different mixtures.

We noted also that the mixture consists of 65%T and 35%DS, present the maximum values of UCS, dry unit weight and suction at MPO.

These results revealed the positive effect of adding sand to improve the suction and the maximum dry unit weight; consequently the mechanical behaviour of the mixtures. They is also proved that the maximum mechanical strength is reached with an optimum sand content of 35%.

3.2.2 Consolidated Drained Triaxial Tests

The failure mode of the samples has been analysed; at the end of each test, where all samples present localized failure planes, inclined according to the

Mohr–Coulomb failure criterion. This confirms the homogeneity of the samples during the shear test (Amini and Hamidi 2014).

The Fig. 5a, b, present the deviatoric stress and the volume strain versus axial strain for T-DS mixtures at different effective confining stresses respectively. The maximum deviatoric strength increases with the confining pressure. Moreover, a typical behaviour of compacted soils was recorded, namely a linear increase of the deviatoric stress until reaching a peak at about 4% axial strain, and then a gradual decrease tending to a plateau of perfect plasticity. Again, the stiffness (strain–stress slope) of the material for the small strains increases with the confining stress. These results are in agreement with those reported by Ajorloo et al. (2012).

The sand content effect on the volumetric response depends on the confining stress (Fig. 5b). For the highest confining stress (450 kPa), mixtures with less
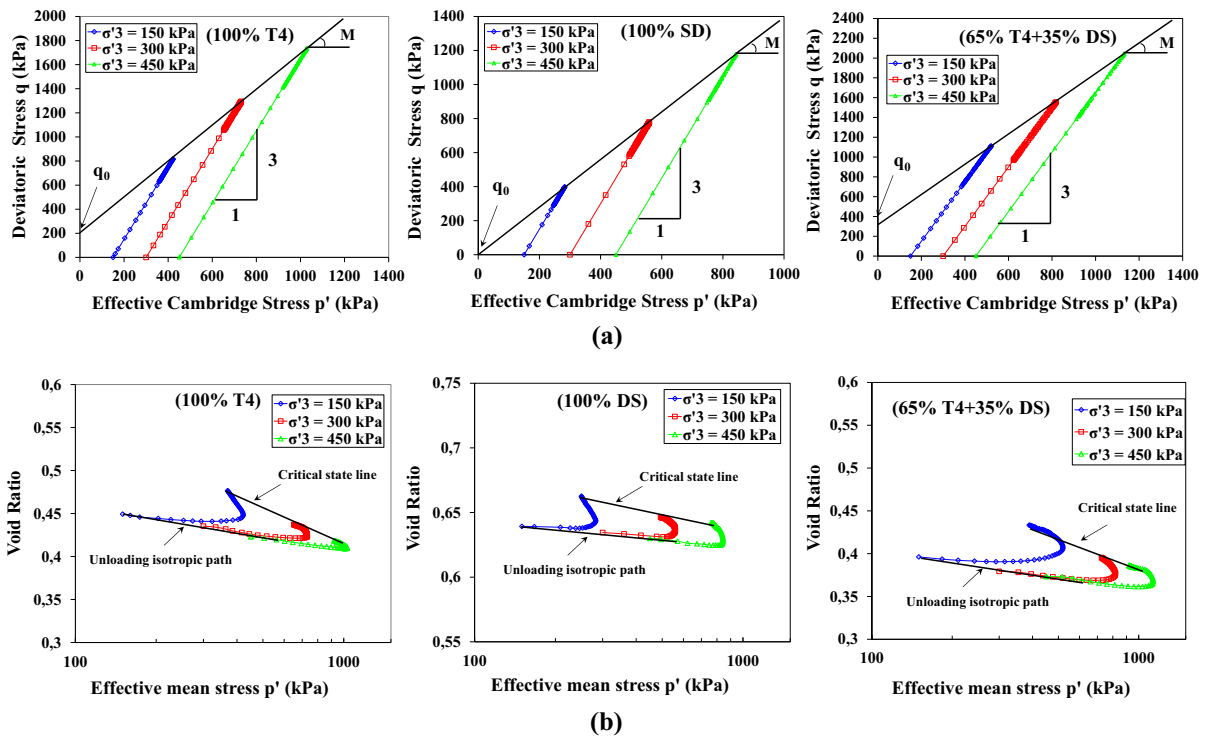
Fig. 6 Consolidated Drained Triaxial tests for natural dune sand (DS); tuff (T4) and optimal mixture (65%T4 + 35%DS) **a** p′–q stress paths and **b** log p′–e volume change

