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Co-valorization of Tuff and Sandy Residues in Roads Construction

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Abstract

In recent years, the use of local materials in pavements has developed to compensate for the lack of normalized standard materials in the Algerian arid regions. The main objective of this research is to assess the co-valorization of two local materials to design a road material with satisfactory characteristics. In this context, the use of tuff in combination with sand residues is explored. The evolution of the characteristics of tuffs mixed with sand residues according to percentages ranging from 0% to 50% is highlighted. The used materials were subjected to physical and mechanical tests. Then, a series of mechanical tests were carried out on mixed samples compacted at the optimal characteristics that were deduced from the modified Proctor test. The obtained results highlight the existence of an optimal formulation composed of 70% tuff and 30% sandy residues, which presented an unconfined compressive strength (UCS) of 5.16 MPs and a CBR index (CBRI) of 42.6 %. Moreover, the results show clearly the evolution of the measured characteristics with time (drying) and without the addition of binders. The possibility of the use of studied mixtures in pavements has been verified regarding the recommendations in use (CTTP 2001) and the Saharan Road Technique (SRT).

Keywords: Local Materials; Tuff; Sandy Residues; Valorisation; Arid Regions.

1. Introduction

The Sahara occupies about three-quarters of the surface of the Algerian territory. Local materials such as tuffs and sandy residues were the subject of several research projects for use in road construction [1–3]. The region of *Adrar* is located in the southwest of *Algeria*, about 1400 km from Algiers by road. Considering its extent (427368 km^2), the region is lightly populated. The climate in the arid regions is characterized by very hot summers (50°C in the shade) with significant temperature differences between night and day and very cold winters. The average annual rainfall is less than 50 mm. The region has, for a few years, seen important economic progress with the development of agriculture and tourism, in addition to oil exploitation. This development has led to an increase in traffic with an extension of road infrastructure that requires a huge need for building materials.

The design of the roads in Algeria depends on numerous technical documents and mainly on the local conditions of each region [4]. This is due to many reasons such as the climate, the available materials, the soil support quality, and the water content of the soil. In arid regions such as the region of Adrar, the design of pavements refers to the

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Saharan Road Technique (SRT) [5]. These recommendations are the results of several years of research and experiments [6]. The main innovation of the SRT has been the use of a wide range of materials in pavement layers, from stony gravel to fine materials [7]. The subgrade layer is compacted in dry conditions to reach densities of about 90% of the modified Proctor optimum. For the foundation layer, the thickness varies between 15 and 30 cm [4], and the bearing capacity is adequate when the Californian Bearing Ratio is higher than 40 % [5, 8]. The compacted base layer at the optimum water content must have a dry density of at least 95% (between 95% and 98%) of the maximum dry density of the modified Proctor. The simple compressive strength under the same compaction conditions must be more than 2.0 MPa in almost dry conditions. The local materials in Adrar, available in huge quantities, consist of tuffs, sand residues from crushing stations, dune sands, and clay. These different materials can satisfy the requirements for the use in road technics and be substituted to standard materials which sometimes are not available or preferably used in other fields (as concrete production).

Recently, numerous studies have been carried out in Algerian arid regions to enhance the performance of local materials. The main advantages of local materials are their abundance and their low transportation cost [9, 10]. Dune sand, tuff and sandy residues are promising alternatives to standard materials for road construction.

Some studies have provided methods to design and optimize local materials [11–13]. The results obtained by Moulay Omar et al. [14] show that the design of experiments can be a useful tool to optimize mixture formulations for Saharan pavements. Other studies were based on mixture techniques and using different kinds of binders. For example, to improve the performance of mixtures of dune sand and calcareous tuff, Akacem et al. [15] have used binders (cement, lime, and cement/lime) as stabilizers. They showed that binders induced improvements in the maximum dry density, bearing capacity, and compressive strength. Smaida et al. [16] have shown that dune sand treated with cement, pozzolan and lime improved the mechanical characteristics of the material and could be used in layers of pavement foundations. Similarly, Daheur et al. [17] showed that the maximum deviatory strength and secant modulus increased with the increase in sand percentage added to tuff. In the same context, they have investigated the behavior of sand-tuff mixtures under small-strain cyclic triaxial tests and constant water content conditions. The obtained results show that the effect of confining stress becomes dominant at the lower suction level and negligible when suction increases [18]. On the other hand, according to Taiba et al. [19], the shape and grain size of granular materials were considered essential parameters to improve the characteristics of the soil to be used.

Azaiez et al. [20] showed that the fraction of fly ash added to granular soil induces an increase in the maximum dry density and a decrease in the optimum moisture content. The results of undrained monotonic triaxial compression tests obtained by Mahmoudi et al. [21] indicate that the use of the global void ratio approach induces significant effects on the mechanical behavior, they showed that the plastic fines content up to the limit fines content seems to be a reliable parameter to be considered in the characterization of the mechanical response of sand and silt mixtures. Boudia et al. [22] have treated the effect of grain size and granular distribution of local sands on the mechanical behavior in terms of strength and stress-strain relationship. Results show an increase in peak friction angle with the increase of particles size and they consider sands as a purely cohesive material. Demdoum et al. [23] investigated the hydraulic conductivity, shear strength, unconfined compressive strength and unconfined tensile strength of material mixtures (bentonite - tuff - sand residues and water) were used as landfill bottom liner. The results showed that a decrease in saturated hydraulic conductivity and increase in compressive and tensile strength. As for shear strength, an increase in shear strength was observed with an increase in limestone sand residues content. The thermal conductivity of a raw and lime-treated calcareous tuff was analyzed during the drying process by Mekaideche et al. [24]. Results show that the drying process and the lime treatment contributed to the reduction of the thermal conductivity of the studied material. Taiba et al. [25] have studied the relationship between saturated hydraulic conductivity and particle shape and density characteristics of silty sand soils. The results obtained indicate that the measured saturated hydraulic conductivity correlates very well with the fines content, density and particle shape.

Our research works undertaken since few years, in the laboratory of Adrar University, have as objectives: the promotion of local materials, particularly the tuffs, dune sands, clays and the sandy residues from the stations of crushing, in the field of pavements works and the improvement of the Saharan road technics knowledge. In this paper, the main objective is to assess the co-valorization of two local materials (tuffs and sandy residues from crushing stations). A grain sizes correction was carried out to improve the physical and mechanical characteristics of these two materials, without addition of binders. The designed materials must meet the specifications of the SRT for the achievement of the foundation layer and the base layer. In the design step, the economic and environmental aspects are also taken into account. Moreover, a comparison of our results with previous studies of Algerian arid regions has been done.

2. Materials, Experimental Program and Methods

2.1. Materials

In the lack of standard materials (as for gravel and sandy materials with desirable grain size distribution), to cover the growing needs in road construction in Adrar region, local materials as tuffs of calcareous crusts are the most used materials in pavements in the region. These materials cover an area of 300000 km^2 of the overall surface area of Algeria [26]. In this study, the tuff used is extracted from a quarry located 10 km to the East of the city of Adrar. The sandy residues are from the station of rocks crushing, located 12 km to the West of the city center. The location of the area of study is shown in Figure 1.

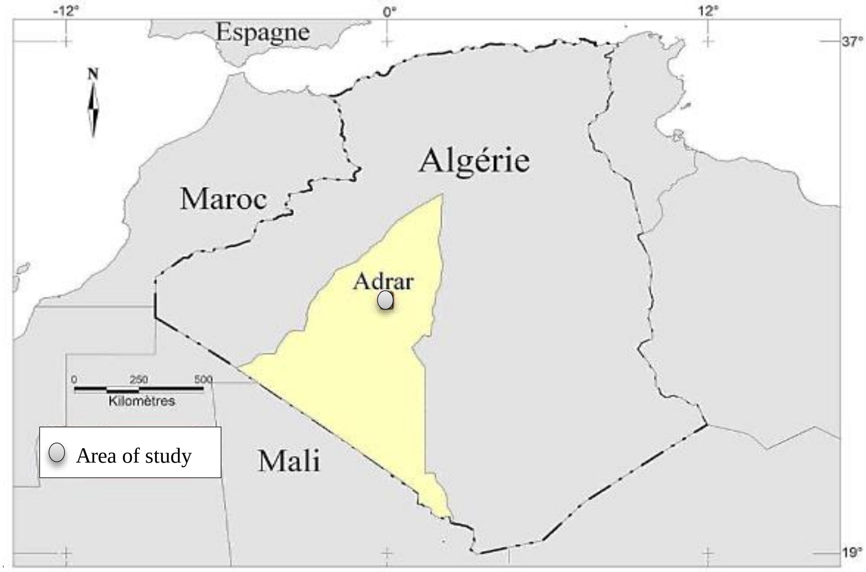

Figure 1. Location of the area of study

In stations of crushing, the sandy residues (with grains size less than 3 mm) present more than 25% of overall production. This fraction contains impurities and undesirable for the concretes industry. Figure 2 shows images of the two materials used.

