



TECHNO-ECONOMIC ASSESSMENT OF RESOURCE-EFFICIENT PERFORATED GEOTEXTILES FOR SUSTAINABLE AEOLIAN SAND SUBGRADES IN ARID ROAD INFRASTRUCTURE

MOHAMMED ABDALLAH TALBI^{1,2}, MUSTAPHA KEBAILI¹, ISHAK GOUDJIL^{1,2},
SAFOUANE ZIREGUE^{1,2}

¹ DEPARTMENT OF CIVIL ENGINEERING AND HYDRAULICS, KASDI MERBAH UNIVERSITY, OUARGLA, ALGERIA.

² LABORATORY OF EXPLOITATION AND VALORIZATION OF NATURAL RESOURCES IN ARID AREAS (E.V.R.N.Z.A.),
OUARGLA, ALGERIA

*CORRESPONDING AUTHOR: talbi.mohammed.abdallah@univ-ouargla.dz

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ABSTRACT

Expanding road infrastructure in desert regions faces severe material constraints due to the scarcity of high-quality local aggregates and the poor load-bearing capacity of ubiquitous aeolian sand. While geosynthetic reinforcement offers a viable stabilization method, raw material costs and transport logistics remain significant challenges for large-scale implementations. This study presents a techno-economic feasibility analysis of utilizing regularly perforated nonwoven geotextile-reinforced dune sand as an efficient pavement subgrade composite. Utilizing experimental California Bearing Ratio (CBR) data and physical sand-geotextile interaction mechanisms, a comparative assessment was conducted across three pavement structural alternatives: conventional soil replacement with imported calcareous tuff, dune sand reinforced with intact nonwoven geotextile, and dune sand reinforced with perforated geotextile configurations. The material balance analysis demonstrates that optimal perforation geometries ($\phi = 10$ mm, $SP = 19$ mm and $\phi = 12$ mm, $SP = 15$ mm) reduce raw geotextile polymer consumption by 21.75% to 50.24%, while maintaining bearing capacities (CBR up to 18.54%) suitable for S2 pavement subgrade classes. Furthermore, direct cost evaluations reveal that in-situ perforated geotextile reinforcement cuts subgrade construction expenditures by up to 89.65% compared to conventional tuff replacement, and yields up to 17.79% direct savings over intact geotextiles. This work demonstrates that resource-efficient geosynthetic perforation offers a cost-effective, sustainable, and scalable technical framework for transportation infrastructure in arid regions.

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1. INTRODUCTION

Transportation infrastructure serves as a vital backbone for socio-economic development, trade, and regional connectivity in desert environments. However, road construction across arid regions, such as the Northern Sahara, confronts major engineering, economic, and environmental challenges. The vast desert landscapes are dominated by aeolian sand (dune sand), an abundant, local, and virtually cost-free material. From a geotechnical perspective, dune sand (DS) is characterized by its lack of cohesion and low compaction capacity (Elipe & López-Querol, 2014; Smaida et al., 2019). DS is also known by its high purity and virtually uniform particle size distribution (Xia, Zhang, Du, et al., 2020). Consequently, standard road engineering design frameworks systematically reject untreated DS for structural pavement layers (Ministère des Travaux Publics, Direction des Routes, 2001).

Historically, the conventional engineering solution to overcome this limitation relied on soil replacement strategies, importing high-quality granular aggregates, such as calcareous tuff, from distant quarry deposits (Khan, 1982). Although this conventional approach can satisfy structural bearing requirements, its economic and environmental viability may be limited by the transportation of aggregates over long distances, the depletion of natural resources, and the environmental impacts associated with quarrying and material supply (Mroueh et al., 2001; Strippel, 2001). Local quarries of natural noble aggregates are undergoing rapid depletion, leading to escalating material purchasing costs, extended transportation haulage, high heavy-vehicle fuel consumption, and heavy carbon emissions (Akacem et al., 2021; de Bortoli, 2023).

To mitigate aggregate scarcity and reduce hauling costs, soil reinforcement utilizing geosynthetics, specifically nonwoven geotextiles, has emerged as a highly effective technique to enhance the mechanical confinement, shear strength, and bearing resistance of marginal sandy soils (Al-Abdullah et al., 2016). However, deploying continuous, intact geotextile sheets across extended desert highway networks involves significant capital expenditure and material consumption. To overcome these economic and physical limitations, the present investigation shows that introducing controlled, regularly perforated patterns into nonwoven geotextiles significantly alters the soil-geosynthetic interaction mechanism. Rather than relying solely on surface friction and confinement, as described by Palmeira (2009), the perforations create an enhanced particle-interlocking mechanism where DS grains penetrate the openings.

