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ORIGINAL PAPER

Co-valorisation of Local Materials Tuffs and Dune Sands in Construction of Roads

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Abstract The main objective of this study is to enhance the performances of local materials in order to be used in road construction sector. To enhance the performances of this local materials, the strategy adopted is to combine the beneficial effects of mixing different materials and treatment using binders. The materials used in this study are tuffs and dune sands. Hence the present work is also a contribution to the co-valorisation of local materials in arid region of the south of Algeria. According to the results obtained, it is shown that the tuffs of the Saharan regions are suitable for the use of Saharan pavements, particularly in base layers and foundations. The incorporation of dune sand up to 20% improves the mechanical performance. The binders treatment (cement, lime and cement/lime) have induced a further improvement in bearing capacity and compressive strength as well as tensile strength. With these improvement, the materials could be used in roads with heavy and important traffic.

Keywords Tuffs · Dune sands · Saharan roads · Co-valorisation

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1 Introduction

In the developing countries, the road remains the vector of economic development in the sense that it allows the opening up of whole regions and the integration of the whole territory in the economic development of a country.

In Algeria, with an area of more than 2.3 million km^2, the roads and motorways network extends over 120,000 km (Sebaa 2006). At the national level, this network accounts for more than 90% of the volume of trade.

Due to the distribution of population density and the vastness of the territory, the density of the road network is greater in the north of the country than in the South.

To open up the southern regions and promote trade with neighbouring African countries to the south, a road network development program has been running for several years. The development of this ambitious program sometimes runs up against the lack of standard materials (which meet national and international standards in terms of physical and mechanical properties) for the execution of roadworks with heavy and dense traffic.

In this context, the use of local materials to build the roads network becomes an inescapable necessity to carry out the development of these programs.

Among the materials available in the south of Algeria, limestone encrustation tuffs cover an area of approximately 300,000 km^2 (Colombier 1988). They have been used since the 1950s in the construction of thousands of kilometres of roads in the form of substitution aggregates. After the construction of more than 2200 km of road in the desert, a Saharan Road Technique (SRT) was developed (Fenzy 1966, 1970). Since then, work has been done on these materials and specifications have been proposed (CTTP 2001; Struillou and Alloul 1984).

According to the studies carried out on the tuffs, one realizes that they have geotechnical characteristics which can be variable. The latter, according to the proportion of fine elements and LA values are more or less accepted for use in roadworks especially in roads subject to dense and heavy traffic (Fumet 1959; Peltier 1959; Alloul 1981; Ben-Dhia 1983; Struillou and Alloul 1984; Ben-Dhia et al. 1984; Boukezzi 1997; Colombier 1988; Hachichi et al. 2000; Améraoui 2002; Goual et al. 2005a, b; Morsli et al. 2005, 2007). Moreover, in the context of a heavy and dense traffic, in a lot of situation the measured characteristics on tuffs are not sufficient to insure an economical design and durability.

The main objective of this study is to enhance the performances of local materials in order to be used in road construction sector with heavy and dense traffic. To enhance the performances of this local materials, the strategy used is to combine the beneficial effects of mixing different materials and the treatment using different binders (Hamrouni 1975; Tagle 1976; Colombier 1988; Hachichi et al. 2001; Morsli et al. 2005, 2007; Daheur et al. 2012, 2019; Cherrak et al. 2015; Smaida et al. 2019). The co-valorisation of local materials will contributes to sustainable development approach by: minimizing the transport of materials, preserving noble materials, reducing CO_2 footprint and enhancing the regional economic development through the establishment of a co-valorisation industry. To give a general character to this study, a comparative study undertaken on materials taken from the three major Saharan cities (distant by few hundreds of kilometres) is also conducted.

2 Studied Materials and Experimental Program

The materials used in this study are primarily tuffs and dune sands from three major regions of southern Algeria (Ouargla, El Goléa, and Adrar). The location of materials quarries is shown in Fig. 1. The three regions are in arid Saharan areas, where the average annual rainfall is very low (Table 1). For wider coverage of the study area, as a comparison, the results of tests conducted on Laghouat tuffs (Goual 2012) and Béchar tuffs (Cherrak et al. 2015) are also discussed. It is to note that the five sites discussed in the present study cover an area of more than 120,000 km^2.

The experimental program set up in this study consists of physical properties identification tests such as the particle size distribution of the materials, the methylene blue value and the consistency limits for the tuffs. For dune sands, the sand equivalent is also measured on the three dune sands studied.

With regard to the mechanical behaviour of the tuffs studied, due to the nature of the materials and the valorisation targeted (road construction), the choice was made to evaluate the resistance of the materials through the Los Angeles tests. A specific study to assess the bearing capacity of the materials with different water content is also undertaken through the Immediate Californian Bearing Ratio measurement test (I-CBR).

To design road materials based on tuffs and dune sands, several mixes with different rates of tuffs and

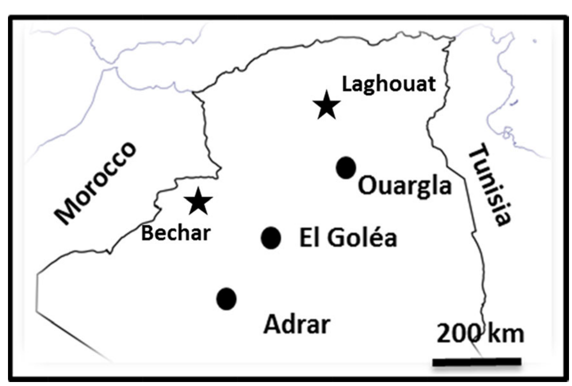

Fig. 1 Location of the studied materials

Table 1 Characteristics of studied regions

Region	El-Goléa	Ouargla	Adrar
Distance from Algiers (km)	870	750	1410
Climate zone	IV		
Hygrometry (mm/year)	H < 100		

dune sand have been studied. These mixes were characterized in terms of the evolution of the physical properties with the substitution rates and also the compaction behaviour and the bearing capacity. To enhance the mechanical performances of the mixes, the effects of treatment, with cement, with lime and with a combination of cement and lime is undertaken.