than 5% of sand content present a dominant compressive response, until high axial strains where it becomes slightly dilatant. In contrast, for lower confining stresses (150 and 300 kPa), all the samples present a small volumetric compression in the initial stage of shearing until 2% of axial strain, then show a strongly dilatant behaviour.

The Fig. 6 presents the stress paths in the plane [p ‘; q] for three materials: Dune sand (DS), Tuff (T) and

mixture with 35% of sand content (Fig. 6a) and the corresponding critical state planes [log p′;e] (Fig. 6b).

In the plane [p′; q], the slope line M represents the envelope of the maximum strength (strength peaks in the plane [ε_1; q] of Fig. 5). Note that this line intersects the q-axis with a value noted q_0. The slope M and the value q_0 are related to the friction angle φ' and to the cohesion C′ of the material using the following formula:

Table 4 Stress paths parameters of triaxial tests

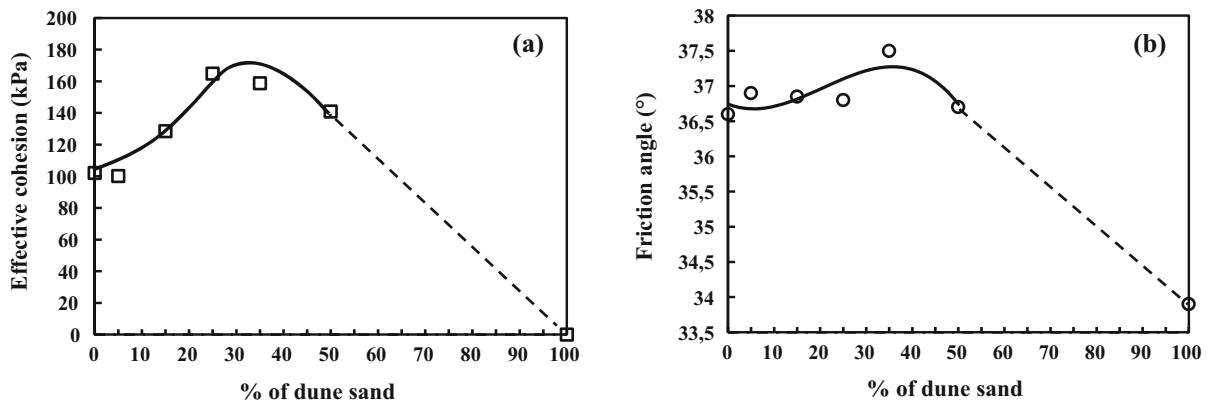| Mixtures	[p′, q] plane		Mohr–Coulomb parameters		Drucker-Prager parameters	
	M	q_0 (KPa)	$\varphi'(°)$	c′ (kPa)	α	κ
100% T4	1.49	204	36.7	102	0.287	117.92
95% T4 + 5% DS	1.50	200	36.9	100	0.289	115.47
85% T4 + 15% DS	1.50	256	36.9	128	0.289	147.8
75% T4 + 25% DS	1.50	330	36.9	165	0.289	190.52
65% T4 + 35% DS	1.53	317	37.6	159	0.294	183.02
50% T4 + 50% DS	1.49	282	36.7	141	0.287	162.81
100% DS	1.37	0	33.9	0	0.264	0