While recent literature has primarily focused on laboratory testing, micro-mechanical interaction modes, and empirical modeling of perforated geotextile-sand composites, a critical research gap remains regarding the practical engineering economics, financial feasibility, and project-level decision-support tools required for real-world implementation. Specifically, the quantifiable trade-offs between geotextile raw-material savings, structural bearing capacity retention, and direct pavement construction cost reductions have not been systematically established.

To bridge this research gap, this study provides a comprehensive techno-economic evaluation of resource-efficient perforated geotextile-reinforced DS for pavement subgrade applications. The primary objective of this research is to quantify the raw material savings and direct financial cost reductions achieved through various geotextile perforation configurations (ϕ , SP) compared to intact geotextiles and conventional calcareous tuff replacement.

2. METHODOLOGY

2.1. Materials and composite performance

The aeolian sand investigated in this study was sampled from the N'Goussa dune field, located approximately 20 km north of Ouargla in southeastern Algeria (latitude: 32.145623°, longitude: 5.318839°, altitude: 137 m). This site was selected because it is representative of the extensive aeolian deposits occurring throughout the northern Sahara and offers convenient access for sample collection. The use of this material is motivated by its widespread availability, low cost, and potential to serve as an alternative material for pavement construction in arid regions where conventional aggregates are often scarce.

The reinforcement system employed in this investigation consisted of a commercially available nonwoven polypropylene geotextile (AS10). This geotextile was deliberately selected from the lower-performance range of the available AS series to assess whether meaningful improvements in the mechanical performance of aeolian sand could be achieved using a relatively low-cost reinforcement material. The product was supplied by the sole geotextile manufacturer in Algeria. A calcareous tuff commonly used in roadbed construction in the study area was also included as a reference material. Its incorporation into the experimental program enabled the load-bearing capacity of the aeolian sand–geotextile (DS/GTX) composite to be evaluated against that of a conventional material widely used in local road construction.

The physical and geotechnical properties of the materials used in this study are summarized in Table 1 and Figure 1.

Table 1. Characteristics of the materials used.

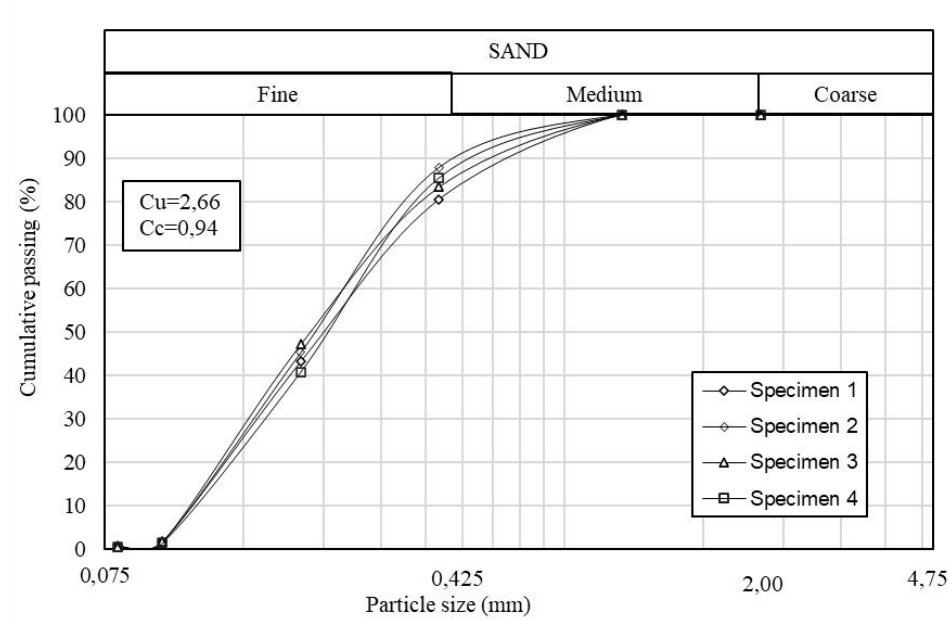
Dune sand		Geotextile		Referential tuff	
Sampling location	N'Goussa	Nomination	AS10	Sampling location	RN3, Pk 647
Unit weight of solids (kN/m ³)	26.5	Surface mass (g/m ²)	100	Maximum dry unit weight (kN/m ³)	18.15
Minimum unit weight (kN/m ³)	15.2	Thickness under 2 kPa (mm)	0.5	Optimum water content (%)	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		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