Sand Residues Tuff

Figure 2. Raw used materials

2.2. Experimental Program

The determination of the physical parameters and the measurement of the mechanical characteristics of the raw materials were conducted according to French standards. The tests are chosen to allow the classification of the materials and explore the possibilities of their uses in road construction. The particle size analysis was carried out according to the French standard [27] on soaked samples in a water bowl for 12 to 24 hours [28, 29]. The liquid limit is measured by the cone penetration method and the plasticity limit by the rolling test method [30]. To assess the ability for compaction and bearing capacity, the Proctor test [31] and the immediate CBR test [32] are undertaken.

2.3. Method of Road Material Design

As explained above, the main objective of the proposed work is to design a road material based on two local materials; tuff and sandy residues from the crushing station. The results of this work will help the preservation of standard materials and better management of sand residues.

The design technic adopted in this study consists of substituting tuff with sand residues. The raw used materials were subjected to identification tests. Then, a series of physical and mechanical tests were carried on tuff and sand residues mixtures samples according to different percentages varying from 0 to 50%. Firstly, a specification was checked to select the mixes that meet the recommendations applied to road construction (SRT, 1966 and CTTP, 2001). Then, the obtained results were compared with other results of previous works. The methodology followed to reach this objective is shown in the flowchart in Figure 3.

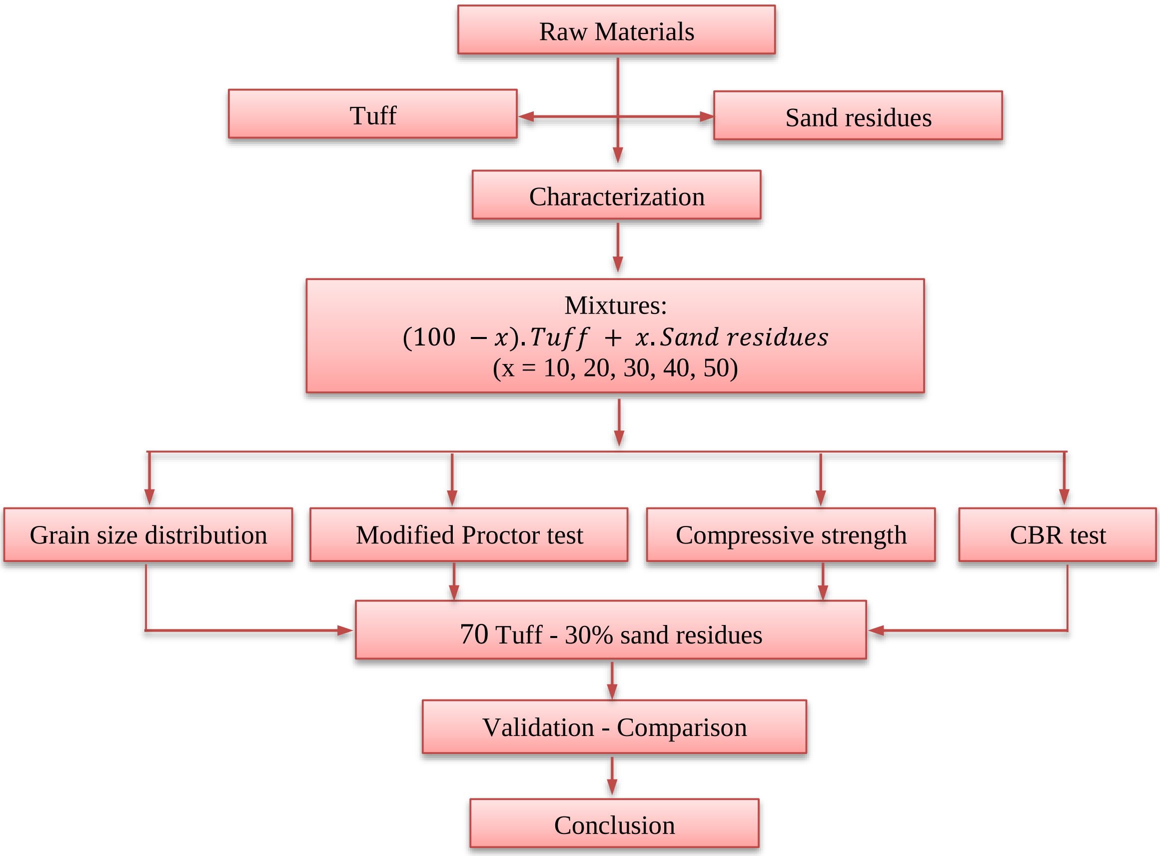

Figure 3. Flowchart presenting the research methodology

The evolution of the characteristics of tuffs mixed with sand residues according to percentages ranging from 0% to 50% is highlighted. The compositions of the different mixes studied are given in Table 1.

Table 1. Designation of the mixes

Mixes symbol	Tuff (%)	Sandy residues (%)
TSC00	100	00
TSC10	90	10
TSC20	80	20
TSC30	70	30
TSC40	60	40
TSC50	50	50
SC00	00	100

The compressive strength and indirect tensile at different ages (0, 7, 14 and 28 days) are measured on cylindrical samples. After preparing the dry masses of raw materials and the optimum water content (for tuff only the 0/5mm fraction was taken in account), the solid materials were manually mixed for 5 min until homogenized. Then, the corresponding water amount was added and the whole was mixed until a homogeneous mixture was obtained. Then, the mixture was kept in a closed plastic bag for 24 h to homogenize the mixture water content even more. The samples were statically compacted, in a double piston mold allowing the distribution of stress over the entire height of the specimen [33, 34]. After demolding, the compacted samples were kept in a horizontal position. The drying of the tested specimens was carried out in experimental room conditions at ambient temperature until stabilization of the specimen masses. Finally, the specimens were stored horizontally in an oven at 105 C for 24 h so that water content is close to zero at the end of the drying phase. The Unconfined Compressive Strength (UCS) test was performed according to NF EN ISO 17892-7 (Standard AFNOR, 2018b) [33]. An electromechanical press with a maximum capacity of 50 kN was used. For all tests, a constant strain rate of 0.5 mm/min was applied. The stress and strain were automatically registered by a central acquisition. Loading was stopped when the measured applied force was decreased by at least 30% compared to the highest measured force or when a net shear plane as shown in Figure 4 was observed.

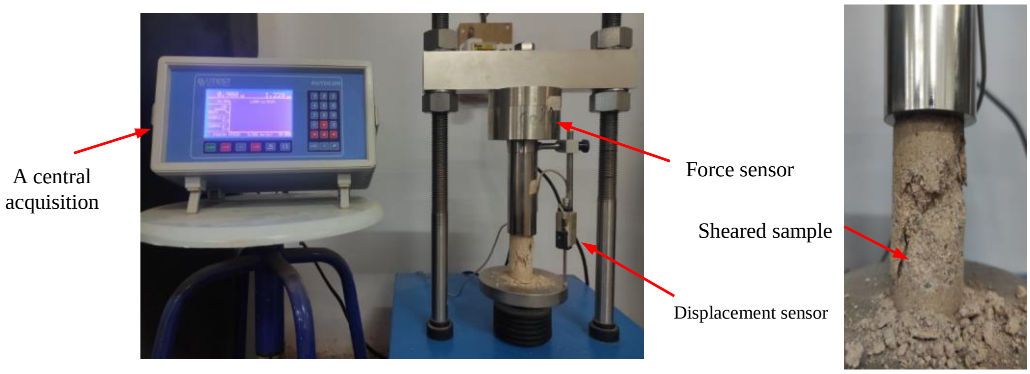

Figure 4. UCS test loading steps

Indirect tensile tests was executed according to NF P98-232-3 [34]. The specimens were prepared in the same way as those for compressive strength. The tensile strength (R_t) was determined in MPa according to Equation 1 [35, 36].

$$R_t = 0.8 \times R_{tb} = 0.8 * 2 * 10^{-2} * \frac{Fr}{\pi \emptyset h} \quad (1)$$

The specimens were subjected to diametric compression strength R_{tb} determined in MPs, F_r is the force applied on the specimen in Newton; ϕ is the diameter of the specimen in centimeters and h is the height of the specimen in centimeters. The CBR index was determined in accordance with NF EN 13286-2 (Standard AFNOR, 2010) [31]. The test consists to punching compacted samples at the optimum modified Proctor characteristics. The punching was performed according to a normalized speed of 1.27mm/min. The CBR index is equal to the larger value between the 2.5mm and 5mm punching stress.

