Reinforcement of Aeolian Sand by Perforated Geotextile for Road Foundations

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Abstract

Roads are one of the most important infrastructures in the modern world. These are built for social, strategic, urban and economic purposes. Dune sand is available at a low cost throughout the North African Sahara, but it is rarely used as a construction material. In addition, the scarcity of noble materials used in road pavement has led to search for other alternatives, such as dune sand. The purpose of this study is to exploit the abundant aeolian sand by reinforcing it with perforated geotextile for use in road foundation layers. The use of perforated geotextile is to enhance its entanglement with the sand and reduce the amount required. This study also aims to evaluate the bearing capacity (CBR) of the sand/geotextile compound. The sand was tested alone using the CBR test and then with the addition of a geotextile layer. This study involves creating holes with varying diameters and spacing between them in order to evaluate the effect of perforating the geotextile on the bearing capacity of the reinforced sand. The results of the experimental tests demonstrate a significant increase in the bearing capacity of the compound (sand/geotextile) as measured by the CBR index. This index increases up to four times that of sand alone and reaches 84.7% of that of a tuff commonly used in the study region. The amount of geotextile used is reduced by up to 50.24%. Regression analysis provided an empirical relationship between the bearing capacity (CBR) of the compound, the grain size of the sand, and the perforation pattern of the geotextile. This contributes to the indirect evaluation of the CBR index of the composite material.

Keywords: Aeolian sand; Geotextile; Perforations; Reinforcement; Roads; CBR; bearing capacity.

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1. Introduction

Aeolian sand is an abundant material in southern Algeria. It is available almost free of charge, but very little is used in geotechnical works and as a construction material [1]. The main intrinsic characteristics of this material, which are considered defects, are the absence of cohesion and its low compaction capacity [2,3].

Aeolian sand accumulated in dunes, hence the name dune sand (DS), is very clean and contains almost identically selected particles [4]. This sand is barely exploited in the fields of tourism, agriculture, and industry, and even less in the fields of roads and engineering structures (railways, airfields, reservoirs, etc.). From a geotechnical point of view, this is chiefly due to the intrinsic defects mentioned above.

On the other hand, the DS exhibits many undeniable physical and mechanical qualities that make it profitable for certain structures such as dykes, drains, backfills, and reinforcement of soft soils. Among these qualities are recognized the large containing of quartz, renowned for its hardness [5–7], good water and air permeability, excellent bearing capacity when confined, and internal friction quite expressed.

Noble materials for the realization of road pavements are not available everywhere in southern Algeria [8,9], especially since they are less and less available in their usual deposits [8]. Therefore, a replacement material is highly sought after to overcome this problem. DS is widely advocated for this purpose, especially because of its abundant availability. This should result in a visibly low price. However, its geotechnical defects must be sufficiently corrected to make it acceptable. That is, complying with the practical requirements and rules of the art.

This study precisely targets the reinforcement of the DS by a geotextile (GTX) material to compensate for its intrinsic defects. The GTX compound was chosen to have low mechanical quality to highlight the economic advantage of the DS/GTX compound. The effect of including GTX in the DS was tested using the California load-bearing test (CBR). This index is, in fact, indicative of the bearing capacity of the material and therefore of its suitability in pavements.

The GTX associated with sand is initially introduced as healthy and then regularly perforated with the aim (among other things) of reducing its quantity while maintaining a sand reinforcement threshold. The chosen values of the diameter of the perforations made on the GTX ($2mm \leq \phi \leq 12mm$) and of the spacing ($5mm \leq SP \leq 21mm$) between these perforations were found to generate sufficiently diversified bearing capacity results to satisfy the intended analysis.

The perforation of the GTX indeed diminishes its tensile strength performance. However, this resistance is not the primary focus compared to the intended objective of utilizing the GTX. Below are some advantages that justified the approach of perforating the GTX:

- Reduction in the quantity of GTX used (see the results in section 4)
- Enhanced entanglement between sand and GTX compared to intact GTX
- Tensile strength of the DS/GTX compound is not the primary target for the integration of perforated GTX. The mechanical suitability of the compound for road surface use is primarily reflected in its resistance to compression and shear.

Nomenclature	
CBR	California bearing capacity
CMD	cross-machine direction
DS	dune sand
GTX	geotextile
MD	machine direction
SP	spacing

2. Research significance

The study elaborated is mainly a research work in this first phase. The idea of performing regular perforations on the GTX sheet has not been detected in many scientific studies that have been consulted. The inclusion of such a perforated GTX in a sand matrix targets a threefold objective:

- Reinforcement of sandy soils is naturally achieved by exploiting the strengthening function of geotextiles manufactured for this purpose. The inclusion of GTX is primarily intended to compensate for the non-cohesive aspect of sand using confinement, entanglement, stress damping, …
- Test the adequacy of the DS/GTX compound to be used as a foundation layer for linear structures (roads, rural roads, railways, trench filling, …), especially in regions where suitable materials are not available.
- Optimize the amount of GTX used per sand-volume unit. Perforation of the GTX obviously decreases the net surface of the GTX layer included in the sand. It also induces an additional retention of sand in place compared with non-perforated GTX. This new layout of the GTX resembles the installation of a geogrid (GGR) or a geonet (GNT), but the cost of the GTX (less perforations) is recognized as low compared to the GGR and GNT [9–11].