3 Results and Analysis

3.1 Raw Materials Characterization

The particle size analysis for the three samples of tuffs and the dune sands is carried out in wet condition according to the standard NF EN 933-1 (2012). For particles smaller than 80 µm, a hydrometer analysis is carried out (NF EN ISO 17892-4 2018). Figures 2 and 3 show the grain size curves of the studied materials. In Fig. 2, the grain size curves of the tuffs studied are compared to the Saharan spindle (Fenzy 1966).

From this analysis, it can be concluded that the three tuffs studied have spreading particle size distribution curves. The maximum diameter of aggregates (D_{max}) is 31.5 mm with a sandy fraction (< 2 mm) ranging from 30 to 66%. The percentage of fine elements (<80 µm) varies between 16 and 45%. The curve of the Ouargla tuffs fits better in the Saharan spindle (Fenzy 1966), the two other tuffs studied (Adrar and El-Goléa region) present grain size curves which lie above the Saharan spindle. They belong to the family III tuffs: materials with high amount of fine particles. The tuffs of El-Goléa and Adrar contains an amount of elements lower than 80 µm exceeding the threshold recommended by the guide in use for roads construction (CTTP 2001) and the Saharan Road Technique (SRT).

In Table 2, the various parameters deduced from the grain size curves of the three studied tuffs, as well as the thresholds recommended by the Saharan Road Technology (SRT) and the technical recommendation

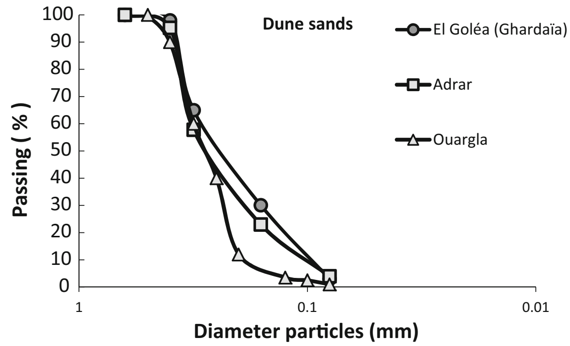

Fig. 3 Particle size distribution curves of dune sands (Adrar–El Goléa–Ouargla)

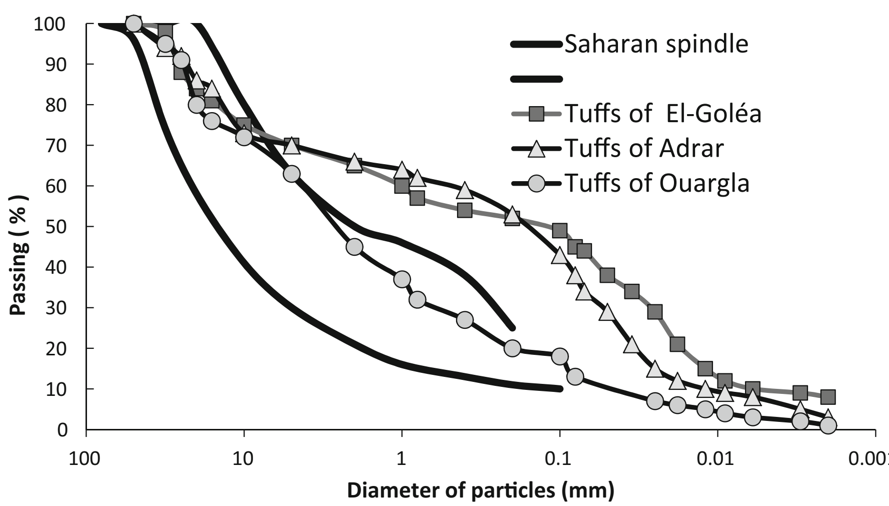

Fig. 2 Particle size distribution curves of the tuffs studied compared to the Saharan spindle (Fenzy 1966)

Table 2 Test results on the studied tuffs

Sample	Tuffs in the region of					Recommended thresholds	
	El Goléa	Ouargla	Adrar	Béchar	Laghouat	CTTP	SRT
0/D	31.5	31.5	31.5	20	31.5	20–40	–
%< 2 mm	65	30	66	65	70	–	–
%< 0.4 mm	54	27	59	54	58	36–52	–
%< 80 µm	45	16	38	40	32	22–30	< 30
D60 (mm)	1.0	0.4	0.65	1.5	0.6	–	–
D30 (mm)	0.027	0.6	0.05	0.75	0.08	–	–
D10 (mm)	0.006	0.036	0.013	40	0.009	–	–
D60/D10	166.7	11.11	50	23.8	67	–	–
$(D30)^2/(D10 * D60)$	0.12	25	0.29	16.2	1.2	–	–
MB(0/D)	0.37	0.14	0.39	55	0.5	–	–
W_L (%)	28.29	23	30.19	11	33	< 40	–
W_P (%)	17.92	N.M	19.08	19.8	22	–	–
IP (%)	10.37	–	11.11	20	11	< 15	< 13
(16/31.5)	51	73	66		52		
W_{opt} (%)	11.8	9.5	9.7		11.3		
γ_{dOPM} (KN/m^3)	19.2	19.2	20.2		19.5		
I-CBR	20	19	27.5		24		

for roads construction (CTTP 2001) are reported. For comparison, results on Laghouat tuffs on the north of the study sites and Béchar tuffs on the west of the study sites are also reported in Table 2. It appears from the results in Table 2 a good similarity between the tuffs of El Goléa and Adrar with those of Béchar and Laghouat.

The methylene blue test is carried out in accordance with standard NF EN 933-9+A1 (2013). The results of the tests are reported in Table 2. It appears that all the measured values are less than 0.5 or even 0.2. According to Colombier classification system for crust-tuffs sands (Colombier 1988), we can conclude that the samples studied are: slightly polluted for Adrar and El-Goléa tuffs, and clean for Ouargla tuffs (Table 3). Similarly, for indicative purposes, the values of Béchar and Laghouat tuffs are reported. Even if overall the measured values remain low, it appears that the values recorded on the Tuffs of Béchar and Laghouat are higher.