3. Results and Discussion

3.1. Raw Materials Characteristics

The obtained results of raw materials characterization are postponed in Table 2. According to Fenzy (1966) [37], Saharan materials intended for road constructions are classified according to their grain sizes distribution in three families. The spindle used in our study is that of Beni-Abbes [5, 7].

Table 2. Physico-mechanical and chemical properties of used Materials

Parameters	Tuff	Sandy residues	Units
Physical			
Grains < 80 µm	2	3	%
Grains < 2 mm	43	74	%
Coefficient of uniformity (C_u)	21.2	10	-
Coefficient of Hazen (curvature) (C_c)	0.48	0.9	-
Liquid limit (W_L)	30.1	23.3	%
Plastic limit (W_p)	21.7	14.8	%
Plasticity index (I_p)	8.4	8.8	%
Sand equivalent	14.63	32.52	%
Specific gravity	26.6	27.2	kN/m^3
Coefficient of Los Angeles	36	-	%
Mechanical			
Modified γd_{OMP}	20.6	20.19	kN/m^3
Modified W_{OMP}	8.64	7.6	%
CBRI	53.93	28.10	%
Chemicals			
Methylene blue value	0.47	0.4	-
$CaCO_3$	34.4	3	%

The particle size analysis (Figure 5) shows that 60% of the tuff elements are located inside the spindle (family II). The particles have a maximum diameter (d_{Max}) of 30 mm, an average diameter (d_{50}) of 3.2 mm and a fraction less than 2 mm of 43%. For sandy residues, 60% of the particles are located above the Beni-Abbes spindle's, it belongs to the family III and the sandy residues exhibit a d_{Max} of 5 mm, a d_{50} of 1 mm and the fraction less than 2 mm of 73%. The fines fraction less than 0.08 mm for both materials is less than 5%.

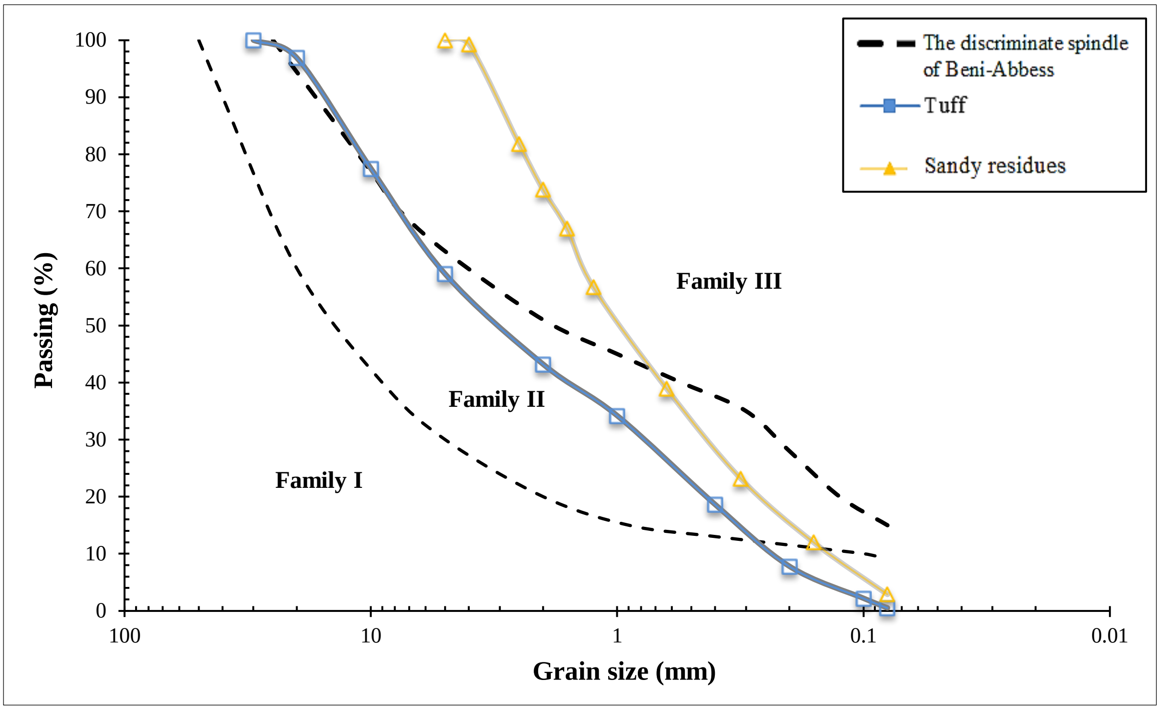

Figure 5. Grain size distribution curve of the two used materials according to Beni-Abbes spindle

The plastic index values measured on both materials are less than 10 % indicating an incompressible character of the materials (Table 2). The "Los Angeles" value measured on tuff material indicates a good ability of this material in regards to the use in road construction.

In terms of the bearing capacity (CBRI), the measured value on the tuff is above 53 % which could be considered as very high value. For sandy residues, the measured value is close to 30, which is also considered an adequate value. The methylene blue value of the tuff and the sandy residues are respectively equal to 0.47 and 0.4. These results confirm the reduced activity of fine particles in both materials and probably an incompressible character of both materials when these results are combined with the Plastic index values.

In terms of materials classification, the unified soil classification system [38], the technical guideline (GRT) on the embankment and capping layer construction [39] and Saharan highway technical specifications [5] have been used. The results of these classifications are reported in Table 3, the compatibility of the characteristics of these local materials with the valorization in road construction technics shows an interesting potential.

Table 3. Classification of used materials

Classifications	Tuff	Sandy residues
USCS/LPC	Gm/GM	Sm/SM
GRT (1992)	B41 ts	B51ts
SRT (1966)	Family II	Family III

3.2. Characteristics of the Different Mixes

3.2.1. Grain Size Distribution

From a point of view of grains size distribution and in regards to the spindle of Beni-Abbes, all the mixes studied in this work belong to the Family II, excepting mixtures TSC40 and TSC50. This family (Family II) represents the category of compactable materials.

Figure 6 and Table 4 show the grain size distribution of mixtures that is ranged between 0.08 and 30 mm. From the values of the grain size coefficients, it is noticed that the mixtures curves are continuous and extended. Moreover, the percentage of elements smaller than 2mm increases with the growth of sand residues rate, this means that the mixtures become richer in fine particles. The coefficient of uniformity values are higher than 6 for all mixes, this result confirms the well-graded character of the different mixes. From Table 4, an increase in the uniformity coefficient up to 30% of sand residues addition was observed. Above 30% of substitution, the coefficient of uniformity drops very quickly.

