Valorization of the Use of Calcareous Tuff and Dune Sand in Saharan Road Design

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Abstract: This research objective is to propose a co-valorization of powdered tuff, containing a slight amount of clay and dune sand, by mixing the two substances at different rates such as 0%, 5%, 15%, 25% and 35% of sand. The adapted criteria formulas are those recommended by the technical Saharan road. The results of the proposed study showed that “tuff-sand” mixtures are denser with a lower optimum water content modified proctor, the fine rate decreases together with the plasticity index, whereas the bearing index (CBR: California bearing ratio test) increases. The intrinsic characteristics, cohesion and sensitivity of mixtures with respect to compactness are almost identical to those of tuff without addition. The optimal adapted sand incorporation rate is estimated at 25% at 96% of compactness. Under these conditions, the amount of fines decreases from 40% to an acceptable level of 25% and the plasticity index from 16.2 to 12. The compaction water content decreases by 36% and the CBR (bearing index) increases by 30% and the compressive strength and sensitivity, according to compactness, of the elaborated material are almost identical to those of tuff without addition.

Key words: Tuff, dune sand, road construction, CBR, water content, consolidated drained triaxial test.

1. Introduction

Algerian Sahara area is about 2 million km². It consists of nearly 40% of desert mountains, 15% of desert plains and about 30% of dune sand, the rest being sebkhas and chotts, and covers about a third of the African continent [1]. Locally available materials are mainly crusting tuffs, crashed sand, granitic arena, silt, clay and dune sand. Conventional aggregate resources are virtually nonexistent [2-3]. However, for nearly half a century, thousands of kilometers of economic roads for region development have been successfully built, using mainly crusting tuffs. These alternative materials are extracted from limestone, gypsum or gypsum-limestone deposits. Calcareous crusts are located in the semi-arid regions (where only from 100 mm to 350 mm of rain per year is recorded), gypsum crusts are located in the hyper-arid areas (less than 100 mm of rain per year), whereas the

gypsum-calcareous crusts can be found within the intermediate zones. All these formations constitute the geographical area spreading from North to South Sahara [4-5].

The good performance of roads built from these tuffs can be attributed to the characteristics of these materials, favorable environmental conditions (soil quality support and rainfall conditions) [6], recommendations of the technical Saharan road and expertise of road technicians [7-10]. Research works have been conducted to better benefit from the advantages offered by these materials [11-15]. Their essential particularity comes from the cohesion derived from the reciprocal affinity of the powdered elements from limestone and gypsum, after compaction and drying. They also have the singular property to harden with age without treatment [16-17]. This curing can be explained by the dissolution of a part of the carbonated fines and gypsum in compaction water by a re-crystallization during the evaporation of the latter giving rise to local cemented

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links [18]. This same process is also behind the formation of crusts from which are extracted tuffs [5].

It is this hardening, also called self-stabilizing, which allowed the use of the crusting tuffs in road pavements, despite the geotechnical characteristics that deviate from the usual specifications for temperate countries. However, tuffs are too sensitive to water and energy compaction, indeed, hardening disappears almost entirely by imbibitions and performances drop significantly for slight decrease in compaction rate. Moreover, a high percentage of fines ($> 30\%$) causes, during the compacting process, a foliation phenomenon making the material unusable in road construction [19-22].

Although dune sand is available in abundance in southern Algeria, there remains a material that has very poor mechanical properties. It is characterized by a granular and mineralogical composition almost similar over the whole desert: 95% silica at least, 1%~2% limestone and traces of various oxides. The diameters of the coarser and the finer grained elements are about 0.5 mm and 0.04 mm, respectively. The uniformity coefficient (ratio of the sieve meshes size for which there are respectively 60% and 10% passing $C_u = D_{60}/D_{10}$) and the coefficient of curvature (ratio of sieve meshes size at 30%, 10 and 60% passing, defined by $C_c = D_{230}/D_{10}.D_{60}$) are of the order of 1.8 and 10, respectively. It is therefore very poorly graded sand. It contains substantially no traces of clay. It has a liquid limit (WL) of about 25 and a plastic limit which cannot be measured. The value of the sand equivalent is greater than 60%. The blue value is around 0.1. Cohesion is almost 0, the bearing index at the optimum values of the modified proctor test is very low [23]. All these characteristics make it difficult to use as a construction material without pre-treatment [24-25]. Its valorization has been the subject of several investigations such as: stabilization of clays, dune sand concrete formulation, mortar and high performance concrete [26-32].