*: Machine direction

** : Cross-machine direction

Source: Own elaboration, 2026

Figure 1. Particle-size distribution of dune sand according to the USCS classification



Source: Own elaboration, 2026

2.2. Experimental program

The bearing capacity of the tested specimens was assessed using the California Bearing Ratio (CBR) test in accordance with AFNOR NF P 94-078 (1997). Two modifications were introduced to the standard testing procedure: sand compaction was performed by vibration, and the geotextile (GTX) sheet was positioned on the surface of the sand specimen contained in the mould (Figure 2 & 3).

Figure 2. Perforation pattern of the GTX

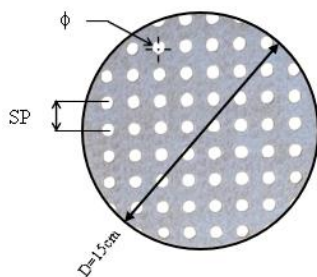


Figure 3. Initial stage of the CBR test (GTX placed between the sand layer and the loading half-discs)



Source: Own elaboration, 2026

As reported in Table 2, the CBR results indicate a substantial improvement in the bearing capacity of aeolian sand following geotextile reinforcement. The CBR value increased from 7.64% for unreinforced sand to 29.96% with intact geotextile and 18.76% with the perforated geotextile configuration exhibiting the highest CBR. These results highlight the influence of geotextile reinforcement and perforation pattern, defined by the perforation diameter, ϕ (mm), and spacing, SP (mm), on the mechanical performance of the sand. Although the intact geotextile yielded the highest CBR value, all perforated configurations achieved substantially higher values

than unreinforced sand, demonstrating the effectiveness of the proposed reinforcement approach.

Table 2. CBR results (%) obtained from the conducted 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	SP 19	SP 21	
	= 2 mm	12,47	13,38	15,64	18,76	---	---	---	---	---	
	= 4 mm	---	10,09	11,69	12,85	15,38	---	---	---	---	
	= 8 mm	---	---	---	11,43	11,89	14,33	17,27	---	---	
	= 10 mm	---	---	---	---	12,04	12,92	15,68	18,54	---	
	= 12 mm	---	---	---	---	---	10,13	10,84	12,74	15,07	

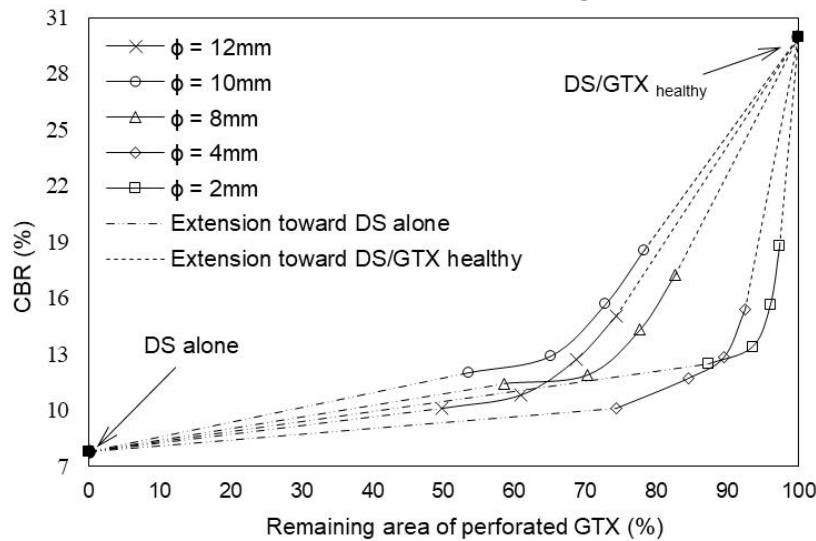
Source: Own elaboration,2026

3. TECHNO-ECONOMIC FEASIBILITY ANALYSIS

3.1. Material savings and direct cost comparison

Figure 4 presents the variation of the CBR index as a function of the remaining geotextile area after perforation (A_{rem}). Figure 4 shows a direct proportionality between the remaining GTX surface area after perforation and the measured CBR index. This proportional relationship is observed for all perforation patterns.

Figure 4. Variation of the CBR index as a function of the remaining GTX surface area after perforation.