The results of this study could not be sufficient to be projected directly on the practice; however, it is an essential step of analysis and contributes to the global information on the suitability of the DS/GTX compound to be used in pavements. Remember that both materials (DS and GTX) are available wherever a road project is planned throughout the northern Sahara. The expected benefits (based on several scientific and technical references, e.g., [12–15]) of implementing a road foundation layer made of DS/GTX material are indisputably compared with those of a compacted material. We distinguish in particular the speed of execution, the reduced number of labour (not even specialised), the saving of compaction energy and irrigation water, open-cast quarries and the simplicity and universality of the usable engines.

This study is fundamentally based on the bearing capacity test (CBR), which is both significant and unavoidable in road studies. This study is intended to be concentrated rather than distributed over several delicately correlated aspects. The targeted analytical objective was to determine the effect of the GTX perforation pattern on the CBR index, which represents the bearing capacity of the compound material.

Studies comparable to this one have not been identified in the widely investigated technical literature. A comparison with previous results was therefore not encouraged. Nevertheless, the few works cited in the references served as support for the study and helped justify some approaches and reasoning adopted. On the other hand, the results and conclusions of the present study constitute a starting point for many scientific investigations analysing the effects of the perforation pattern (shape, dimensions and spacing of perforations) of GTX included in the sand, the confinement loads, density, particle size of the matrix material.

3. Analytical approach

The elaborated study is mainly based on the immediate CBR test. This test is governed by various standards with slightly different methodologies [16–19]. The evaluated CBR index is measured on the DS alone and then on the sand reinforced with GTX to evaluate the contribution of GTX in terms of bearing capacity. On the other hand, the results obtained from the CBR index of the DS/GTX compound were compared with those of a reference tuff ($Tuff_{ref}$). The latter is usually used in the region of Ouargla located in the southeast of Algeria (Latitude: 31.9629, Longitude: 5.34193, Altitude: 123 m to 315 m).

The GTX included in the sand was perforated according to a regular grid (diameter of the holes and spacing between them). Furthermore, by reducing the quantity of GTX included in the sand matrix, GTX is perforated to promote entanglement between the two materials (DS and GTX). The analytical approach adopted in this study focuses on observing the effect of perforations (diameter and spacing) on the CBR index of the DS/GTX compound.

In addition, the obtained results were processed and analysed using regression techniques. The parameters considered characteristic of GTX and DS are highlighted to predict the bearing capacity of the compound (DS/GTX) through a mathematical relationship, particularly showing the type of sand and the perforation pattern of GTX. The CBRDS/GTX relationship depending on the type of sand, the diameter of the perforations made on the GTX, and the spacing between them is indeed interesting insofar as an order of magnitude of the soil bearing capacity (made of DS/GTX material) is obtained even before the implementation of this material in situ.

The CBR tests are performed following the procedure [17], except that a GTX layer must be included in the sand. The work of [20] indicates that the highest CBR values are obtained when a GTX (perforated or non-perforated) layer is associated with a sandy matrix and placed on the test specimen surface. The installation of the GTX layer is therefore accomplished by simply placing it on the surface of the sand specimen and then applying the confinement discs (figures 1 and 2). Laying the GTX on the surface of the sand layer is considered advantageous from an on-site implementation point of view. This is because when the sand (component of the foundation layer of a road for example) is confined by the GTX in the cover, the spreading and compaction of the overlying layer (base layer) becomes less painful than if the sand was not covered by the GTX. Studies conducted by [21] also attest that the greatest values of the CBR are obtained when a single GTX layer is associated with sand, corresponding to a GTX confinement load applied by a 1 cm sand layer.

Fig. 1. Beginning of a CBR test (GTX is put on top of the sand).

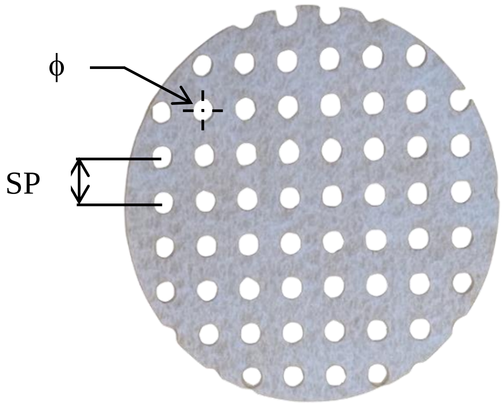

Fig. 2. Perforated GTX pattern.

4. Results and interpretations

The 'immediate CBR' tests are carried out according to the standard methodology using sand in a dry state. This is to simulate as best possible the hygroscopic conditions in the south of Algeria. The CBR mould was simply filled with sand and vibrated to an identical reference volume for all tests. Table 1 shows the usual characteristics of the materials tested (sand, geotextile and a tuff of reference). The particle size distribution of the DS used is specifically explained in Figure 3. Table 2 shows the results of the CBR tests carried out: on the sand alone, the DS/GTX compound, and the tuff of reference usable in the Ouargla region. In table 2, (ϕ) denotes the diameter of the perforations and (SP) denotes the spacing between these perforations. The two sizes (ϕ) and (SP) are expressed in mm. Among the combinations (ϕ, SP) shown in table 2, the minimum percentage of the area of the perforated GTX compared with that of the non-perforated GTX is 49.76%.

Table 1. Characteristics of the used materials.