In road construction, stability of dune sand can be

obtained by “blocking” the grains against each other, and the quality of this block is variable. Consideration may be given either to be a simple setting of the grains by incorporation of a finer substance (fly ash and paper mud) that fills the voids, or to a setting and stiffening by techniques such as “sand-paper mud-cement, sand-fly ash-cement and sand-fly ash-lime” or to a single stiffening by hydraulic setting (sand and hydraulic binder), or by thermal setting (sand-bitumen) [33-38]. A co-valorization of mixed material, having complementary characteristics, is also possible [39-40].

2. Characterization of Studied Materials

Both studied materials come from the region of southern Algeria: Béchar for tuff and Ouargla for dune sand. Geotechnical identification of tuffs as currently practiced in Algerian road laboratories is performed according to accepted classical geotechnical standards, however, with some modifications according to the recommendations of the Saharan Road techniques:

- The determination of the percentage of gypsum and/or limestone is performed on the particle size fraction smaller than 1 mm;
- Particle size distribution is performed on a sample that has been put to soak in a tank of water for 12 h to 24 h;
- A rough metal cup is recommended for determining the Atterberg limits.
- During compaction tests (proctor test), we do not reuse the same sample for different water content levels;
- The blue test aims to determine the fine activity and determine the presence of the clay. It is performed on the fraction 0~2 mm according to NF P 94-068. The result is the VB (blue vage), expressed as g of methylene blue absorbed by 100 g of material;
- The CBR (California bearing ratio) test is a punching shear. It is retained in the specifications of many countries [40]. It is performed according to the

procedure of the standard NF P 94-078. This test is used to define a bearing index I_{CBR} . Practically, for a given soil, the bearing index I_{CBR} is the greater of two values: pressure at 2.5 mm of sinking/0.7; pressure at 5 mm of sinking/1.05.

Cohesion is appreciated by simple compression test performed on samples prepared in cylinder moulds of 50 mm diameter and 100 mm height with materials having a granularity 0~5 mm. Compaction is done statically using a compressive bearing press with

a speed of 1.25 mm/min at different compactness values, at the optimum water content for the modified proctor test. The readings are recorded every 15 s.

The results of chemical, geotechnical and mechanical identification are summarized in Figs. 1, 2 and Table 1.

3. Methodology

In order to enhance the properties of the studied materials, a co-valorization of both particles at different rates has been conducted.

Fig. 1 Grading curves of dune sand and tuff.

Fig. 2 Proctor curves of dune sand and tuff.

Table 1 Physical and mechanical characteristics of tuff of Bechar and dune sand of Ouargla.

	Tuff of Bechar	Dune sand of Ouargla
Chemical composition		
Limestone CaCO_3 (%)	81.64	Traces
Silica SiO_2 (%)	17	86
Particle size distribution: NF: P 94-056 and NF: P61-057		
d/D	0/20	0.2/0.4
< 80 μm (%)	40	1.3
Coefficient of uniformity: C_u (%)	-	1.5
Coefficient of Hzen (curvature): C_z (%)	-	11
Coefficient of Los Angeles (NF 18-573): LA (%)	55	-
Atterberg limits: NF: 94-051		
Limits of liquidity : W_l	40	23
Limit of plasticity: W_p	23.8	-
Plasticity index: I_p	16.2	-
Sand equivalent (NF P 18-598): ES (%)	4.83	81.2
Blue value (NF P 94-068): VB	0.75	0.1
Compaction and bearing : NF P 94-093 et 078		
Optimum water content: W_{opt} (%)	11	9
Maximum dry density: γ_{opt}	1.98	1.74
Bearing index I_{CBR} after soaking (%) at 95% compactness	20	5
Compressive strength (MPa) at 95% compactness	13.9	0

The objective of the procedure is for better understanding the assessment of the geotechnical and mechanical characteristics of the “tuff-sand” mixtures. The judging criteria for the elaborated mixture are given by the order of priority [8]:

- a minimum amount of fines;
- a minimum plasticity;
- a maximum density;
- a maximum bearing capacity;
- a maximum strength.

The study will be conducted in the range (95% to 98%) of usual compactness used on site. As a reminder, the compactness is the ratio of the material density in place to the modified proctor maximum dry density.

Tests have been carried out on mixtures incorporating 0%, 5%, 15%, 25% and 35% of dune sand, respectively.