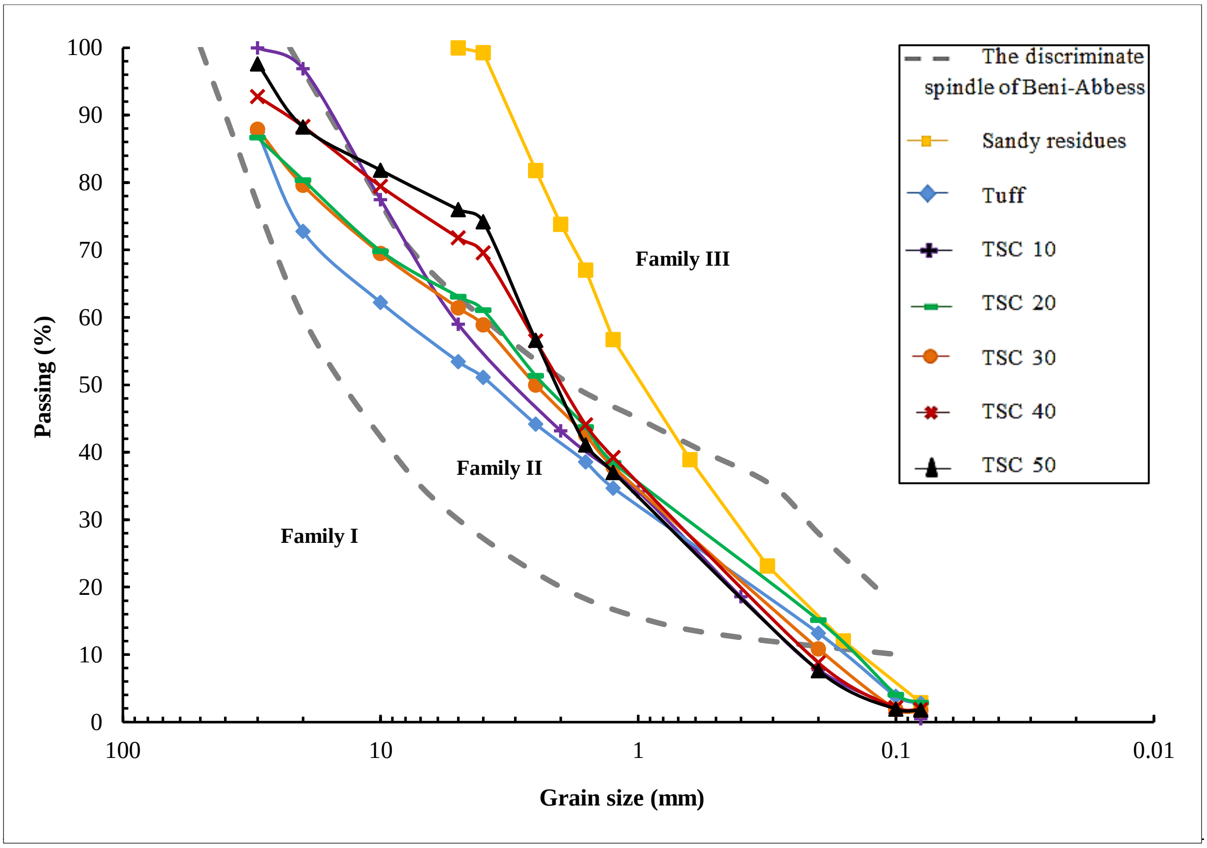

Figure 6. Grain size distribution curve of the two used materials according to Beni-Abbes spindle

Table 4. Mixes particle size characteristics

Mixes	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	< 2mm (mm)	$C_u = d_{60}/ d_{10}$	$C_c = d_{30}{}^2/d_{60}{}^* d_{10}$
TSC00	0.25	0.8	5.3	43	21.2	0.48
TSC10	0.16	0.85	8.5	41.5	53.12	0.53
TSC20	0.2	0.75	4.5	46	22.5	0.62
TSC30	0.15	0.65	3.9	48	26	0.72
TSC40	0.23	0.75	2.95	49	12	0.82
TSC50	0.24	0.85	2.8	50	11.66	1.07

3.2.2. Modified Proctor Test

Figure 7-a presents the tuff, sandy residues and the different mixes compaction curves. It is noted that, when the amount of the sand residues increases, the maximum dry density increases and the optimal water content decrease. This increase of dry density can be justified by the filling of voids between large tuff particles by fine particles of sand residues. The addition of sand residue to tuff material increases also the spreading of the particle size curve. As shown in Figure 7-b, an increase in the maximum dry density was noticed with the increase in sand residues rate until 30% that present the optimum of substitution, and all percentages greater than 30% decrease the maximum dry density to tend to that of tuff.

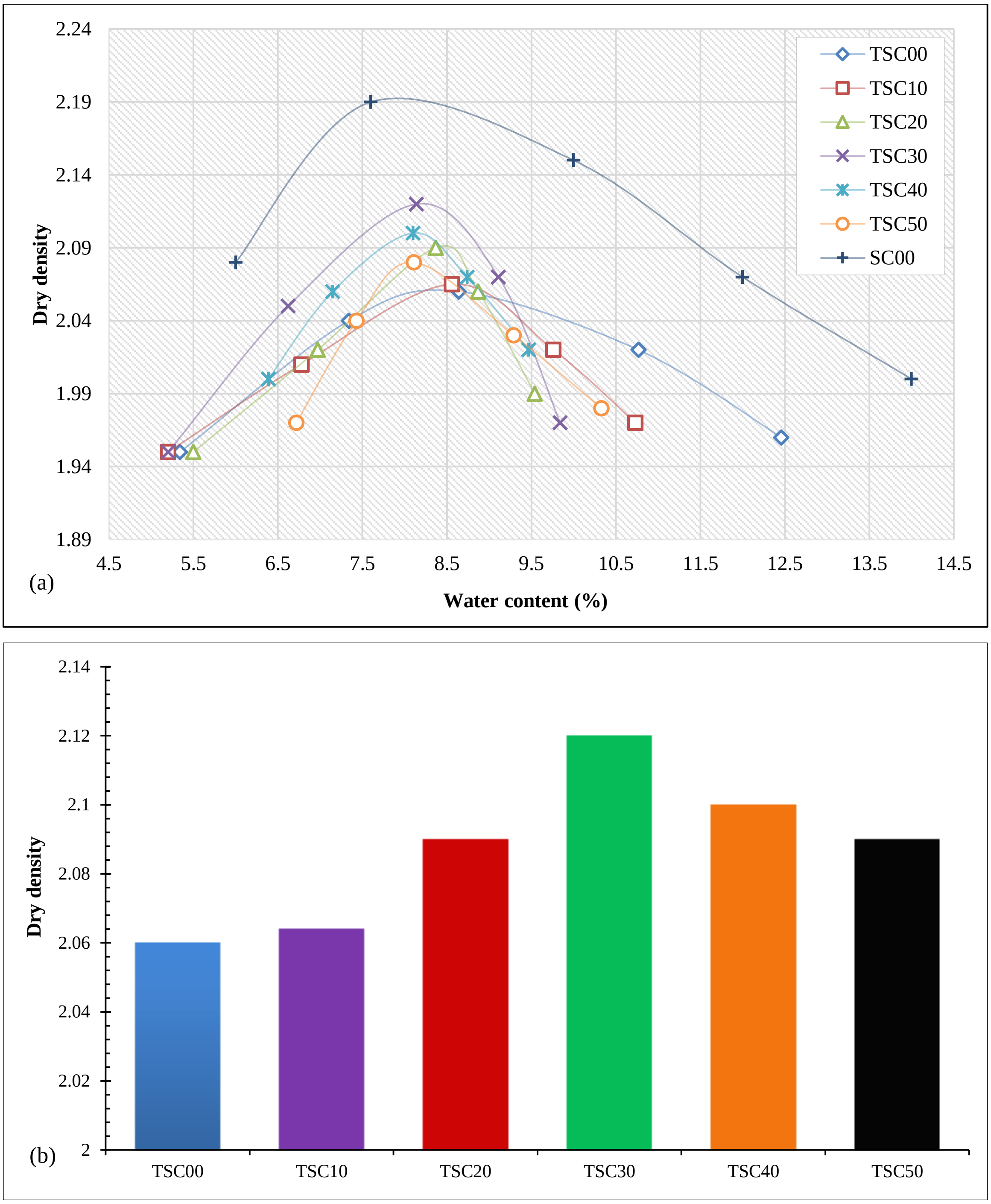

Figure 7. Influence of the incorporation of the sandy residues on the tuffs modified Proctor characteristics

3.2.3. Compressive Strength

The impact of the substitution of sandy residues and the evolution of the unconfined compressive strength (UCS) as a function of the curing time is represented in Figure 8. According to these results, a quick increase of the unconfined compressive strength an early age (between 0 and 7 days) was observed for all mixtures. After 14 days of curing in the experimental room ambient temperature, it appears that the maximum unconfined compressive strength was achieved for mixtures with a percentage of sand residues less than 30%. For a higher amount of substitution, a decrease in the unconfined compressive strength is recorded between 14 days and 28 days of cure. According to these results, the TSC30 mix gives the highest value of unconfined compressive strength (5.16 MPa).