Dune sand		Geotextile		Referential tuff	
Sampling location	N'Goussa	Nomination	AS10	Sampling location	RN3, Pk 647
Unit weight of solids (kN/m^3)	26.5	Surface mass (g/m^2)	100	Maximum dry unit weight (kN/m^3)	18.15
Minimum unit weight (kN/m^3)	15.2	Thickness under 2 kPa (mm)	0.5	Optimum water content (%)	10.39
Maximum unit weight (kN/m^3)	18.1	Tensile strength (kN/mm) MD	6	Natural water content (%)	1.94
Natural unit weight (kN/m^3)	17.4	Tensile strength (kN/mm) CMD	7		
Sand equivalent (%)	86.62	CBR puncture resistance (kN)	1.0	CBR (%)	35.37
Porosity (%)	17.75	Resistance to pyramidal punching (kN)	0.7	Uniformity coefficient Cu	1.38
Natural water content (%)	3.1	Permeability normal to the plane (m/sec)	0.08	Insoluble (%)	27.30

MD: Machine direction CMD: Cross-machine direction

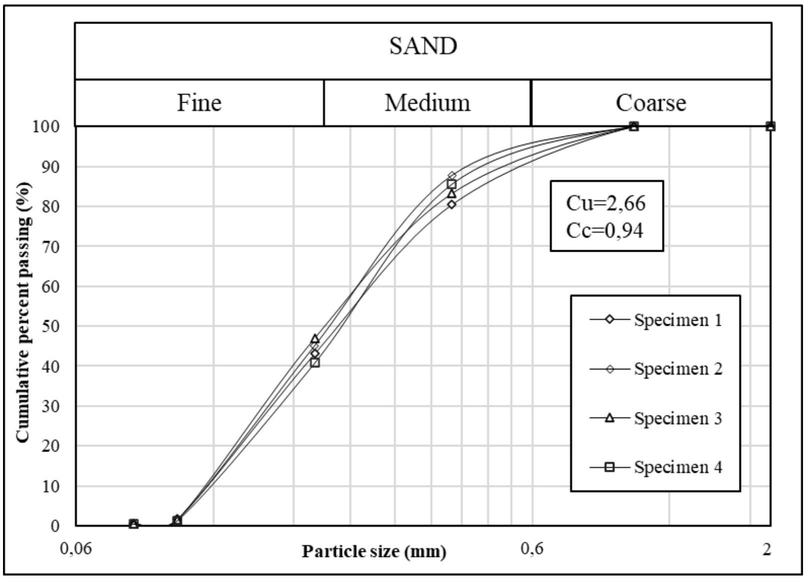

Fig. 3. Particle size distribution of dune sand based on the MIT classification.

The physical and mechanical parameters presented in Table 1 and Figure 3 show:

- medium sand with a fairly tight grain size. The stationarity of the results of the particle size analysis, obtained from several sand samples, reflects the intrinsic identity of that size, i.e., granulometry. Furthermore, the natural density state of the sand is close to that of the densest. This means that the sand is naturally almost compacted. These two characteristics of aeolian sand (tight grain size and fairly dense compactness) contribute to a behaviour that is as good as mediocre from the viewpoint of compressibility towards sliding and brittle fracture. The sand in the sampling area is almost dry, which is understandable because of the aridity of the entire geographical area concerned. Finally, the sand was perfectly free of cohesion and appreciated friction.

- a geotextile product designated by the AS10 code, which is of low mechanical quality. It is a GTX made of polyester, which is usually used for separation purposes. AS10 is the lowest-performing range among the entire GTX AS family manufactured by the same company.

- that the referential tuff is quite dense and has an appreciable bearing capacity because of its CBR index. The high rate of soluble matter (72.7%) indicates that the tuff in question is highly sensitive to leaching/dissolution agents. Tuff is also naturally almost dry. This is always a result of the hot and arid climate in the study area.

Table 2. CBR results (%) of the performed tests.

Referential tuff	35.37							
Sand alone	7.64							
DS/GTX	Non-perforated GTX	29,96						
	Perforated GTX	SP 5	SP 7	SP 9	SP 11	SP 13	SP 15	SP 17
	ϕ= 2 mm	12,47	13,38	15,64	18,76	---	---	---
	ϕ= 4 mm	---	10,09	11,69	12,85	15,38	---	---
	ϕ= 8 mm	---	---	---	11,43	11,89	14,33	17,27
	ϕ= 10 mm	---	---	---	---	12,04	12,92	15,68
	ϕ= 12 mm	---	---	---	---	---	10,13	10,84

The results shown in table 2 clearly indicate the contribution of GTX to bearing capacity when incorporated into the sand. The bearing capacity of the sand alone is low (7.64%), but it increases up to 29.96% when the sand is reinforced with the non-perforated GTX and 18.76% when the GTX is perforated. This gain in bearing capacity is implicitly due to the introduced GTX and its perforation pattern (diameter and spacing). The maximum recorded value of CBR (non-perforated GTX: 29.96% and perforated GTX: 18.76%) reaches (respectively) 84.7% and 53% of the CBR index of the referential tuff. If a GTX of better mechanical qualities is used, exceeding the CBRtuf value (= 35.37%) does not seem impossible for a specific combination of (ϕ) and (SP).

At this stage of the study, it should be noted that the referential tuff (CBR = 35.37%) is one of several usable tuffs. If a tuff of a lower bearing capacity was chosen as a reference, the DS/GTX material would have been considered appreciable. On the other hand, the best result obtained from the DS/GTX compound (= 29,96 % if the GTX is non-perforated and 18.76% if the GTX is perforated) can be considered independently of the tuff chosen as a reference. In fact, in the geotechnical design of a road (and other linear structures in general), the layer considered (DS/GTX) must have a CBR index between those of the adjacent layers: upper and lower. Subject to other conditions to be satisfied, the DS/GTX compound may be retained for its CBR index if it is intermediate between those of the adjacent layers. Moreover, the CBR value = 18.76% which is dependent on the combination (ϕ=2mm, SP=11mm) corresponds to almost 63% of the CBR of the compound with GTX without perforations. The combination (ϕ=10mm, SP=19mm) also provides good bearing capacity (around 62%). The ratio between the CBR value of the compound and the surface of GTX provided (function of the perforation pattern) can be optimized via additional tests which can be quite voluminous.