The percentage of fine, the sand equivalent, the methylene blue test value and plasticity index have been estimated for each incorporation rate of sand.

Modified proctor curves are plotted for each incorporation rate of sand and the proctor characteristics are identified.

The samples have then been prepared using the optimum water content modified proctor of each mixture but at different theoretical compactness rates, notably at 95%, 96%, 97% and 98%. The proctors values are determined for each incorporation rate of sand, considering an average of three specimens. The true compactness values are then evaluated for each specimen tested.

The experimental curves are plotted against true compactness of specimens. Tuff only and optimal mix of tuff with sand dune shall be subject to a consolidated drained triaxial test.

The analyses of the results and discussions are made on the basis of the curves deducted from experimental graphs.

The mechanical performances are analyzed according to the rate of incorporation rate of sand and

the compactness rate.

4. Experimental Results

4.1 Rate of Fines and Clay Content in Mixtures

The incorporation of dune sand has lowered the plasticity index, the percentage of fines, the sand equivalent and the blue value (Figs. 3a-3d). All these indices have been evolved in a way to promote the compaction of mixtures.

4.2 Ability of Mixtures to Compaction

Addition of dune sand moves the modified proctor curves to the left (Fig. 4) with an improvement of the optimal characteristics: reduction of water content and increase in dry density (Figs. 5 and 6). This behavior is similar to the classic behavior of materials compacted at different energies [41].

This phenomenon may be explained by the reduction of fines and their replacement by particles which, due to their shape and size, facilitate their movement by directing them in order to form a denser structure.

Beyond certain amount (25% in our case), dune sand no longer plays the role of lubricant and aims to replace the basic material by imposing its own characteristics. Eventually, the density should tend towards those of sand.

4.3 Bearing Index Evolution (I_{CBR})

Bearing index, according to compactness, presents a linearity in results. This linearity has been confirmed by trend curves of Fig. 7 and equations of Table 2.

The elaborated “sand dune-tuff” material is as sensitive as the tuff without additions at different compaction rates: a compactness drop from 98% to 95% results in a decrease in the bearing index of 38% or up to 40% with mixture containing 35% of sand. The incorporation of sand does not attenuate the close dependency between the bearing and the compaction rate.

Fig. 3 Evolution of the characteristics of the mixtures according to the rate of incorporation of sand: (a) evolution of the percentage of fines; (b) evolution of the sand equivalent; (c) evolution of the plasticity index; (d) change in the methylene blue test value.

Fig. 4 Influence of the addition of sand on modified proctor curves.

For influence of the incorporation rate of sand on the bearing index, to understand the evolution of the bearing index according to the incorporation rate of sand, curves have been plotted (Fig. 8) based on the results of Table 2.

It should be noted that, in general, the addition of sand improves the bearing index whatever the compactness. However, the shape of the curves is different from that of compression strength (Figs. 9 and 10).

Fig. 5 Variation of the compaction water content.

Fig. 6 Variation of maximum dry density according to the incorporation rate of sand.

Fig. 7 Evolution of bearing index of mixtures according to compactness.

Table 2 Equations of trends curves and bearing indices at different compactness rates.

Sand (%)	Equations of trends curves	Bearing index I_{CBR} at different compactness rates				$(I_{CBR98} - I_{CBR95})/I_{CBR98}$
		95%	96%	97%	98%	
0%	$I_{CBR} = 4.889C^* - 443.2$; $R^2 = 0.973$	21.25	26.14	31	35.92	41%
5%	$I_{CBR} = 4.613C^* - 415.3$; $R^2 = 0.987$	22.93	27.54	32.16	36.77	38%
15%	$I_{CBR} = 5.362C^* - 486.8$; $R^2 = 0.991$	22.59	27.95	33.31	38.67	41%
25%	$I_{CBR} = 4.694C^* - 418.1$; $R^2 = 0.990$	27.83	32.52	37.22	41.91	34%
35%	$I_{CBR} = 5.110C^* - 468.3$; $R^2 = 0.985$	17.15	22.26	27.37	32.48	47%

*: designed compactness rate.

For this test, the punching is done after imbibitions without previous drying: the hardening phenomenon does not occur. A new arrangement of the grains can justify this gain in bearing capacity.

Indeed, up to 25% of addition, the sand plays a particle size corrector role and/or plasticizer, reducing the amount of water compaction, improving the dry density and reducing the clay content and the fines percent which constitutes elements to the

improvement of the bearing mixtures (Fig. 8).