For all the mixes, the quick increase of the simple compressive strength between 0 and 7 days is due to the desiccation of the samples by evaporation of water. To confirm this hypothesis, measurement of the water content has been done at a different time, as shown in Figure 9. The specimens were stored in ambient room temperature until stabilization of their masses. This drying method makes it possible to prevent cracking of the tested specimens under the effect of a fast decrease in water content.

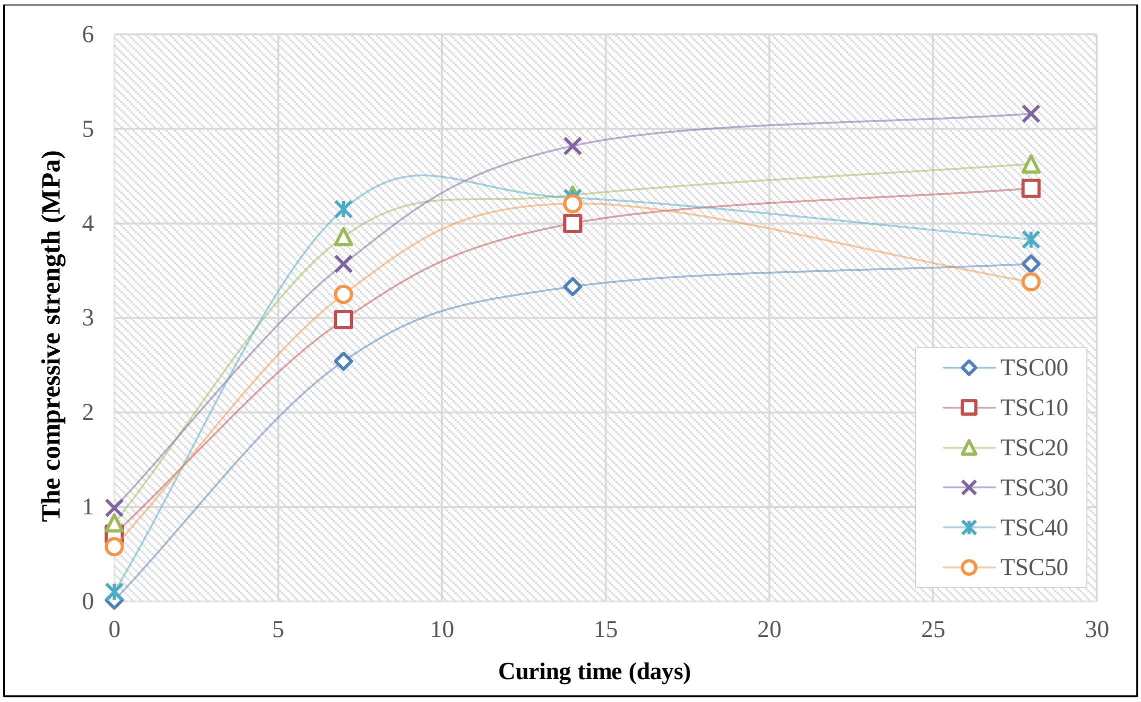

Figure 8. Effect of the curing time on the compressive strength of the mixes

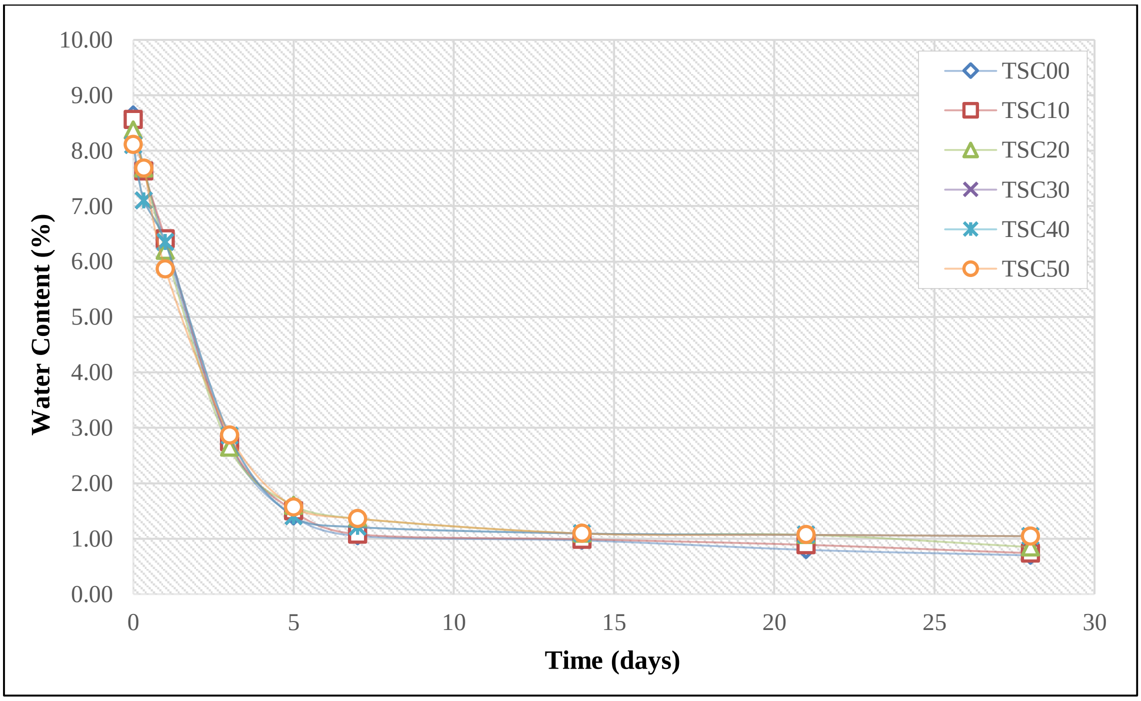

Figure 9. Effect of the curing time on the water content of specimens

The drying kinetics of specimens was controlled. A quick drying phase lasting 0 to 3 days was observed, followed by a slow drying phase (3 to 7 days). Then from 7 days, a horizontal plateau was reached, revealing the stabilization of the sample mass (between 14 days and 28 days). It should be noted that, there is a relationship between the specimens drying kinetics and the evolution of the unconfined compressive strength. The improvement of the unconfined compressive strength was ensured by the capillary cohesion forces created by the drying of the samples (water evaporation). It should be noted that these results are in agreement with those reported by Moulay Omar (2021) [40].

The increase in the unconfined compressive strength can be justified also by an increase in contact number between the grains, due to the filling of the voids by the fine elements contained in the sandy residues. The fine elements of the sandy residues improve the compactness of the tuff by occupying the voids between the grains of tuff (at least until a substitution of 30%), which was generated by an increase in the dry density (in the range of substitution between 0% and 30%), consequently an increase in the unconfined compressive strength as shown in Figure 10.