Table 3 Degree of pollution according to the value of methylene blue (MB) (Colombier 1988)

MB	Degree of pollution
< 0.2	Clean material
0.2 < MB < 0.5	Slightly polluted material
0.5 < MB < 1	Polluted material
MB > 1	Very polluted material

The quality of the fine particles can also be characterized by consistency tests such as the Atterberg limits (NF P94-051 1993). In Table 2, the results of the Atterberg limits for the three tuffs studied are presented. The results of the consistency limits show that Adrar and El-Goléa tuffs have some plasticity; this coincides with the results of the grain size analysis where we have seen that the samples of the studied tuffs have a percentage of fine particles (< 80 µm) of 38% for the Adrar tuffs and 45% for the El-Goléa tuffs. A comparison with the results of Béchar and Laghouat tuffs shows quite similar values in terms of plasticity index. However, as for the methylene blue values, the liquid limits of the two tuffs are higher than those of the tuffs studied in this work. The plastic limit for Ouargla tuffs was not possible to be measured with the used method. The values of the LA coefficient measured on the particle size class 16/31.5 for the tuffs studied are reported in Table 2. The test is undertaken according to test standard NF EN 1097-2 (2010). We notice that the LA coefficient values of the three studied stuffs exceed 40%. According to the Los Angeles results, it can be deduced that the tuffs of the three regions studied are very friable materials (LCPC-SETRA 1992). They fall into the category of pulverulent tuffs. The values measured on the tufts of Béchar and Laghouat, even if the values seem lower than that measured on the studied tuffs in this work, leads in terms of friability to the same conclusion.

To evaluate the compaction behaviour of the three studied tuffs, Modified Proctor compaction tests were carried out (NF EN 13286-2 2010). In Fig. 4, the Proctor curves for the three materials studied are presented. The existence of a non-negligible proportion of fine particles (< 80 µm) in the materials, combined with the sensitivity of the materials to the presence of water makes it possible to explain the shape of the Proctor curves (bell form curve). The optimum water content is quite high compared to the usual road materials.

In terms of water content and dry density at the optimum, the values measured on the curves of Fig. 4 are reported in Table 2. Similarly, a comparison of the values measured in this study with those measured on the Tuffs of Béchar and Laghouat shows comparable results. This similarity can also be identified on the basis of the I-CBRs (NF EN 13286-47 2012).

For dune sands, particle size analysis for the three sands is carried out by the dry method according to the test standard NF EN 933-1 (2012). The results are shown in Fig. 3. The shape of the particle size distribution curves reveals a relatively steep slope which characterizes materials with narrow granulometry and poor gradation. The diameter of the largest elements for sands does not exceed 0.4 mm. These dune sands contain almost no fine elements (4% for dune sands of Adrar < 80 µm). Since fine particle in dune sands are almost absent, measured MB values are almost nil and the values of the sand equivalent (SE) are also very high as shown in Table 4. The (SE) value is measured according to test standard NF EN 933-8+A1 (2015).

Table 4 Sand equivalent (SE) and methylene blue value (MB) for dune sands

Origin of dune sands	SE (%)	MB
Adrar	85	0.03
Ouargla	81	0.02
El Goléa	75	0.02

3.2 Design of Road Materials Composed of Tuffs and Dune Sands

The geotechnical characteristics of the three tuffs studied are low in terms of bearing capacity for use in roadworks in a base layer. For this purpose, an improvement of these characteristics by adding dune sands is considered in the first part of the study. To design road materials based on tuffs and dune sands, several mixes with different amount of both components have been tested. These mixes were