Beyond 25% of addition, the characteristics of the sand are beginning to emerge, leading to a significant decrease in bearing index.

4.4 Compressive Strength

4.4.1 Compressive Strength According to Compactness

All curves are upward: strength increases almost

Fig. 8 Influence of the incorporation rate of sand on the bearing index at different compactness rates.

Fig. 9 Influence of compactness on compressive strength.

Table 3 Equations of trends curves of strength at different compactness rates.

Sand (%)	Equations of trends curves	Compressive strength R_C at different compactness rates				$(R_{C98} - R_{C95})/R_{C98}$
		95%	96%	97%	98%	
0%	$R_C = 0.232C\% - 20.76; R^2 = 0.995$	1.28	1.51	1.74	1.98	35%
5%	$R_C = 0.223C\% - 19.52; R^2 = 0.983$	1.66	1.89	2.11	2.33	29%
15%	$R_C = 0.213C\% - 18.67; R^2 = 0.985$	1.56	1.78	2.00	2.20	29%
25%	$R_C = 0.206C\% - 18.13; R^2 = 0.985$	1.44	1.65	1.85	2.05	30%
35%	$R_C = 0.169C\% - 15.06; R^2 = 0.982$	1.00	1.16	1.33	1.50	33%

linearly with compactness for all studied incorporation rates of sand (Fig. 9 and Table 3).

The addition of sand did not reduce this dependence. A decrease of about 30% in the compressive strength has been observed for a decrease in compactness of 3% (Table 3).

4.4.2 Influence of the Amount of Sand Addition on Compressive Strength

All curves have the same shape (Fig. 10). They all pass through a maximum at 5% addition of sand. Up to an amount of 25% of sand incorporation, the

considered curves are all situated above the straight line representing the strength of tuff without addition monitored at 95% of compactness.

It should be noted that, at 5% of incorporation, the grains of sand do not seem to affect the particular property of tuff for developing cohesion after compaction and drying. However, they play a role of plasticizer and a water reducing admixture: the compaction optimum water content is less than that of the tuff without addition, i.e.: $w_{opm}(\text{tuff sand} + 5\%) = w_{opm}(\text{tuff without addition}) - 2\%$. In fact, this amount

of water is corresponding to the optimum water content which develops the maximum cohesion of the material [18]. This situation has been repeated at different compactness rates leading to a strength variation between 1.7 MPa and 2.33 MPa. Beyond 5%, the compaction water content decreases and becomes insufficient to ensure the dissolution of part of the carbonated fines necessary for the development of local cemented links which lead to a gradual decrease of the strength.

When the rate of sand reaches significant values (> 25%), the decrease in compaction water content and the reduction of carbonate fines replaced by dune sand particles combine to contribute towards significantly reducing the cohesion of mixtures [13, 16, 21].

4.5 Triaxial Test

We conducted a consolidated drained triaxial test

“CD” because, for pavement, material is the static long-term behavior that is most important. Indeed, the loads applied in permanence produce consolidation and water drainage is required for the durability of roads. For a more realistic representation of this, consolidated drained test best reflects reality. In these conditions, the effective stresses are equal to the total stress. Consolidation is under hydrostatic pressure ($\sigma_1 = \sigma_2 = \sigma_3$) for each specimen, and the stress σ_3 which was used for consolidation will be kept constant during loading to failure.

The specimens destined for the triaxial test are made with tuff granularity 0/5 mm. These are cylindrical samples of 5 cm in diameter and 10 cm in height. They were statically compacted under optimal conditions (γ_d, w_{opt}) under the hydrostatic pressures at 1, 2 and 3 bars. This compaction is achieved by a press of a CBR type traveling speed equal to 1.27 mm/min.

Fig. 10 Influence of sand addition rate on compressive strength at different compactness rates.

Fig. 11 Stress-strain curves: (a) tuff of Bechar; (b) tuff of Bechar + 25% of dune sand.

Fig. 11 shows the curves “stress-strain” at different lateral stresses (σ_3) only tuff of Bechar and mixed with 25% sand dune Ouargla.