Fig. 7 Evolution of **a** Effective cohesion, **b** friction angle, versus dune sand content

$$\sin \varphi' = \frac{3M}{6 + M} \text{ and } C' = \frac{q_o(3 - \sin \varphi')}{6 \cos \varphi'}$$

In the [log p′; e] plane (Fig. 6b), the initial states of the different samples are located on the unloading isotropic path. The void ratio follows first the unloading isotropic path, called contractancy phase, then moves towards the critical state line, during its dilatancy phase. The Table 4 summarizes the stress paths parameters for all the mixtures. It is observed that the friction angle is not really affected by the addition of sand and ranges to an average value of about 37° (Fig. 7b). On the other hand, the effective cohesion increases significantly from 100 kPa

Fig. 8 Principle of determination of minimum strain of contractancy and of maximum strain of dilatancy

approximately, for the brute tuff, to 159 kPa for mixture with 35% of sand content (Fig. 7a). We note also that a maximum friction value of about 37.6° was recorded for this mixture. Though the samples with 100% of dune sand content are non-cohesive granular materials and they owe their resistance to the internal friction between particles ($\varphi' = 34°$).

These findings prove clearly that the Mohr–Coulomb parameters $\varphi'$and C' are reached with an optimum sand content of 35%.

These results have also been analyzed in terms of contractancy and dilatancy, by deducing the minimum volume strain (contractancy) and the maximum volume strain % (dilatancy) from [Axial strain; volume strain] plane (Fig. 8).
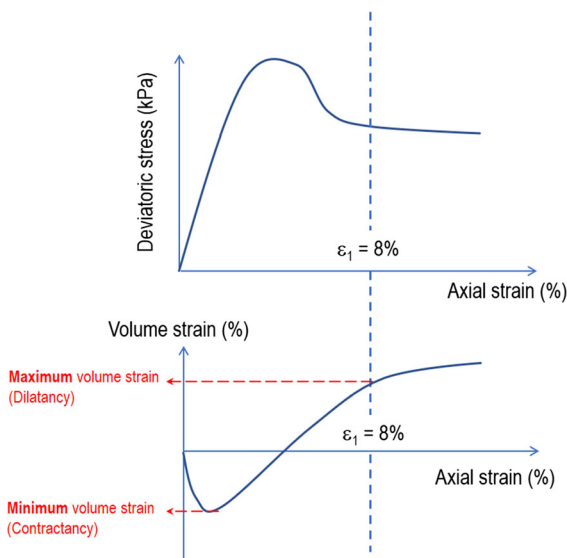
The minimum strain value corresponds to the phase change point (transition from contracting to dilatant behavior). While, the maximum value of the strain of the dilatancy was determined for an axial strain $\varepsilon_1 = 8\%$, corresponding to the beginning of the residual strength plateau in [Axial strain; deviatoric stress].

The Fig. 9 presents the variation, versus the sand content, of the initial void ratio (Fig. 9a), of the minimum volumetric strain (Fig. 9b) and of the maximum volumetric strain (Fig. 9c). When sand content increases from 0 to 35%, the maximum contractancy of the mixtures decreases and its dilatancy increases. Beyond 35%, these two parameters tend to stabilize. This result confirms the fact that adding sand to the tuff improves the density of the material.