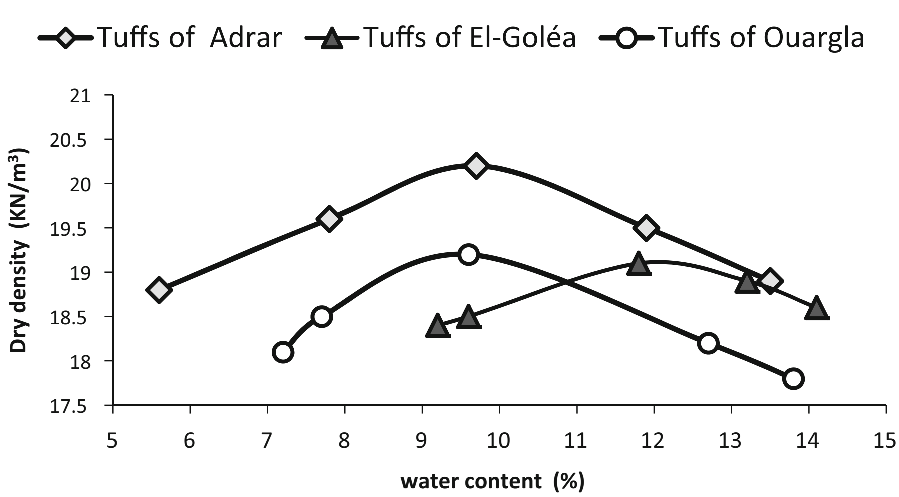

Fig. 4 Variation of dry density versus water content

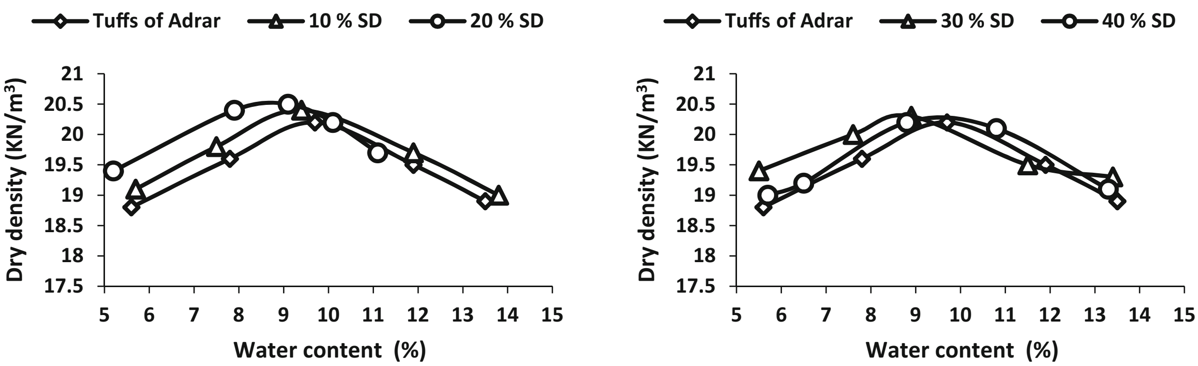

Fig. 5 Modified Proctor curves of the different tuffs/dune sands mixes of Adrar region

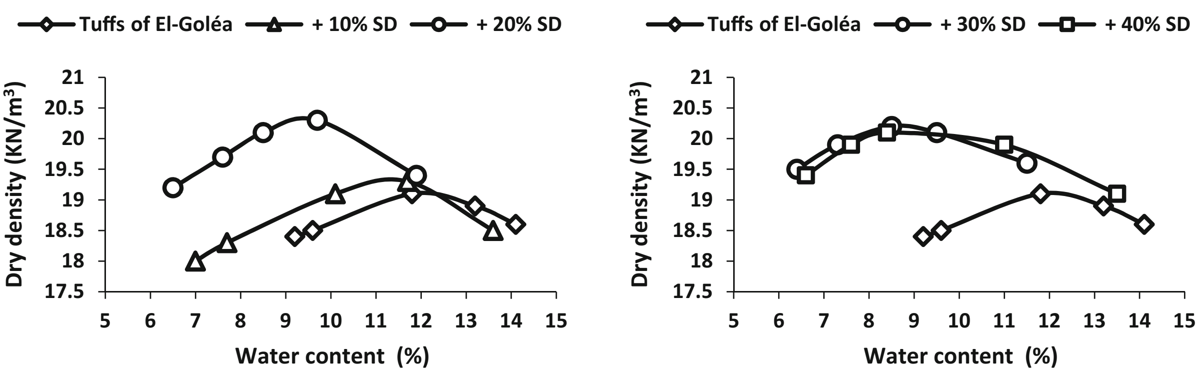

Fig. 6 Modified Proctor curves of the different tuffs/dune sands mixes of the El-Goléa region

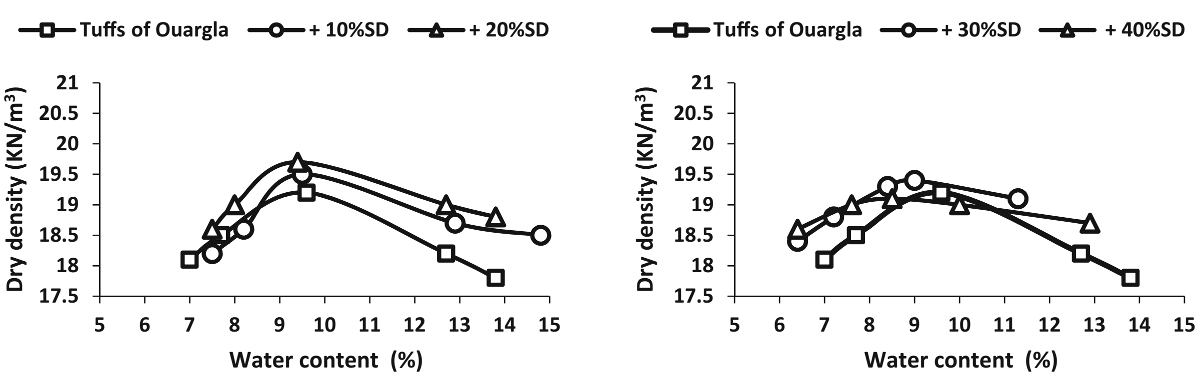

Fig. 7 Modified Proctor curves of the different tuffs/dune sands mixes of the Ouargla region

characterized in terms physical properties evolution with the amount of dune sand addition. Also the evolution of the compaction characteristics and the bearing capacity is also analysed.

The dune sands substitution rates used in this study are 10%, 20%, 30% and 40% of the studied tuffs.

In terms of Proctor curves for the different mixes studied, in Figs. 5, 6, and 7, the results obtained are reported. Examination of the different curves shows that the Proctor curves flatten with the increase in the percentage of dune sands in the mix. Proctor optimum moisture contents tend to shift to the left for increasing substitution rates with dune sands. Dry densities at the optimum Proctor tend to increase with the addition of sands. The measured values of Proctor optimum characteristics for all the mixes are reported in Table 5.

Table 5 Optimal Modified Proctor characteristics of different mixtures

Mixtures	100% tuffs	10% SD*	20% SD	30% SD	40% SD
Adrar					
W_{OPM} (%)	9.7	9.4	9.1	8.9	8.8
γ_{dOPM}	2.02	2.04	2.05	2.03	2.02
I-CBR	27.5	31	35	34	29
El Goléa					
W_{OPM} (%)	11.8	11.5	9.7	8.5	8.4
γ_{dOPM}	1.91	1.93	2.03	2.02	2.01
I-CBR	20	24	28	32	29
Ouargla					
W_{OPM} (%)	9.6	9.5	9.4	9.0	8.5
γ_{dOPM}	1.92	1.95	1.97	1.94	1.91
I-CBR	19	25	30	28	26