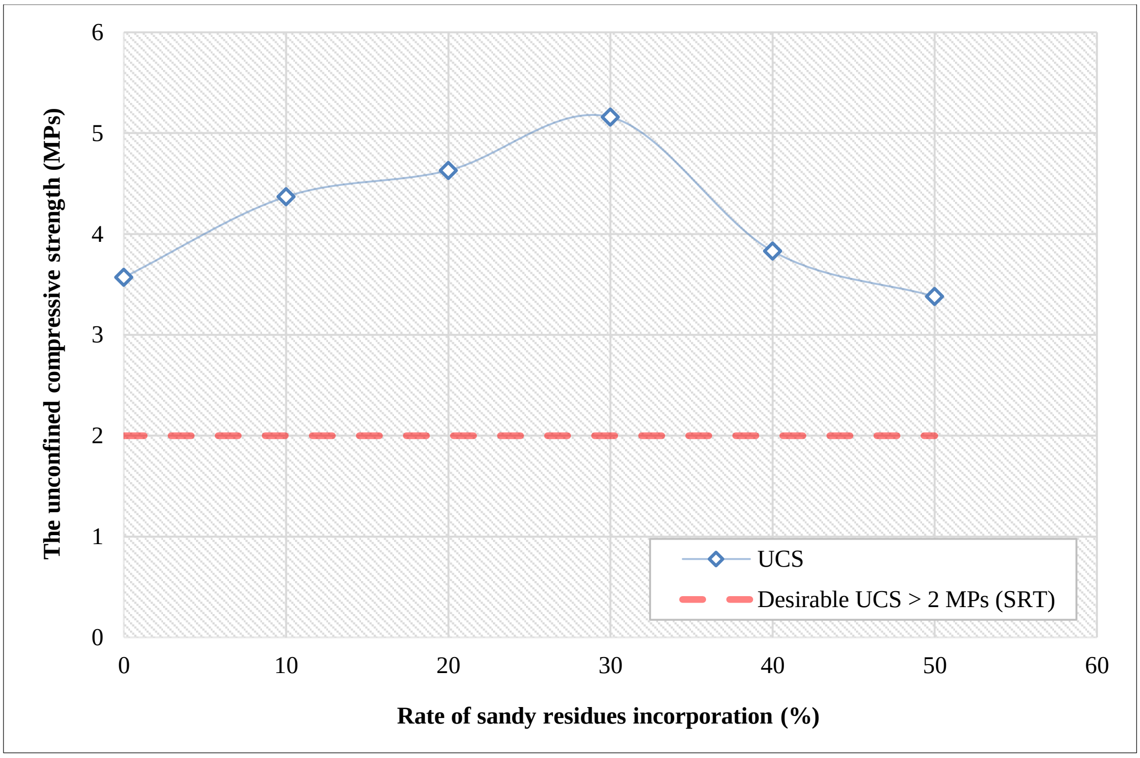

Figure 10. Sand residues effect on the unconfined compressive strength of the mixes

3.2.4. CBR Test

The CBR index is considered one of the most important parameters for pavement design in arid regions. The CBR value was determined immediately from compacted samples at the optimum modifies Proctor characteristics. The obtained results show an almost constant value of CBRI up to 20% substitution of sandy residues. Then, for substitution rates greater than this percentage, a continuous decrease in CBR index was observed (Figure 11). This decrease in CBR index is independent to the variation in dry density. The proof, there were two mixtures with the same dry density (2.092) for two different levels of substitution 20% and 50% (Figure 7-b), have respectively two different values of CBR index 56 and 20% (Figure11).

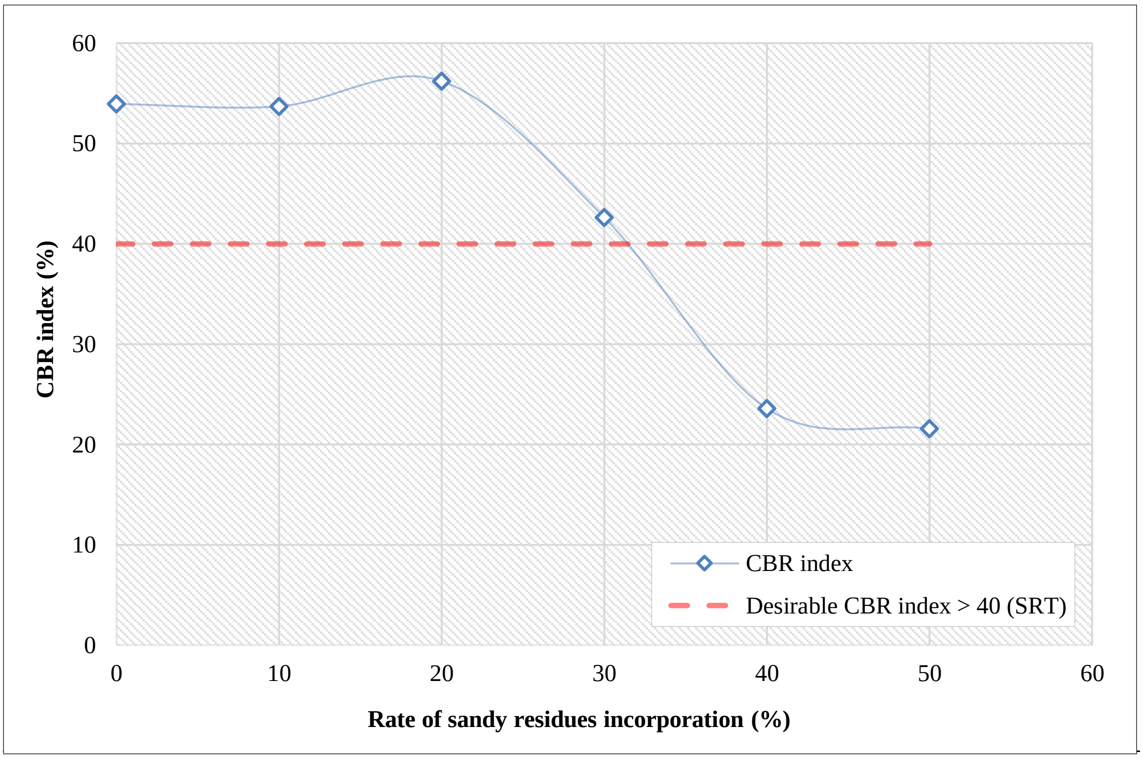

Figure 11. Effect of the sand residues rate on the CBR index

Comparing the CBR test results with the SRT specifications, it is observed that the tuff, TSC10, TSC20, and TSC30 mixtures meet the recommendations for the use of soils in pavement as base and subbase layers. The other mixes (TSC40 and TSC50) have a CBR index below the threshold value, but these values are acceptable for backfill use.

Comparing the evolution of the CBR index with the change in the plasticity limit for the different substitution rates seems more reasonable (Figure 12). An increase in plasticity index was accompanied by a decrease in the CBR index. The same relationship was be found by Naeini et al. (2009) [41] in their study carried out on design and reinforcement road pavement structure.

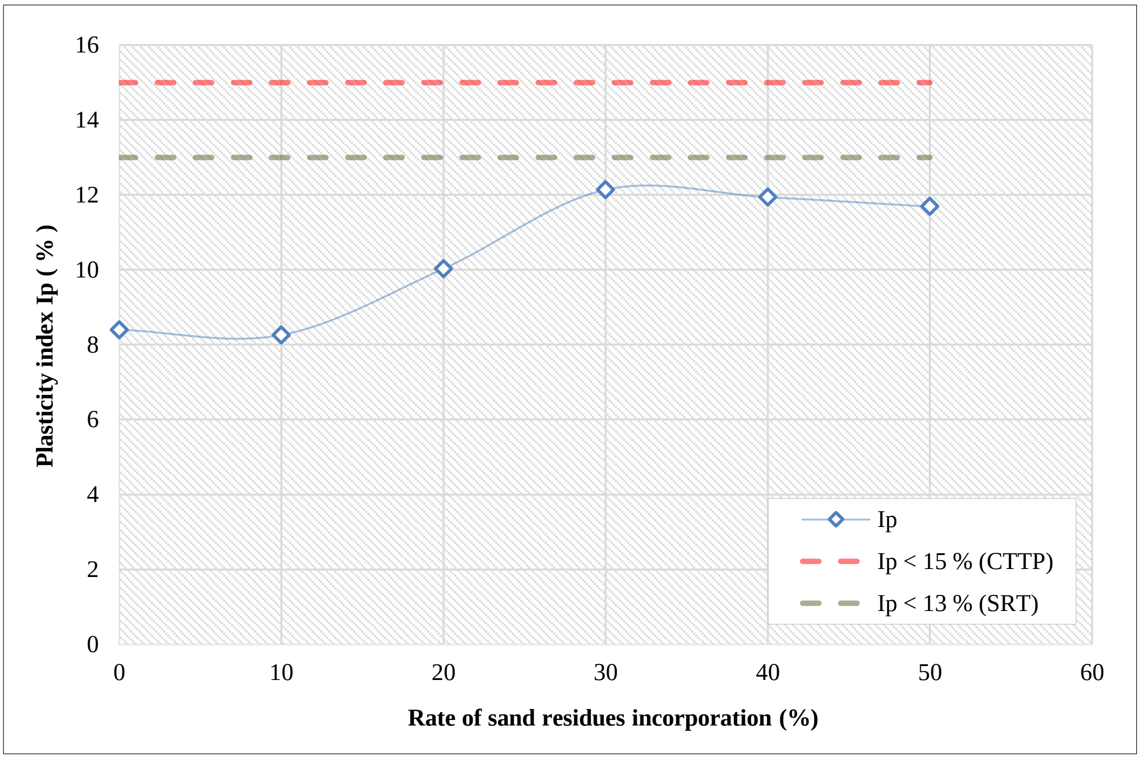

Figure 12. Effect of the sand residues rate on the plasticity index

Concerning the plasticity index, according to CTTP and SRT requirements, the conditions of acceptability of the soils constituting layers of pavements are respectively (I_p<15) and (I_p<13). It is observed that all the studied mixes comply with these two conditions as shown in Figure 12. Table 5 summarizes the parameters of the different mixes, their classifications, and the validation according to the road guides used in pavement design [4, 5].