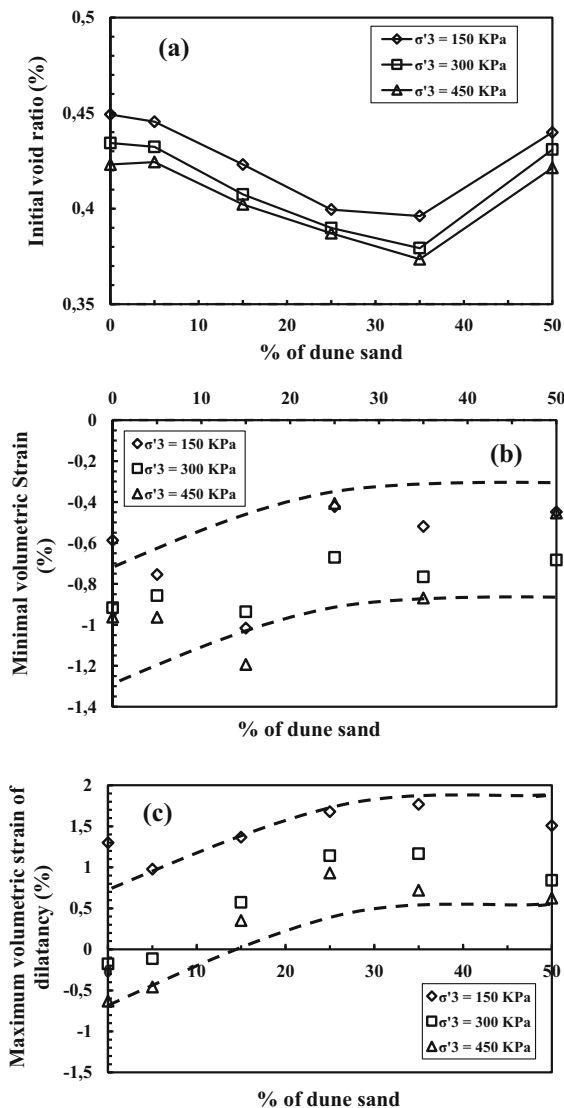The Fig. 10 present respectively the secant modulus E_{50} and the maximum deviatoric strength versus

Fig. 9 Variation, versus sand content, of **a** initial void ration; **b** minimum volumetric strain and **c** maximum volumetric strain

the sand content (a, b) and suction at MPO (c, d). E_{50} is defined as the secant modulus for a strain level ε_1 (50) corresponding to 50% of the maximum strength.

The Fig. 10a show that the E_{50} increases with the sand content until an optimal percentage ranging between 25 and 35%. For a defined sand percentage, the secant modulus increases linearly with the effective stress σ'_3. As well, the maximum strength varies similarly with the percentage of sand added (Fig. 10b).

3.3 Synthesis

The main properties of the T-DS mixtures are listed in the Table 3. The analysis of these results revealed that the addition of dune sand load varying from 25 to 35% allows obtaining a formulation that meets the targeted criteria for the road embankments engineering.

4 Conclusion

The present paper presents an experimental investigation on the mechanical behaviour of tuff-sand mixtures and the effect of the sand incorporation percentage. Therefore, the influence of dune sand on the geo-mechanical characteristics of a tuff originated from the province of Ouargla in Algeria has been analyzed. The notable results obtained are:

- Adding sand decreases the fine particles content and Atterberg limits of the mixtures.
- As the sand content increases, the optimum water content decreases whereas the maximum dry unit weight increases until achieving a maximum for sand content between 25 and 35%.
- An increase in the dry unit weight corresponding to a decrease in water content is an advantage regarding the lack of water in the arid regions such as the Sahara.
- CBR index reaches a maximum value for a sand content of 25%.
- Unconfined compressive strength and initial suction value of wet samples increase with the increase in sand content up to 35% where they reach a maximum value and then drop. Conversely, the UCS of dried samples decreases with the sand content.
- On triaxial path, the confining pressure and the sand content influence the stress–strain response. The increase in strength was significant until 35% of sand added.
- The effect of the sand incorporation percentage on the volumetric response depends first on the confining stress. For high confining pressure, the behaviour is dominantly compressive, although, it becomes slightly dilatant at high axial strain. Moreover, strongly dilatant behaviour was observed; for lower confining stresses. The small
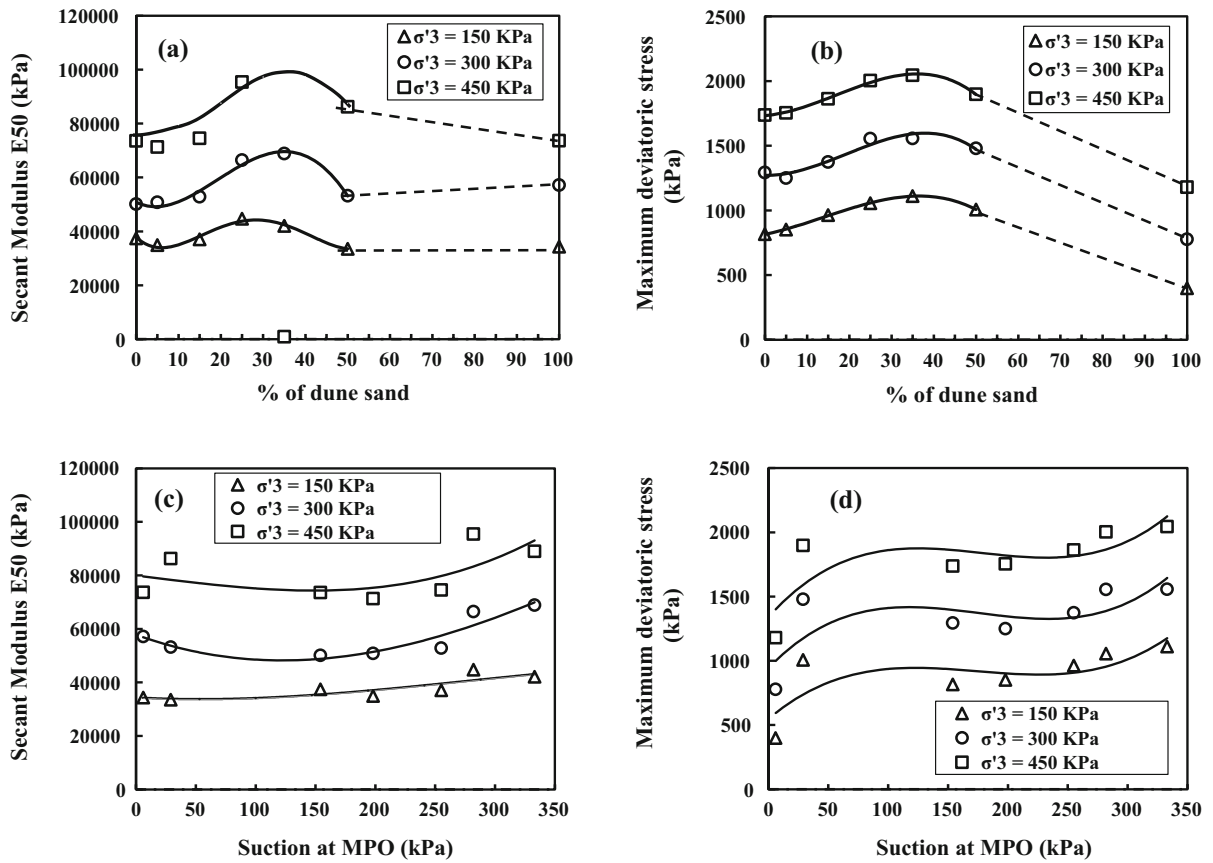
Fig. 10 Evolution of secant modulus and Maximum deviatoric stress, versus dune sand content and suction at MPO

volumetric compression occurred only during the initial stage of shearing.

- Incorporating sand improves significantly the effective cohesion, which reaches a maximum value for 25% of sand content. The friction angle remains almost unchanged.
- The secant modulus E_{50} and the maximum strength increase with the sand content up to an optimal percentage ranging between 25% and 35%.

The proportions of the constituent materials based on 65% tuff and 35% dune sand as chosen can be considered as the optimal formulation. As a result, it produces the best characteristics meeting the current standards. As a perspective, the next step is to study the behaviour of the chosen formulation and submitted to various hydro-mechanical loadings.

Considering the approach and the results obtained in this investigation, it can be noted that there is a real possibility of using local dune sand materials for the design of roads in arid regions, to meet economical and environmental constraints. As well as, the mechanical behaviour of the elaborated road material can be significantly improved.

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