* Dune sand

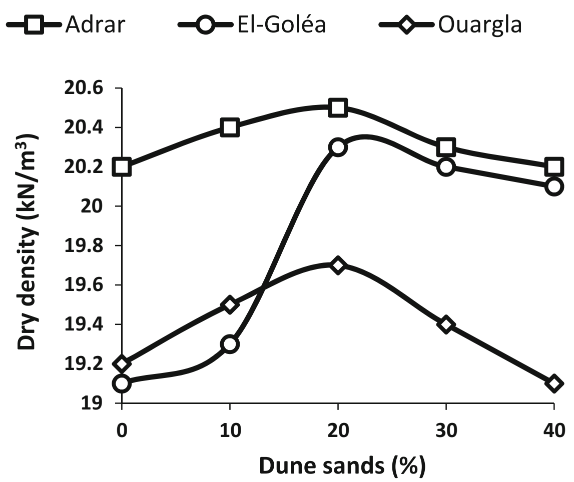

Fig. 8 Influence of dune sands on the maximum dry density of the different mixes (tuffs/sands)

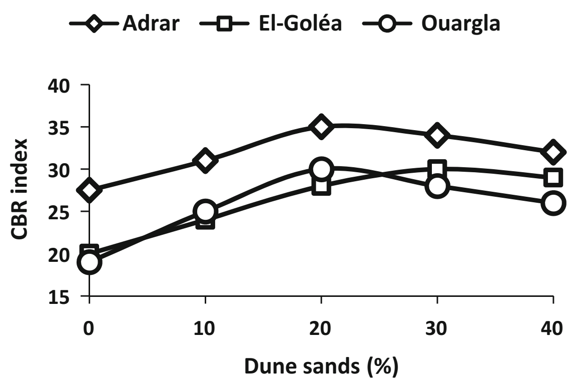

Fig. 9 Influence of dune sands on the I-CBR of the different mixes (tuffs/sands)

The evolution of the characteristics of the mixes at the Proctor optimum as a function of the substitution rate of dune sands in the mix clearly shows the moderate impact in terms of dry density on the Adrar and Ouargla tuffs (with an optimal value obtained for a substitution rate of 20%) and a stronger influence for El Goléa tuffs (Fig. 8).

Regarding the evolution of the I-CBR, a comparable trend is observed for the three tuffs with equivalent substitution level. It is important to note, that the maximum I-CBR value is reached for a substitution rate between 20 and 30% for the 3 studied tuffs (Fig. 9).

In terms of physical properties measured on the mixes studied, it appears from Fig. 10a that the value of methylene blue is almost zero, regardless of the mix analysed. The liquidity limit decreases linearly with increasing dune sands addition in the mix (Fig. 10b). The effect of sand addition in the mix affect less the evolution of the plastic limit (Fig. 10c).

3.3 Effects of Treatment with Binders on the Road Materials Design

Although the addition of dune sands to the tuffs has improved the I-CBR, however, the measured values relative to the intended application remain low. To improve the bearing capacity of the mixes, in a second step, a treatment with different types of binders is explored. In this research work, two levels of treatments (3% and 6%) and three different binders (lime, cement and a combination of lime and cement) are tested.

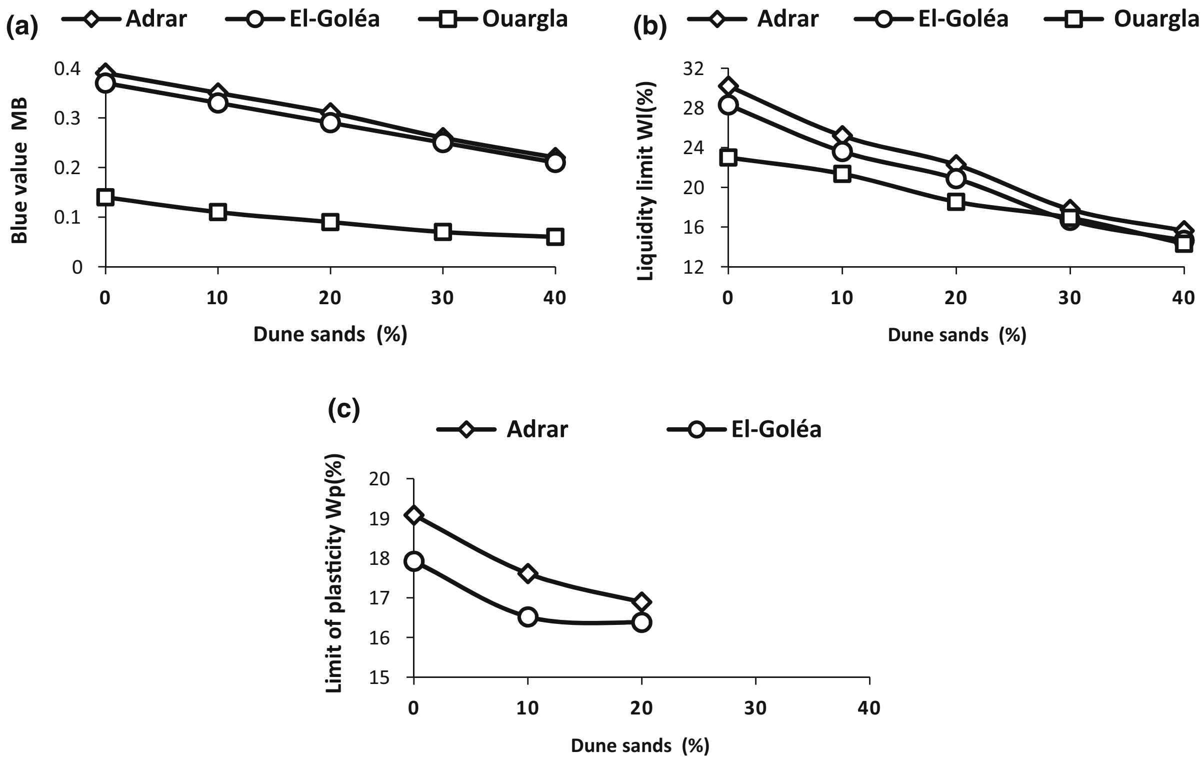

Fig. 10 Influence of dune sands on the cleanliness and consistency of the different studied mixes (tuffs/ sands)

This work is undertaken on the mix composed of Adrar tuffs and Adrar dune sands with a substitution rate of 20%. This mix is named in the following TSD mix. It is to note that this mix is representative of the optimal mixes. For this mix, in Fig. 11, the Proctor curves for the two treatment levels and the three types of binders are shown.