Table 5. The parameters of mixes and their validations according to CTTP and SRT recommendations

Mixes	$\gamma_{d\ max}$ (KN /m^3)	ω_{OPM} (%)	e_{Opt}	ICBR (%)	Ip (%)	UCS $_{28}$ (MPa)	Classification		Validation	
							LPC	GTR	CTTP	SRT
TSC00	2.06	8.64	0.29	53.93	8.40	3.57	Gm	B_{41} ts	Yes	Yes
TSC10	2.064	8.56	0.29	53.69	8.26	4.37	Gm	B_{41} ts	Yes	Yes
TSC20	2.09	8.37	0.28	56.20	10	4.63	Gm	B_{41} ts	Yes	Yes
TSC30	2.12	8.14	0.26	42.62	12.1	5.16	Gm	B_{41} ts	Yes	Yes
TSC40	2.1	8.10	0.28	23.58	12	3.83	GA	B_{51} ts	Yes	No
TSC50	2.09	8.11	0.29	21.58	11.7	3.38	GA	B_{51} ts	Yes	No

3.2.5. Mechanical Performance

The mechanical performance of the studied mixes was explored through the tensile strength improvement ($R_{t\ impr}$) and the unconfined compressive strength improvement (UCS_{impr}), as a function of the percentage of sand residues. For each parameter, the improvement can be estimated by Equations 2 and 3:

$$R_{t\ impr} = \left[\frac{R_{t28}\,(tuff+sand\ residues)-R_{t28}(tuff)}{R_{t28}\,(tuff)}\right] \times 100 \quad (2)$$

$$UCS_{impr} = \left[\frac{UCS_{28}\,(tuff+sand\ residues)-UCS_{28}(tuff)}{UCS_{28}\,(tuff)}\right] \times 100 \quad (3)$$

Comparing the tensile strength of the tuff estimated at 28 days and those of the mixes at the same curing time, a continuous improvement was observed up to 30% of sand residue addition, and then it reaches its maximum (30.8%) as shown in Table 6. For sand residue rates above 30%, the tensile strength decreases.

Table 6. The mechanical performance of the mixes

Mixe	R_{t28} (MPa)	UCS_{28} (MPa)	$R_{t\ impr}$ (%)	$UCS_{\ impr}$ (%)
TSC00	0.44	3.57	0	0
TSC10	0.69	4.37	18.3	36.3
TSC20	0.72	4.63	22.9	38.9
TSC30	0.76	5.16	30.8	41.8
TSC40	0.66	3.83	6.8	33.4
TSC50	0.55	3.38	-5.6	19.4

In a related subject, Moulay Omar (2021) [40], Loualbia et al. (2017) [42] and Soulié (2008) [43] found that the decrease in the water content of the specimens causes an increase in the suction, which thickens the material hence a greater resistance.

3.3. Effect of the Sands Addition on the Characteristics Evolution of the Mixes

The CBR index (Californian Bearing Ratio), the characteristics deduced from the modified Proctor test, and the grading characteristics are the most important parameters used to evaluate the performance of road materials in southern Algeria. In the following section, firstly an attempt has been carried out to correlate the physical characteristics of the mixtures with the added sand residue rate. Secondly, in the same way, the correlations of the CBR index with the mixes physical characteristics were explored.

3.3.1 Effect of Sand Residues Addition on the Evolution of the Physical Characteristics of the Mixes

In the following section, the effects of Sand Residues Percentage (SRP) on curvature coefficient, the percentage of particles less than 2 mm, the optimum water content values and the plastic index are presented. The equations provided in Table 7, suggest linear relationships. The coefficient of determination (R^2) was close to 0.9 for Equations 4 to 7. These values of R^2 could be considered as good values to support this type of correlation. However, for Equation 6, the plasticity index is not well correlated with the Sand Residues Percentage (SRP), the low value of R^2 cannot support this relationship. This result is in agreement with those found by Aniekan (2018) [44].

Table 7. Predictive regression equation between parameters

Characteristics	Equations	R^2	Equation N°
Curvature coefficient	Cc = 0.011[SRP (%)]+ 0,45	0.93	4
Percentage of particles less than 2 mm	< 2 mm = 0.17 [SRP (%)] + 42	0.87	5
Plasticity index	Ip = 0.085 [SRP (%)] + 8,4	0.54	6
Optimum water content	Wopt = -0.012[SRP (%)] + 8,6	0.90	7
	Wopt = -0.07 (< 2 mm) + 11,44	0.91	8

From the experimental results, it was noticed that the optimum water content decreases continuously with the increase of sand residues, consequently with the increase of particles smaller than 2 mm. A correlation value R^2 of 0.91, Equation 8 seems to confirm the proposed linear relationship.

3.3.2. Relationships between California Bearing Ratio and Physical Characteristics

The correlation of CBR index with the curvature coefficient (Equation 9) was acceptable. While those with the percentage of particle less than 2 mm (Equation 10), and the plastic index (Equation 11) seems to be unsuccessful regarding the obtained R^2 values. It is noted that the obtained results are in agreement with those reported by Katte et al. [45] and Farias et al. [46] (Table 8).

Table 8. Relation between CBR Index and physical characteristics

Characteristics	Equations	R^2	Equation N°
	CBR = -65.9(Cc) + 88.5	0,82	9
California bearing ratio	CBR = -3.87(< 2 mm) + 221	0.70	10
	CBR = -3.96(Ip) + 88.1	0.30	11

3.4. Comparison of Present Results with Results Extracted from Different Studies

The results of the current study, particularly the maximum dry density and unconfined compressive strength have been compared with those of different studies undertaken on comparable materials. In the comparative study, the first results are related to studies conducted at another site in the Adrar region [15]. The second data set is relative to El Golea site [15]. The third data is relative to a study where a tuff is mixed with dune sands of Ouargla region [17]. The fourth data is relative to tuff mixed with calcareous sand (considered as sand residues) of Laghouat region [2]. The fifth data set is relative to tuff of Bechar mixed with dune sands of Ouargla regions [47]. A comparison between the different arid regions of Algeria was carried out to position the current results compared to previous results.

3.4.1. The Maximum Dry Density

The maximum dry density results of different Algerian arid regions had been compared. For all regions, the maximum dry density of tuffs has been varied between 1.88 and 2.32. It is to note that in the current study, the dry density for different sand residues rate has been varied between 2.06 and 2.12. The addition of sand to tuff generally induces an increase in the dry densities of the mixes except for the fifth data set (mix of Bechar tuff with Ouargla dune sand). When the sand improves the dry density, the optimal amount of addition varies between 10 % and 30% as shown in Figure13.