Figure 4 shows the results obtained from the CBR indices (table 2) attributed to the surface of GTX remaining at the end of each perforation combination (ϕ, SP) expressed as a percentage of the solid surface of the GTX layer. The curves in figure 4 are extended considering the observation and logic set out below:

- The CBR bearing capacity values of the DS/GTX compound shall converge to that of sand alone when the surface of the GTX is increasingly reduced by perforation.
- Conversely, when the GTX is less perforated, the lift of the DS/GTX compound must converge towards that of the DS/GTX compound with healthy GTX, i.e., non-perforated.

Three remarkable aspects can be seen in figure 4:

- The percentages of the GTX surface after perforation (Arem) of all tests carried out were calculated for each combination (ϕ, SP); the CBR results obtained tend, in fact, to join those of the sand alone and of the sand integrating the healthy GTX (DS/GTX healthy). In addition, these results were extrapolated to extreme points (sand alone and sand with healthy GTX).

- The convergence of CBR bearing capacity values from that of sand alone to that of DS/GTX healthy is different according to the perforation diameter. As the GTX is perforated, the small perforation diameters (2mm and 4mm) slowly converge towards the CBR index of the SD/GTX healthy compared with the coarser ones (8mm, 10mm and 12mm). This means that for the same percentage of perforation of the GTX, i.e., the same rate of reduction of the surface of GTX, the diameters of perforation ϕ=10mm and ϕ=12mm show a bearing capacity of the DS/GTX compound much higher than those in ϕ= 2mm or in ϕ=4mm. This observation constitutes a contribution to the criterion for choosing the perforation pattern of the GTX included in the sand concerning the saving in surface area of the GTX used.
- The order of the curves ϕ=10mm and ϕ=12mm is reversed despite the multiple repetitions of the tests for these two perforation diameters. It is concluded from this that the optimum perforation diameter of the GTX, considering the variations presented in figure 4, is between 10mm and 12mm. This optimum perforation diameter could be related to the average size of the sand grains (which is almost the same for all grains). A value of the perforation diameter between 10mm and 12mm is certainly important to remember and recommend as part of the materials and objectives included in this study. The spacing between these recommended diameter perforations will remain the only parameter to be approved for the targeted bearing capacity of the DS/GTX compound.

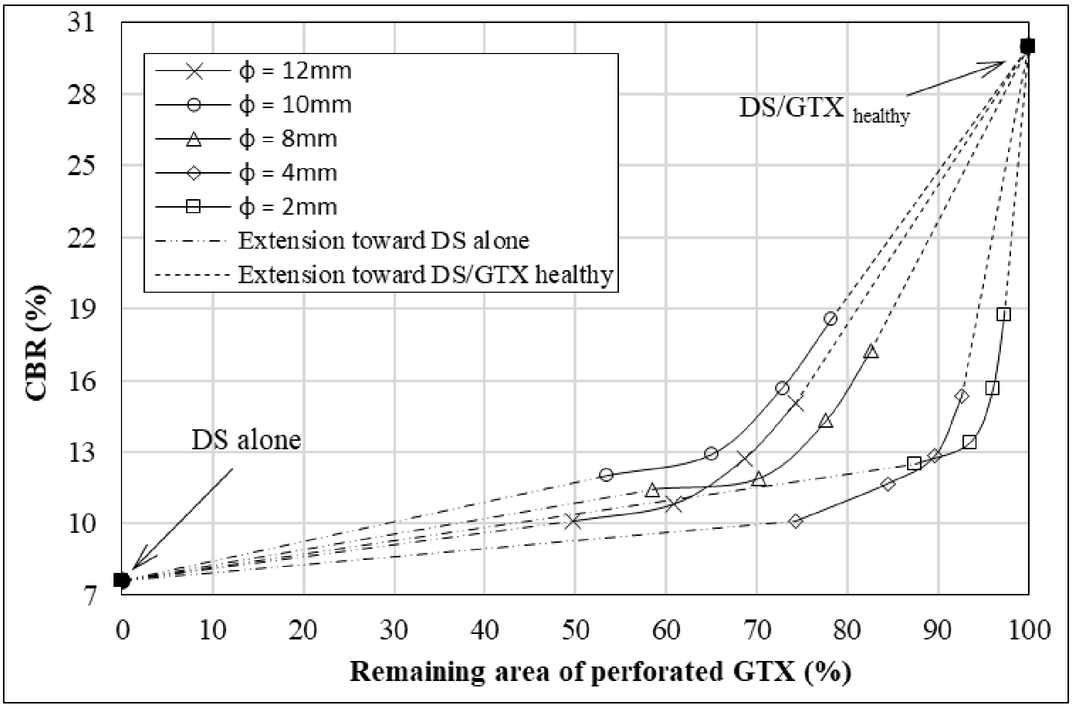

Fig. 4. Variation of the CBR index according to the remaining GTX surface after perforation

Figure 5 shows a graphical presentation of the obtained CBR results according to (SP) and (ϕ). The increase in the bearing capacity is clearly visible as a function of the increase in (SP) and decrease in (ϕ). Variations in bearing capacity (CBR) are found to be logical for (at least) two considerations:

- The CBR index varies in descending order: DS/GTX healthy, DS/GTX perforated, and DS alone. This highlights the contribution of GTX to sand reinforcement: the greater the quantity of GTX, the stronger the sand.
- An increase in the diameter (ϕ) of the perforations or a decrease in the spacing (SP) between the perforations leads to the same result, i.e., a reduction in the CBR bearing capacity. This identity of the result obtained was predictable because the two variations (of ϕ and of SP) imply the same fact: reduction of the surface of GTX integrated into the sand.