It appears from the analysis of Fig. 11 a flattening of Proctor curves with the addition of binders. In terms of the evolution of the characteristics at the Proctor optimum (Fig. 12), it is clear that the dry density decreased and the optimum water content increased with the level of treatment. This increase is less marked between 3 and 6% of treatment compared to the evolution recorded between the raw mix and the mixes treated with 3% of binders.

In terms of the evolution of I-CBR, as shown in Fig. 13, the effect of the treatment results in a substantial increase of I-CBR. For a treatment with 3%, the value of the I-CBR is improved by about 15% on average to approach 25% increase for a treatment with 6%. The effect of cement treatment on the I-CBR seems better than that of lime. The combination of lime and cement could constitute a good compromise from an economical point view. With a combined treatment, the I-CBR recorded for the studied mix rich 60%.

To characterize the ability of the treated material to withstand the traffic demands after curing, the results for simple compressive strength is shown in Fig. 14. It is to note that the treatment with binders gave a significant increase in the simple compressive strength of designed mixes. These increases are related to the age of preservation, the type of binder and its content in the mix. For a treatment with 3% of cement (Fig. 15), we notice an improvement of the simple compression which reaches 4.5 MPa after 28 days of preservation in the open air, which represents a gain of 85% compared to the untreated TSD mix, where this resistance does not exceed the value of 2.4 MPa. For a cement content of 6%, the simple compressive strength reaches 6.5 MPa. For treatment with the combination of cement and lime, the obtained results are encouraging. For a binder content of 6%, after 28 days of conservation, the simple compression strength is almost equal to 6 MPa. For comparisons,

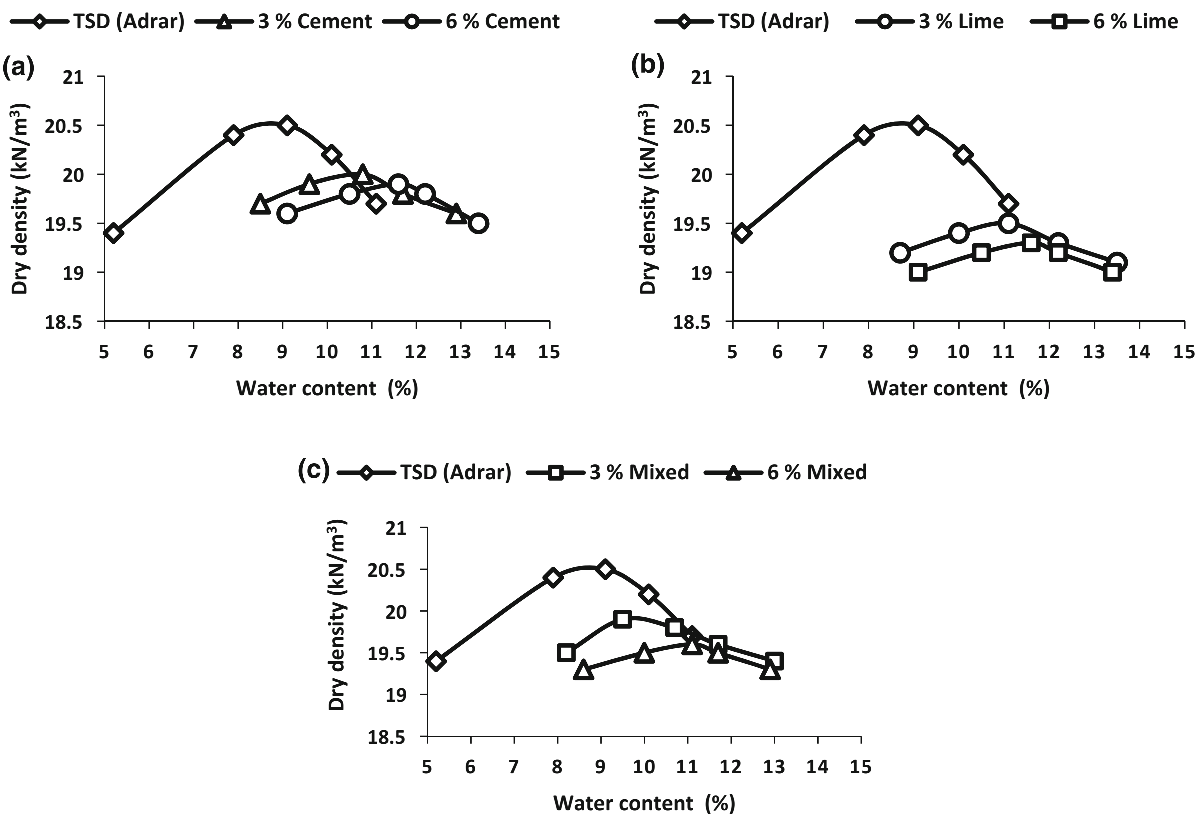

Fig. 11 Proctor curves of the TSD mixture treated with **a** cement, **b** lime and **c** cement/lime

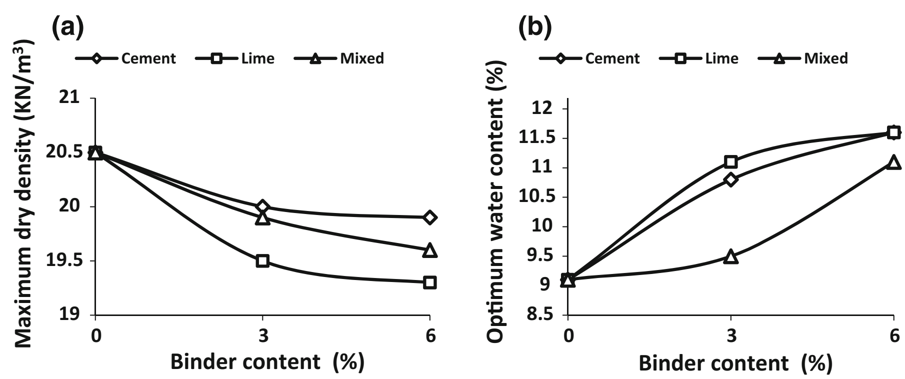

Fig. 12 Influence of binder content on optimal compaction parameters **a** maximum dry density and **b** optimum water content

the obtained results in this work in comparison to previous studies on dune sands alone or tuffs mix with calcareous sands, showed that to reach this level of strength a treatment above 9% of cement is necessary (Smaida et al. 2019; Boukezzi 1997; Goual 2012). This results, induce a substantial increase in the cost of the material due to the amount of treatment.