Studying these curves shear, we notice a nonlinear elastic deformation and plastic deformation. So we can assign an elastoplastic behavior in the tuff. The triaxial test allows us to determine the shear strength which is expressed in terms of cohesion C , friction angle ϕ and the normal stress σ to the fracture surface by Coulomb’s law: τ (shear strength) = $C + \sigma \tan \phi$. The results of C and ϕ obtained for only tuff and tuff with 25% of dune sand are summarized in Table 4. There are also values of conventional materials used to make comparisons.

Comparing intrinsic characteristics of our samples (tuff and tuff + 25% sand dune) with constants other road conventional materials, we deduced that:

- The internal friction angles of our samples are slightly lower than those of other materials;
- The cohesions of our two samples are much higher compared to other materials. This strong

cohesion is explained by the presence of a significant percentage of fines in the tuff. This specificity provides our base material to withstand higher loads in the case of low stress, and this justifies the good performance of pavements built in tuff low and medium traffic;

- As regards the effect of the addition of sand dune on the intrinsic characteristics of the base material, it was observed an increase of the friction angle of 1.5° and a decrease in cohesion of 0.3 bars. It was predictable that the sand has no cohesion and with an angle of friction greater than that of other materials.

4.6 Recapitulation of the Main Characteristics of the Mixtures

The main characteristics are listed in Table 5.

From the analysis of the obtained results, it should be noted that the most appropriate formula is that containing an amount of 30% of sand at the condition to reach a compactness of 98%.

Table 4 Shear properties of tuff, tuff + 25% sand dune and conventional materials.

	Tuff	Tuff + 25% dune sand	Crushed grave	Corrected grave	Rolled grave
C (bars)	1.3	1	0.68	0.20	0.16
ϕ (degree)	34.69	36.25	53	47	45.5

Table 5 Geotechnical and mechanical characteristics of different mixtures.

Incorporation rate of sand		0% (tuff)	5%	15%	25%	35%	100% (sand)	TRS^*
Optimum dry density		1.98	2.00	2.01	2.10	2.00	1.74	> 1.70
Optimum water content (%)		11	9	8	7.5	7.5	9	-
Fines content (%)		40	38	30	25	20	0	<30%
Sand equivalent (%)		4.83	5	6	12	24	81.2	-
MBT (methylene blue test) value		0.75	0.74	0.73	0.70	0.68	0.1	-
Plasticity index (%)		16.2	15	14	12	9.5	/	<13
Compressive strength R_C at different compactness rates (MPa)	95%	1.28	1.66	1.55	1.44	1	0	> 1.50
	96%	1.51	1.89	1.78	1.65	1.16	0	
	97%	1.74	2.11	2.00	1.85	1.33	0	
	98%	1.98	2.33	2.20	2.05	1.50	0	
Bearing index I_{CBR} at different compactness rates	95%	21.25	22.89	22.90	27.87	17.15	-	-
	96%	26.1	27.6	27.95	32.5	22.3	-	
	97%	31	32.16	33.31	37.22	27.37	5	
	98%	35.92	36.6	38.67	41.91	32.48	-	

*Thresholds imposed by the TRS .

However, at 25% of addition and for a reasonable compactness of 96%, the formula may also be acceptable, where the values of the experimental results are conformed to thresholds imposed by the TRS (Technical Saharan Road), given in the last column of Table 5. Under these conditions, the amount of fines goes from 40% to a reasonable content of 25% and the plasticity index from 16.2 to 12. Whereas, the compaction water content decreases by 36% and the bearing index increases by 30%. The intrinsic characteristics (C , ϕ), compressive strength and sensitivity of the elaborated material according to compactness are almost identical to those of tuff with no sand incorporation.

5. Conclusions

The co-valorization based on a simple mixture of dune sand and a calcareous tuff matches with a basis principle in road engineering which consists of using a maximum of local materials.

The incorporation of dune sand improves the density and bearing capacity of mixtures and these characteristics remain however dependent on the compactness.

The optimum proportioning material mix consists of 75% of tuff and 25% of dune sand for a compactness of 96%.

This mix content may be changed to 70% of tuff and 30% of dune sand provided to ensure compaction of the elaborated material that guarantees up to 98% of modified proctor density.

An adapted stabilization of the elaborated material tuff-dune sand may allow increasing sand content in the mixture.

This study could be extended to other types of tuffs in order to identify factors influencing the optimal rate of incorporation of dune sand.

The material placing and the long-term behavior of the tuff-dune sand mixture must be investigated in order to elaborate a procedure standard.

The stabilization technique by incorporating dune

sand opens perspectives that will enhance local materials in areas without conventional materials.

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