The results shown in figure 5 explicitly indicate a decrease in the immediate bearing index (CBR) when the diameter (ϕ) of the perforations is increased. This is valid regardless of the spacing maintained between the perforations. Similarly, for the same spacing between the perforations (SP), the CBR index decreases when the diameter (ϕ) of the perforations decreases. The variation in the bearing index of the compound (DS/GTX) tested can also be represented as shown in figure 6. The CBR index of sand alone (DS) is improperly represented by the horizontal dotted line.

Other representations of the same results obtained are obviously possible and could reveal aspects that are not very visible in figures 5 and 6. The intervals of the selected values for the diameter of the GTX perforations and the spacing between them ($2mm \leq \phi \leq 12mm$ et $5mm \leq SP \leq 21mm$) are adopted as preliminary. In other words, to obtain an initial idea. Only on the basis of these results is an optimization of the perforation pattern possible. The desired optimum result obviously does not depend on the preliminary adopted patterns. However, some conditions affected the (ϕ) and (SP) values chosen in this study. These conditions are summarised as follows:

- dimensions of the mould containing specimens of the (DS/GTX) compound. The latter cannot be other than those of the CBR mould to be able to use the universal formula that gives the CBR index of a tested material.
- the diameter of the perforations is smaller than that of the CBR mould. The CBR mould itself is approximately 15cm in diameter, according to the cited standards [17–20]. A regular perforation of the GTX with a diameter greater than 15cm simply means that the GTX is absent, i.e., the sand is unique without reinforcement. Furthermore, the diameter of the perforations must be limited (as a first approximation) to that of the piston used among the accessories of the CBR test (ϕ_{piston}=50mm). The purpose of this is to guarantee a minimum support surface for the piston on the GTX laid on the sand surface.

The investigation of the effect of the dimensions (ϕ and SP) on the bearing capacity of the DS/GTX compound can be extended to values much higher than those adopted in this study. This may be the case with the plate test performed on site. The dimensions (ϕ and SP) could then reach orders of magnitude comparable to the diameter of the loading plate (60cm). The results of the plate tests can be compared or correlated with those of the CBR tests; however, the conclusion mentioned below (already insinuated in the previous paragraph) is still valid and can be retained on a provisional basis:

the more the GTX is perforated, the less it contributes to the bearing capacity of the (DS/GTX) compound.

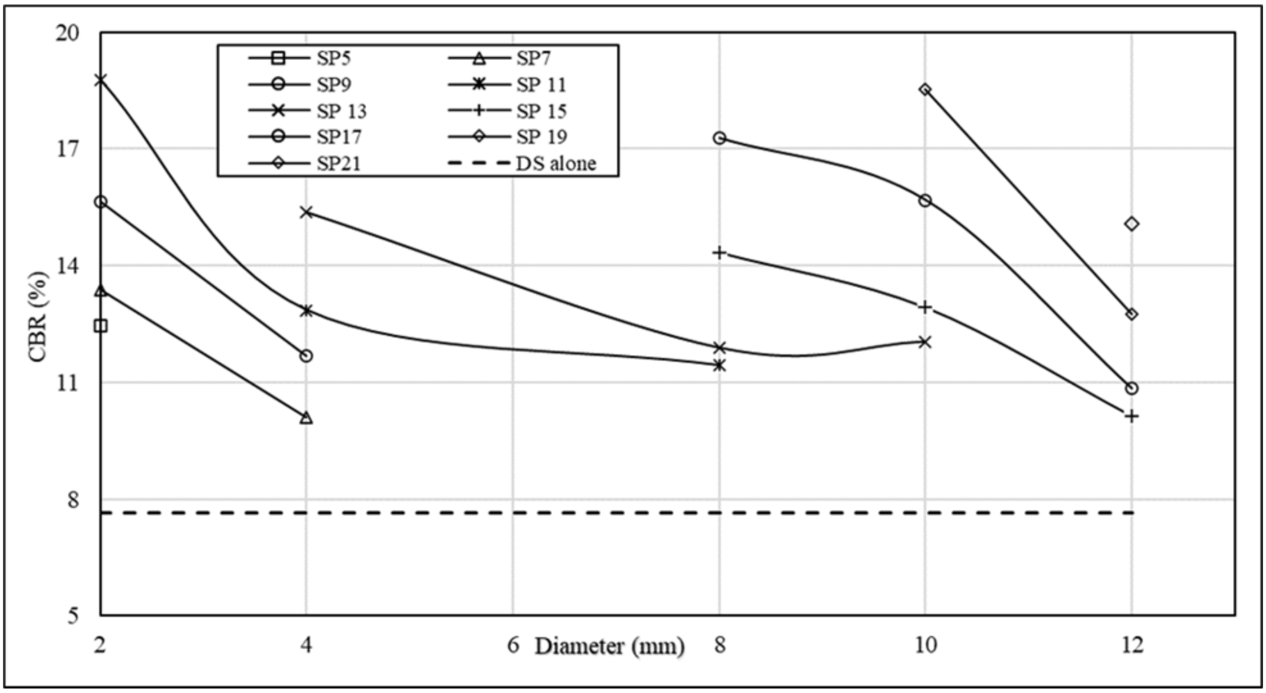

Fig. 5. Variation of the CBR index according to the diameters of the perforations for various spacings.