Source: Own elaboration,2026

The results presented above is perfectly consistent with the increase in the load-bearing capacity of the DS/GTX pair when the GTX is less and less perforated. Indeed, both the tensile strength and elongation at break of unperforated GTX are better than in the case of the same GTX but perforated.

Given the harmonic shapes of the curves shown in Figure 4 (solid line segments), it is evident that the CBR tends towards that of sand alone as the remaining surface area of the GTX approaches zero, and towards that corresponding to the DS/healthy-GTX as the perforated

surface area of the GTX decreases. The dashed lines are therefore drawn by simple extrapolation, reflecting this logic.

From a practical standpoint, the best GTX perforation method is not necessarily using unperforated GTX. It is important to strike a balance between:

- the technical efficiency of the DS/GTX compound, represented by the CBR index, and
- the economic aspect of the material: represented by the remaining GTX surface area after perforation, but also by several factors related to the implementation process itself.

When the CBR index required for, for example, a road embankment project is reached, increasing the remaining GTX surface area is no longer necessary. Instead, the perforation pattern must be carefully chosen.

Furthermore, Figure 4 shows that the same CBR index value can be obtained for various remaining GTX surface areas after perforation. It will obviously be advantageous to opt for the minimum remaining perforated GTX surface area.

Interestingly, specimens exhibiting comparable remaining geotextile areas did not necessarily produce identical CBR values. The perforation pattern with relatively large, widely spaced diameters results in the same CBR index as a pattern with finer, more closely spaced perforations. However, the amount of GTX (represented by the effective surface area of the latter) is significantly lower in the larger-pore variant.

Consequently, the proposed perforation strategy transforms the design problem from maximizing reinforcement area to maximizing reinforcement efficiency. Instead of increasing the quantity of geotextile, the objective becomes identifying the perforation pattern that provides the highest bearing capacity per unit area of reinforcement.

The implemented experimental program reveals three perforation configurations corresponding to different engineering objectives (Table 3).

Table 3. Representative perforation configurations for different purposes

Configuration	GTX reduction (%)	CBR (%)	Purpose
Intact GTX	0.00	29.96	Maximum bearing capacity
=2mm, SP=11mm	3.60	18.76	Maximum bearing capacity among perforated GTX
=10mm, SP=19mm	21.75	18.54	Best compromise between performance and material saving
=12mm, SP=15mm	50.24	10.13	Maximum material saving

Source: Own elaboration,2026

3.2. Quantitative Direct Cost Analysis for Standard Two-Lane Road Subgrades

In desert road projects across Southern Algeria, the conventional design strategy relies on replacing unsuitable DS subgrades with imported calcareous tuff over a typical subgrade layer thickness of $h = 0.30$ m. The direct unit cost of conventional soil replacement ($C_{\text{replacement}}$) per square meter of road subgrade is calculated as:

$$C_{\text{replacement}} = (V_{\text{tuff}} \times P_{\text{tuff}}) + (V_{\text{tuff}} \times d_{\text{haul}} \times C_{\text{trans}}) + C_{\text{excavation}} \quad (1)$$

where:

- V_{tuff} is the volume of imported tuff (m^3),
- P_{tuff} is the quarry purchase price of calcareous tuff (DZD/ m^3),
- D_{haul} is the one-way haulage distance from the quarry to the construction site (km),

- C_{trans} is the unit transport tariff per kilometer (DZD/m³.km),
- $C_{excavation}$ is the unit cost of excavating and dumping the existing dune sand (DZD/m²).

Conversely, the unit cost of in-situ perforated geotextile reinforcement ($C_{reinforced}$) per square meter is expressed as:

$$C_{reinforced} = (P_{P.GTX} \times (1 - \frac{M_{saving}}{100}) \times S_{GTX}) + C_{trans} + (V_{DS} \times P_{DS}) \quad (2)$$

where:

- $P_{P.GTX}$ is the unit purchase price of the perforated GTX (DZD/m²),
- M_{saving} is the percentage reduction in material consumption achieved via perforation,
- S_{GTX} is the GTX surface area required for the project (m²),
- C_{trans} is the unit transport tariff per kilometer (DZD/m³.km),
- V_{DS} is the volume of DS (m³),
- P_{DS} is the quarry purchase price of DS (DZD/m³),

Table 4 illustrates the comparative direct construction cost per kilometer for a standard two-lane road subgrade (width $W = 6$ m, subgrade volume = 1800 m³, $d_{haul} = 15$ km).