The effect of treatment with binders (on the TSD mix) on the tensile strength is shown in Fig. 16. The same observations than those made on the improvement of the simple compression strength could be made. The cement confers better improvement compared to the mixed treatment, which itself is better than the treatment with lime. For a treatment with 6% of cement, the specimens kept in the open air for 28 days have exhibited a tensile strength of about 1 MPa.

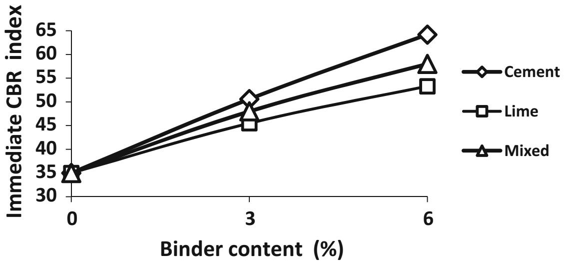

Fig. 13 Influence of the binder content on the I-CBR index

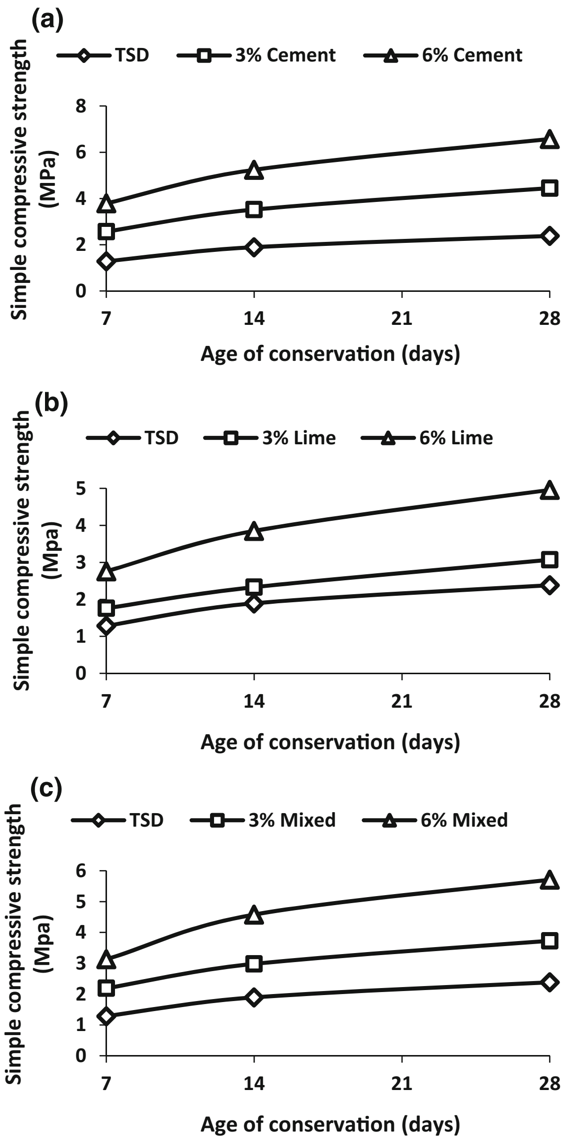

Fig. 14 Evolution with time of the compressive strength of the TSD mixture treated with **a** cement, **b** with lime and **c** cement/lime

The compiled results obtained for TSD mix in regards of the SRT and few guides in use for roads construction are summarized in Table 6.

According to the results, one can see that the tuffs of the Saharan regions are suitable for the use in pavements, particularly in base layers and foundations. As shown in this study, the incorporation of dune sand up to 20% improves significantly the I-CBR values, and the treatment with binders (cement, lime and combination of cement and lime) has conferred further improvement in bearing capacity, compressive strength as well as tensile strength. The improvements of the tuffs characteristics by adding dune sands, prior to binder treatment, has allowed to reduce probably the amount of binders necessary to reach the targeted characteristics. As we can see from Table 6, the TSD material with 3% treatment with cement confers the mix an I-CBR of 50% and a compressive strength of 4 MPa which respect the SRT preconisation for use in base layer.

4 Conclusions

In this work, the main objective was to design a road material for roads with heavy and dense traffic by using local materials (in this work tuffs and dune sands). To give a general character to the obtained results, the materials used is this study are sampled from different regions. After a first characterization of the tuffs, it was shown that the properties of these materials were incompatible with the intended uses. The technique of improving the properties of the tuffs by incorporating dune sand offers new perspectives that give the possibility for valorisation of local materials in the regions devoid of standard materials. The dune sands used in this study are characterized by a narrow grain size distribution and poorly graded. The diameter of the largest elements for sand does not exceed 0.4 mm and it contain almost no fine elements (maximum of 4% for Adrar sand dunes). For use in roadworks, and to improve the geotechnical characteristics of studied tuffs in terms of bearing capacity, substitution of 20% by sand dunes was found as optimal. This results were verified on different combination of materials from different regions. The obtained results are in line with other published results where an optimal sand substitution between 20 and