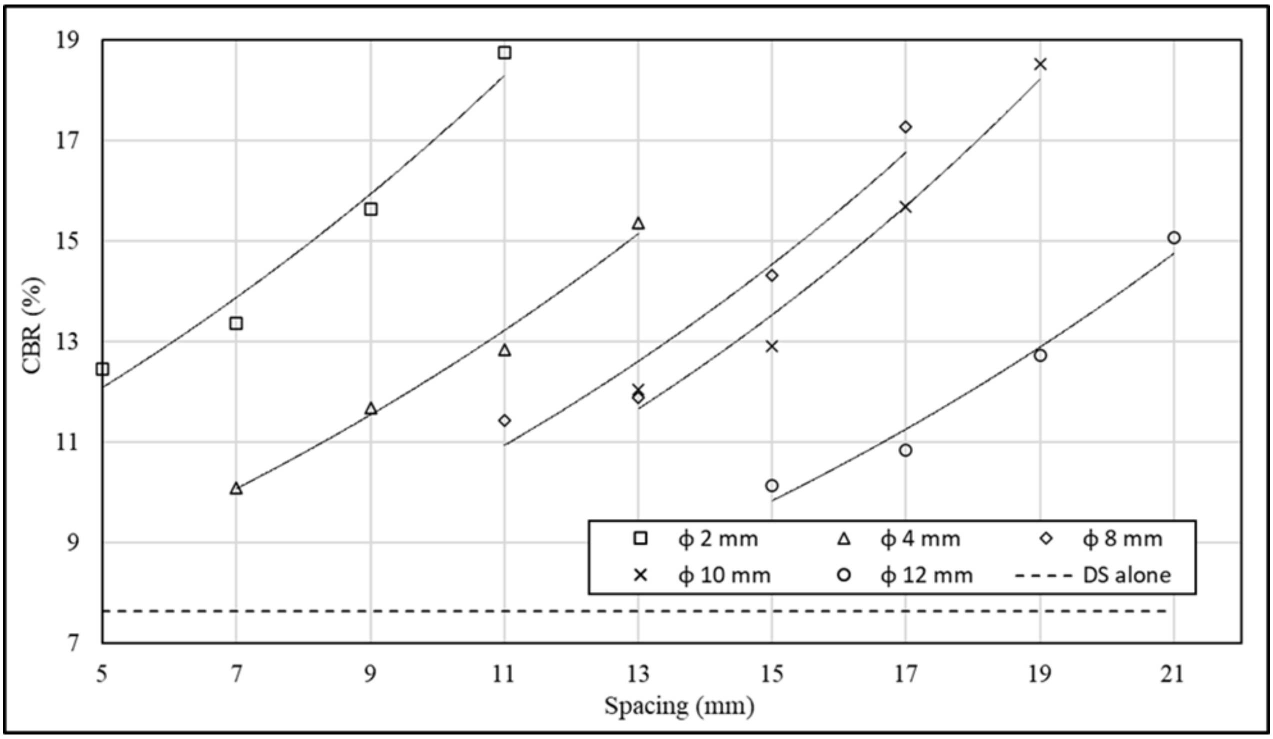

Fig. 6. Variation of the CBR index according to the spacing between the perforations of various diameters

The results obtained from the CBR of the reinforced sand (figures 5 and 6) follow a logical variation insofar as they are all closer to that of the sand alone when the diameter (ϕ) of the perforations increases and/or the spacing (SP) between these perforations decreases. This is also confirmed by the fact that the results of CBRDS/GTX tend towards those of non-perforated GTX reinforced sand as the diameter of the perforations decreases and/or the spacing between these holes increases. This logic attests to the harmony and compatibility of the results of the tests. This trend is originally justified by the obvious fact that the bearing capacity of the sand alone is lower than that of the non-perforated GTX reinforced sand. All variants of the DS/GTX compound with any perforation pattern must have intermediate bearing capacity values between sand alone and GTX healthy reinforced sand.

5. Analytical processing

The results obtained for the CBR index of sand reinforced with perforated GTX (figure 6) are visibly close to the trend curves. The correlation coefficient between the experimental results and the trend curves is at least 95% and reaches 99% for the series ϕ= 4mm. In addition, the asymptotic branches of the plotted curves show almost the same curvature. This is a visibly remarkable aspect of the results obtained, which must represent a common and constant parameter for the tests carried out. After an analytical examination of several mathematical functions of the simulation, the exponential function was found to be the best adjusted to the results obtained (points shown in figure 6). Thus, the development and deepening of the investigation prompted the adoption of the following relationship: $Y = a.e^{b.X}$ (1)

Where

Y: CBR (%)

X: spacing between the perforations (mm)

a and **b:** constants characterizing the DS/GTX compound

Being two integrated materials (DS and GTX), the two constants (a and b) are analytically sought to be calibrated to these two components: one of the two constants (a or b) must characterize the sand, and the other (b or a) the GTX introduced into the sand.

Table 3 summarizes the functions representative of the CBR results (figure 6) obtained from the regression analysis based on several functions, which are then concluded in the exponential function.

Table 3. Mathematical functions representative of the obtained results.