Table 4. Comparative direct construction cost per kilometer for a standard two-lane road subgrade

Construction method		Construction cost per kilometer (DZD)	Savings relative to Tuff Replacement (%)	Primary Structural & Economic Feature
Conventional Tuff replacement		11 760 000,00	0.00%	High cost due to excavation & haulage
DS with intact GTX reinforcement		1 480 000,00	87.41%	High bearing capacity (CBR = 29.96%)
DS with perforated GTX reinforcement	$\phi=2\text{mm}$, SP=11mm	1 527 747,00	87.01%	Higher due to high hole density
	$\phi=10\text{mm}$, SP=19mm	1 406 731,88	88.04%	Optimal structural-economic balance
	$\phi=12\text{mm}$, SP=15mm	1 216 774,80	89.65%	Maximum financial & material saving

Source: Own elaboration,2026

As detailed in Table 4, replacing imported calcareous tuff with in-situ DS reinforced with perforated geotextile yields extraordinary financial savings:

1. Comparison with Conventional Aggregate Replacement:

The baseline cost of conventional tuff replacement reaches **11,760,000.00 DZD/km**, primarily driven by long transport logistics, fuel consumption, and quarry extraction fees. Implementing in-situ dune sand reinforcement reduces direct subgrade construction expenditure down to **1,216,774.80 DZD/km** (Configuration $\phi = 12$ mm, SP=15 mm), achieving an overall financial cost reduction of **89.65%** (**10,543,225.20 DZD saved per kilometer**).

2. Comparison with Intact Geotextile Reinforcement:

Compared to intact geotextile reinforcement (**1,480,000.00 DZD/km**), Configuration B ($\phi = 10$ mm, SP=19 mm) lowers the total subgrade cost to **1,406,731.88 DZD/km** (4.95% direct savings) while maintaining a nearly identical load-bearing capacity (CBR = 18.54%). For project requirements where maximum material efficiency is prioritized, Configuration C ($\phi = 12$ mm, SP = 15 mm) cuts construction expenditure to **1,216,774.80 DZD/km**, securing a net financial saving of **17.79%** over intact geotextiles.

4. CONCLUSION

This study presented a comprehensive techno-economic evaluation of resource-efficient regularly perforated nonwoven geotextile-reinforced DS for pavement subgrades. By integrating experimental load-bearing capacity metrics (CBR), material balance analyses, direct construction cost modeling, the research demonstrates that introducing controlled perforations into geotextiles offers a transformative approach for sustainable transportation infrastructure in arid regions. The main conclusions derived from this investigation are summarized as follows:

- Introducing regular circular perforations into nonwoven geotextiles enhances the mechanical particle-interlocking mechanism with DS grains. Across various configurations pattern, the reinforced sand composite achieves CBR values between **10.13%** and **18.76%**, representing up to a **245%** increase over untreated dune sand (CBR = **7.64%**). These values successfully satisfy the structural criteria for S2 (medium bearing capacity) pavement subgrade classes defined by official Algerian road catalog standards (Ministère des Travaux Publics, Direction des Routes, 2001).
- Replacing conventional soil replacement strategies (imported calcareous tuff) with in-situ perforated geotextile-reinforced DS dramatically reduces direct subgrade construction expenditure. Comparative cost calculations reveal that direct construction costs drop from **11,760,000.00 DZD/km** for conventional tuff replacement down to **1,216,774.80 DZD/km** for Configuration C ($\phi = 12$ mm, SP = 15 mm), securing an overall financial cost reduction of **89.65%** (a direct net saving of **10,543,225.20 DZD per kilometer**). Furthermore, compared to intact geotextile reinforcement (**1,480,000.00 DZD/km**), perforated configurations reduce total project expenditure by up to **17.79%**.

4.1. Limitations and Future Research Directions

While this study establishes a strong techno-economic baseline, several limitations should be addressed in future investigations:

- Long-Term Dynamic Performance: Future research should evaluate the fatigue and dynamic response of perforated geotextile-reinforced sand under repetitive traffic loading cycles and field plate load testing.
- Alternative Geometries and Environmental Exposure: Investigating non-circular perforation patterns (e.g., triangular, hexagonal, or staggered grids) and the long-term durability of polymer composites under extreme thermal variations and moisture intrusion remains a valuable direction.
- Full Lifecycle Cost Analysis: Conducting pilot-scale field installations and long-term pavement monitoring will provide empirical maintenance and durability data to refine overall lifecycle cost models.

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