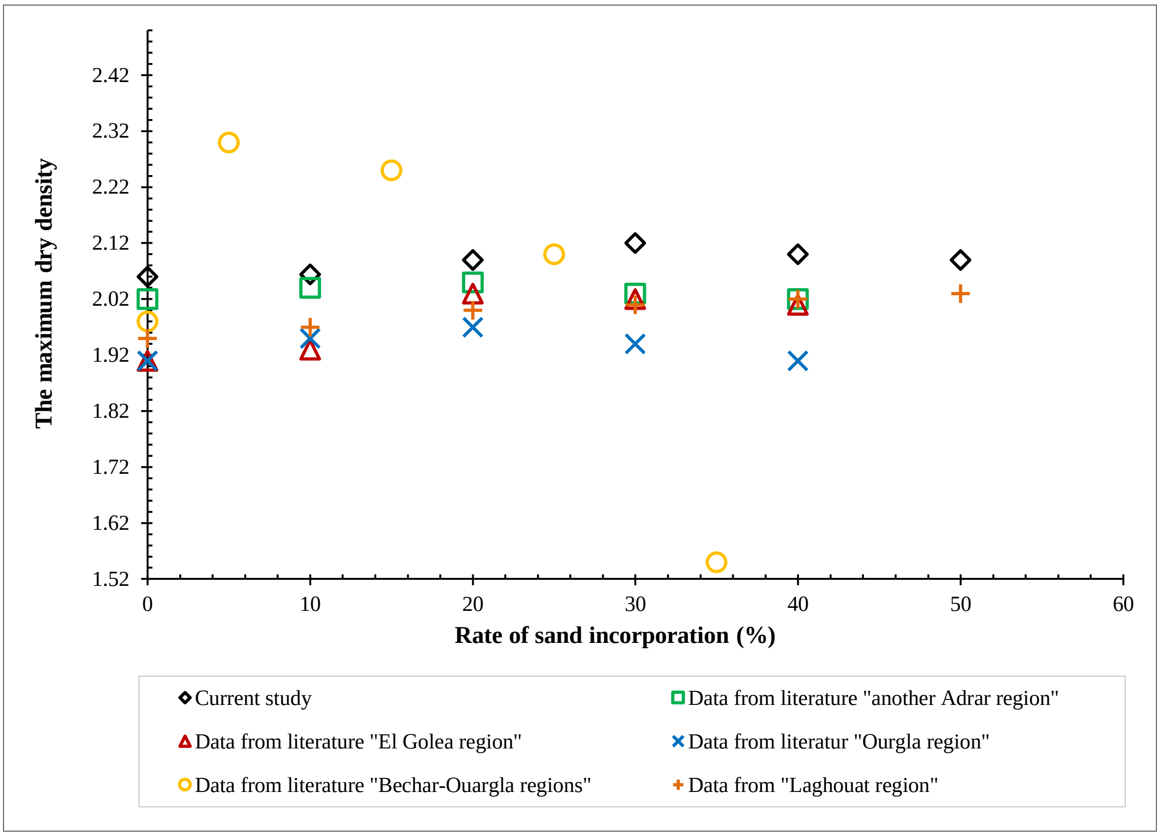

Figure 13. The sands effect on the maximum dry density mixes (Algerian arid regions)

3.4.2. The unconfined compressive strength

According to Figure 14, apropos the current study, in the Laghouat region and that of Bechar and Ouargla, the evolution of the unconfined compressive strength of mixtures of tuffs-sands at different percentages has allowed us to note that there was an increase in the unconfined compressive strength, and then it reaches an optimum, presenting the best formulation. On the other hand, concerning the results obtained in another site of the Adrar region and the region of Ouargle, a continuous decrease in the unconfined compressive strength of the tuff-sand mixtures was noticed.

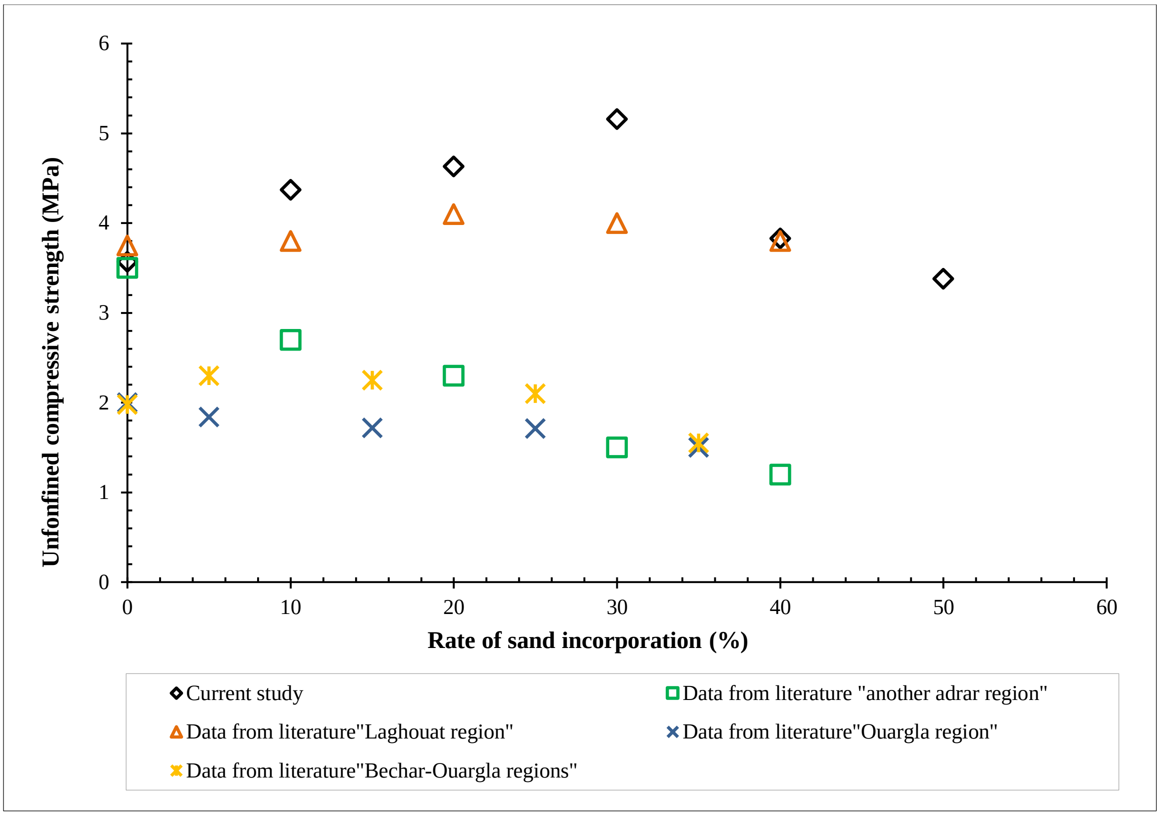

Figure 14. The sands effect on the unconfined compressive strength mixes (Algerian arid regions)

4. Conclusions

Based on the laboratory tests, the improvement of the tuff characteristics by the sand residue addition in view of their use in road construction was the object of this paper. From the experimental results obtained, the following conclusions can be drawn:

- The incorporation of the sand residues at different percentages corrected the particle size distribution of tuff, where all the mixes are part of the Family II SRT spindle; either entirely for a rate of sandy residues varying from 0 to 30%, or partially for a rate of sandy residues between 40% and 50%.
- Modified Proctor compaction tests of tuff and sand residue mixes have shown that the maximum dry density increases with the rate of sand residues up to 30%, which corresponds to the optimal formulation (TSC30). Beyond this percentage of substitution, the density of the mixes decreases. The optimum water content decreases continuously with the increase in the sand residue substitution rate.
- The bearing capacity is considered a very important parameter in the field of road construction. The results show that there is no change in the CBR index until 20% of sand residue substitution. Beyond 20% of substitution, a decrease in the values of the CBR index is observed. This decrease can be attributed probably to the change in the grains size distribution (change in the coefficient of curvature and or the fraction less than 2 mm in the mixes) and the plasticity index. The tentative correlation of the CBR index with these parameters was unsuccessful considering the correlation coefficient (R^2) values calculated.
- However, according to the recommendations used in road construction techniques, a maximum rate of 30% sand residue substitution is largely sufficient to ensure a CBR index value satisfactory to the recommendation in effect.
- The mechanical performance of the mixes studied is evaluated through the tensile strength and the unconfined compressive strength. The last one has shown that the mixes with a substitution rate of up to 30% exhibit improved unconfined compression strength. The same tendencies were observed based on indirect tensile strength. However, all the mixes, recorded at 28 days are compatible with the recommendation target for the unconfined compression strength.
- The comparison of the obtained results in the current study with those of the literature in arid regions showed that there is a great similarity in the characteristics of tuff-sand mixtures. In order to generalize the possibility to use and valorize local materials, especially tuff and sand, in pavement design in arid regions, an optimized formulation range of 70 to 80% tuff and 20 to 30% sand is proposed.

5. Declarations

5.1. Author Contributions

Conceptualization, H.M.O. and R.Z.; methodology, R.Z.; validation, B.M. and M.M.; formal analysis, M.M.; investigation, H.M.O.; resources, A.M.; data curation, A.M.; writing—original draft preparation, H.M.O.; writing—review and editing, H.M.O.; supervision, B.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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