	Function	Correlation coefficient (%)
ϕ= 2 mm	$CBR=8,5604e^{0,0691SP}$	97
ϕ= 4 mm	$CBR=6,2625e^{0,068SP}$	99
ϕ= 8 mm	$CBR=4,9949e^{0,0712SP}$	95
ϕ= 10 mm	$CBR=4,4321e^{0,0744SP}$	98
ϕ= 12 mm	$CBR=3,5653e^{0,0677SP}$	98

The equations presented in table 3 represent the trend curves in figure 6. Parameter (b) in equation (1) is substantially constant, with an average value of 0.071. This parameter is attributed to the parabolic slope of the curves in Figure 6, which are almost the same. Therefore, parameter (b) is independent of the GTX perforation diameter and the spacing between these perforations. By elimination resonance, the single parameter connected to the compound (DS/GTX) and simultaneously independent of the GTX (regardless of the configuration of the latter), must obviously be associated with the sand matrix. As a result, coefficient (b) is attributed to the sand, which is the same for all performed tests.

Sand is strongly characterised by its fairly tight grain size (figure 3 and table 1: $C_u = \frac{d_{60}}{d_{10}}$ = 2.66). The diameters from d_{15} to d_{90} are almost the same. The uniformity coefficient (C_u) of the sand is an intrinsic characteristic of the latter and is very representative of it. Parameter (b) can be related to (C_u). Therefore, parameter (b) can be written as: $b=0.071=0.027xC_u$. (2)

Based on the analysis expressed after the presentation of equation (1), the parameter (a) considered related to the GTX is dependent only on the diameter of the perforations, not on the spacing between them (see figure 6), where a=f(ϕ).

Parameter (a) of equation (1) being considered related to the GTX, in view of the curves in figure 4, this parameter must be related to the diameter of the perforations performed on the GTX: a=f (ϕ).

A simple representation of the values of the parameter (a) as a function of the diameter (ϕ) of the perforations (figure 7) highlights:

- a linear relationship of the type $a = 8.81 - 0.45\,\phi$ (3)
- also, a better adjusted relationship: $a = 9.9 - 0.9\,\phi + 0.03\,\phi^2$ (4)

Given the values close to the correlation coefficients shown in Figure 7, the linear trend is preferred because of its simplicity. Therefore, relationship (3) is retained to express parameter (a) according to the diameter of the perforations performed on the GTX.

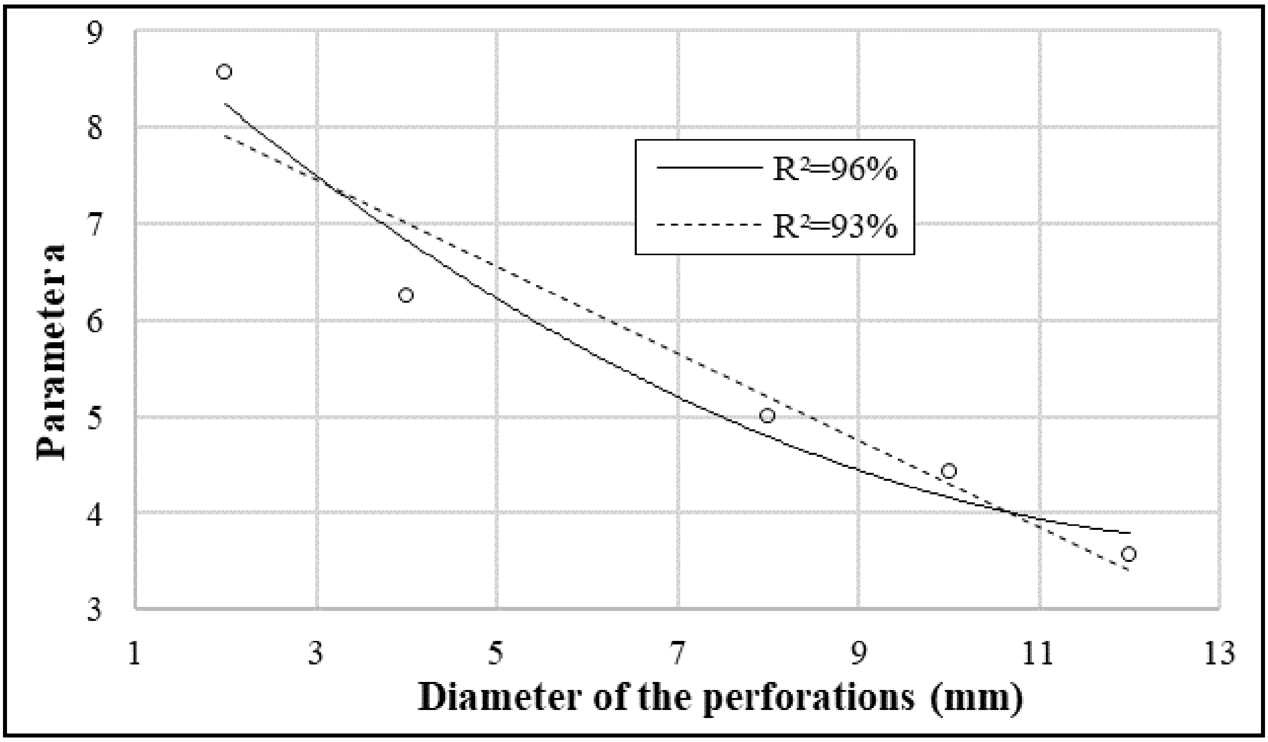

Fig. 7. Parameter (a) function of the diameter (ϕ) of the perforations.