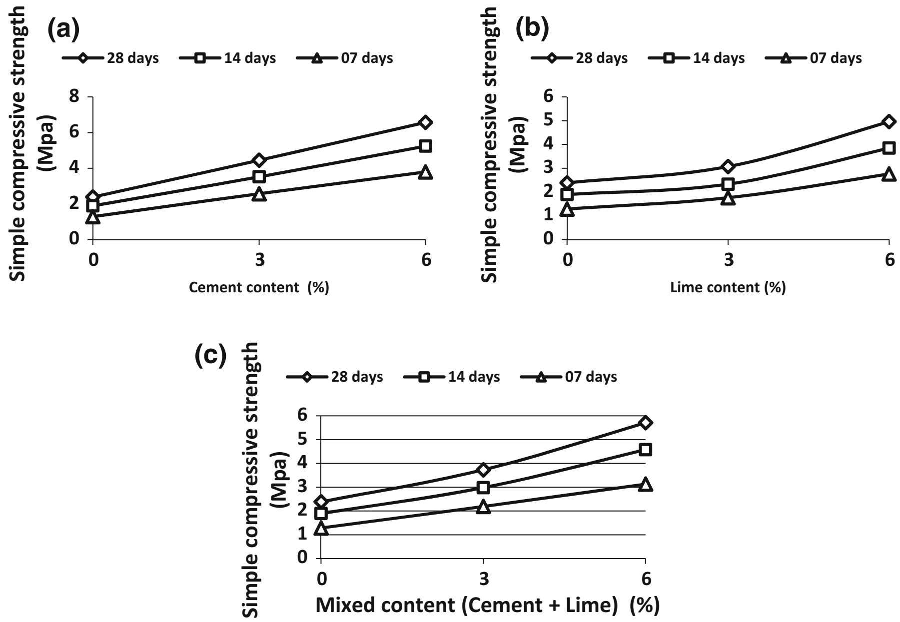

Fig. 15 Variation in the compressive strength of the treated TSD mixture **a** mixed cement, **b** lime and **c**, depending on the binder content

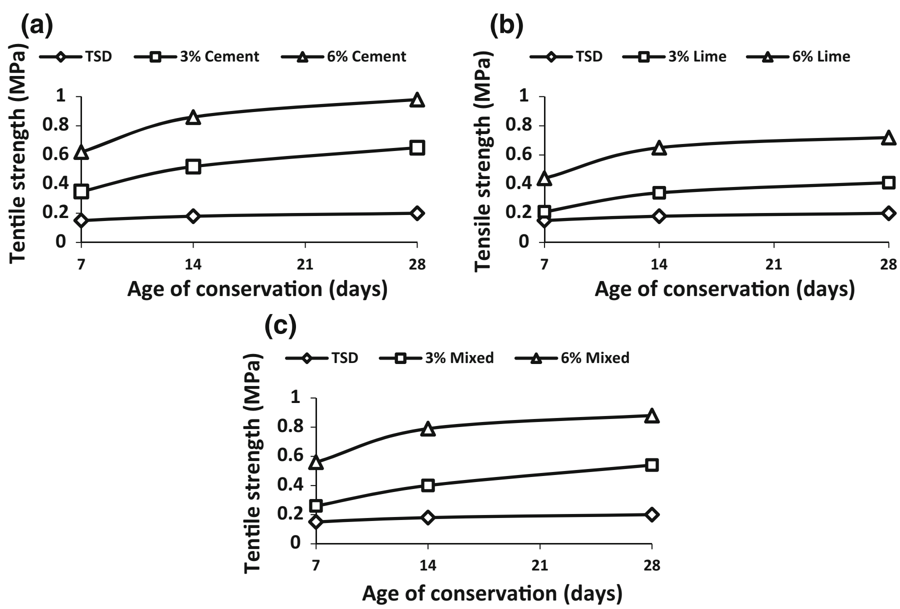

Fig. 16 Evolution with time of the tensile strength of the treated TSD mixture **a** cement, **b** lime and **c** cement/lime

35% is reported (Cherrak et al. 2015; Goual et al. 2012; Daheur et al. 2019).

To improve further the mechanical performance of studied mixes, a treatment with binders is explored (cement, lime and combination of cement and lime). The treatment with binders made it possible to bring the values of the mix characteristics to the thresholds recommended by the SRT. The evolution of the compressive strength and tensile strength of the TSD mix treated with 3% and 6% of binder (cement, lime and cement/lime) is significant: it is related to the age of conservation, the type of binder and its content in the mix. The improvement of the tuffs characteristics by adding dune sands makes it possible to reach for 3% cement treatment, after 28 days of conservation in the open air, 4.5 MPa representing an 85% increase of strength in comparison to untreated mix. This results in the context of sustainable development approach is

Table 6 Specifications for the use of road materials in base layer and foundations

Feature	Layer (F–B)	Specifications				Tuffs Adrar	TSD	TSD (+ 3%cement)
		SRT	Struillou and Alloul (1984)	CTTP (2001)	LCPC (1992)			
D_{max} (mm)	F–B	–	–	20–40	< 50	31.5		
%< 80 μm Max	F–B	< 30	≤ 30	22–32	≤ 35	38	31	–
I-CBR	–	> 40	–	–	–	27.5	35	50
Los Angles coefficient - max	F	–	100	–		66		
Los Angeles coefficient - max	B		35–100 (depending on traffic)					
% Carbonate $CaCO_3$	F	–	> 60	45		30		
% Carbonate $CaCO_3$	B		> 70					
%< 0.425 mm Max		–	–	36–52		59	66	
MB (0/D)					< 1.5	0.39	0.31	
Limit liquidity w_L (%)		–	–	< 40		30.19	22.27	
Index plasticity IP (%)		< 13	< 10 area II < 13 area III < 16 area IV	< 15	≤ 12	11.11	5.38	
% Sulphite $CaSO_4$		–	Track area II < 5 area III			3.19		
Compressive strength (MPa) 28 days		> 2	–	–		3.5	2.4	4.5

encouraging for at least three main reasons: the use of local materials in road construction which gives benefits in reducing transport of materials over a long distance, the use of optimised amount of binders which allows to the reduce the CO_2 foot print in designing road materials and the development of local economy which gives the opportunity to develop local materials valorisation platforms.

Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

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