The coupling of equations (1), (2), and (3) results in the following overall equation:

$$CBR_{DS/GTX} = (8.81 - 0.45\,\phi)e^{0.027C_u \times SP} \quad \textbf{(5)}$$

Where:

CBR (%): CBR index of the DS/GTX compound

C_u: uniformity coefficient of the sand

ϕ (mm): diameter of the perforations

SP (mm): spacing between the perforations

Equation (5) relates the fundamental quantities characterising the materials used (sand and geotextile) to the bearing index (CBR) of the compound (DS/GTX). This relationship can be retained as a forecast of the CBR index of the DS/GTX compound when the grain size of the sand and the perforation pattern of the GTX (diameter of the perforations and spacing between them) are known.

Relationship (5) is empirical and implicitly applicable to the materials (DS and GTX) considered in this study. Apart from the grain size of the sand and the pattern of perforation of the GTX, the few quantities indicated below can (more or less) distinguish the sands from each other and the GTX from each other:

- **Distinction between dune sands:** This study only considers dune sands. The latter are recognised as comparable in terms of particle size [22]. This observation coupled with the identical quartz nature of all these sands makes it possible to deduce that it is a question of an apparent density that differs little between the dune sands. The elementary relationships (6) and (7) below confirm this conclusion:

$$\gamma_d = \frac{\gamma_s}{\text{[illegible]}} \quad \textbf{(6)} \qquad \textbf{with} \qquad e = \frac{V_V}{\text{[illegible]}} \quad \textbf{(7)}$$

Where **γ_d**: dry density of the sand. This is the same as the apparent density due to the almost dry natural state of the soil.

γ_s: density of the solid grains. This value is also the same for all dune sands because of their geological quartz nature. On a general scale [23], the density of all solid soil grains on the earth's crust rarely exceeds the interval [26 to 27] kN/m^3.

e: void ratio of the sand. As long as the shape of the grains is very rounded, the ratio between the volume of the voids and that of the solid grains does not vary depending on whether the grains are a little coarse or a little fine (provided that these grains are of comparable sizes, i.e., tight grain size such is the case in the present study).
The deduction of the small difference in apparent densities between the dune sands is also indicated by [3,24].

- **Distinction between geotextiles:** From the viewpoint of the perforation pattern, no distinction is made between GTX types. All can be perforated indiscriminately according to the same chosen pattern.

The notable differences between the multitudes of GTXs exist in particular in terms of their physical and mechanical characteristics. The range of differences between all these GTXs is visibly reduced by the fact that this study considers one of the lowest-performing GTXs, as reported in section 1 (Introduction). Therefore, the results of this study can be adapted to slightly different GTXs than those used in this study.

6. Conclusion

This study focuses on testing the bearing capacity (CBR) of a sand/geotextile compound. The sand in question is abundant in the northern Sahara, and GTX was chosen among those with the lowest performance. This is to highlight the economic aspect of the compound DS/GTX. The GTX is perforated according to a regular rectangular network of circular perforations and introduced into the dune sand. Thus, the amount of GTX used is reduced by 50.24% compared with that of the non-perforated GTX, and the entanglement between the two materials is improved. The resulting compound is proposed for use as a foundation layer for pavements.

The study conducted is typically experimental. First, it highlights the logic of the results obtained:

The highest CBR index corresponds to confined sand of non-perforated GTX, whereas sand alone without GTX has the lowest CBR index. The bearing capacity of the compound (in view of the CBR index) is all the more diminished as the GTX is perforated with a large diameter and small spacing between the perforations. The contribution in bearing capacity of the perforated GTX reaches almost 63% of that of the healthy GTX. This CBR bearing capacity is achieved for the two combinations (ϕ=2mm, SP=11mm) and (ϕ=10mm, SP=19mm), but the latter is preferred in view of the surface savings of the GTX used.

The study also shows that the (CBR) index of the DS/GTX compound under the same combinations (ϕ, SP) that have been indicated is increased to 246% compared to that of sand alone, and it reaches 53% of the bearing capacity of a tuff usually used in the body of pavements across the study area. This observation constitutes a contribution to the criterion for choosing the perforation pattern of the GTX included in the sand concerning the saving in surface area of the GTX used.

A regression analysis of the obtained results enabled the establishment of an empirical relationship between the characteristic parameters of the two materials (sand and geotextile). The deduced formula relates the Californian bearing index of the DS/GTX compound to the uniformity coefficient of the sand and the perforation pattern of the GTX. Therefore, this formula contributes to an indirect evaluation of the CBR index of the DS/GTX compound.

7. Recommendations

At the end of this study, some recommendations are provided to enrich and deepen the investigation in the context of the subject addressed. These are particularly highlighted in relation to the experimental programs that can be designed.

- The tests carried out in this study can be repeated while varying the type of sand reinforced with perforated GTX, the type of GTX itself, the perforation pattern of the GTX (shape, dimensions and spacing of perforations), the number of GTX layers integrated into the sand, the anchorage depth of the GTX in the sand specimens and the types of bearing capacity tests that can be performed: in the laboratory or on-site.

- Similarly, a numerical simulation of the bearing capacity of sand reinforced by a perforated GTX appears interesting; however, it requires several tests to evaluate the interface effects between DS and GTX for each perforation pattern. It is best to rely on tests to evaluate this bearing capacity.

- The investigation technique according to the method of design of experiments (DOE) is strongly indicated in order to detect the parameters with dominant effect on the bearing capacity of the compound: the shape of the perforations, dimensions of the latter, spacing between the perforations, thickness of the GTX, tenacity of the latter, ...

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