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Dune Sand Incorporation for the Sahara Road Engineering Design

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Abstract:

This paper examines the valorization of local materials from the Algerian arid region, particularly dune sand and limestone rock, which are abundantly available. The experimental program investigated the effect of adding limestone fines (LF) on the physical properties and mechanical behavior of dune sand. After the geotechnical characterization of both materials, five dune sand-limestone fines (DS-LF) mixtures were prepared, and their physicomechanical characteristics were determined. A series of unconfined compressive strength (UCS) tests was then carried out on samples compacted at the Modified Proctor Optimum (MPO). Laboratory results showed that the incorporation of limestone fines increases the optimum water content (w_{mpo}), maximum dry density (γ_{dmax}), California Bearing Ratio (CBR) index, and UCS of dune sand. The optimal formulation, consisting of 60% dune sand and 30% limestone fines, was selected to balance economic and environmental constraints. This experimental investigation demonstrates that the incorporation of dune sand produces a material that meets standard requirements and can be used in Sahara Road construction. The study confirms that dune sand, an abundant material, can be valorized at minimal cost by adding limestone fines, thereby reconciling economic feasibility with environmental considerations.

Key words: Dune sand, Valorization, local materials, Saharan geotechnical road, mechanical strength.

1. Introduction

The Trans-Saharan Road is currently identified as a priority under the New Partnership for Africa's Development and remains a challenge for neighboring countries (Renninger et al., 2023). This major project spans Algerian territory, extending from the Mediterranean coast to the southernmost part of the country over a distance of 2760 km, and continues into bordering countries. Construction began in 1970 and is still ongoing (Daheur et al., 2023).

The Algerian segment has faced numerous difficulties, including adverse climatic conditions such as extreme thermal contrasts and arid climate, as well as construction challenges due to the limited or even nonexistent availability of standardized road materials in certain regions (Akacem et al., 2020; Bouacha et al., 2023).

In recent years, national authorities have launched an ambitious program that includes the construction and rehabilitation of an extensive road network (notably the Trans-Saharan Road), highways, and engineering structures, along with the development and integration of Algeria's highland and southern regions (Bouzid et al., 2023).

This program requires large quantities of conventional road materials ("good quality" aggregates) that exceed natural supply. In some Saharan regions, conventional materials are scarce or entirely absent, and excessive extraction can cause long-term problems (Daheur et al., 2021). For this reason, it has become essential to explore alternative local materials such as dune sand, with the aim of conserving regional resources, minimizing pollution, and reducing environmental impacts (Akacem et al., 2020; Almadwi el al., 2021; Jadoon et al., 2023; Ghrieb et al., 2014; Smaida et al., 2022; Wahhab et al., 1997).

The Sahara covers about one-third of the African continent and represents more than 80% of Algeria's land area, of which approximately 30% consists of sand dunes (Daheur et al., 2023). These figures highlight the strategic importance of road construction in the Sahara, where infrastructure remains limited, and emphasize the value of dune sand in research promoting the use of local materials. In Algerian Saharan regions, dune sand has been extensively studied as an amendment to local materials for incorporation into pavement design (Cherrak et al., 2015; Daheur et al., 2023; Ghrieb et al., 2014; Morsli et al., 2007; Omar et al., 2022; Smaida et al., 2019).

This study focuses on the valorization of locally abundant materials in the arid regions of Algeria, with particular attention to the potential use of dune sand in Saharan Road construction. Specifically, it evaluates the improvement of the physical and mechanical properties of dune sand through the incorporation of limestone fines. The experimental program was carried out in three phases: first, characterization of the physicomechanical and chemical properties of the selected soils; second, preparation of dune sand-limestone fines mixtures with varying proportions, followed by analysis of their physical properties; and third, compaction, bearing, and UCS testing to assess performance.

2. Materials

Two materials with distinct characteristics were selected for this study: dune sand (DS) and limestone fines (LF). Both were collected from the Oued Metlili region, located 45 km south of the city center of Ghardaïa Province, about 600 km south of Algiers. This Saharan area is characterized by an arid climate with extremely hot conditions lasting nearly five months of the year, where the average shaded temperature exceeds 40 °C (Miara et al., 2022; Morsli et al., 2009) (Figure 1). Dune Sand (DS) is a porous material composed of discrete, rounded grains of nearly uniform diameter (Figure 2).

Dune Sand (SD): This is a porous material, visibly composed of discrete, rounded grains of uniform diameter (Figure 2). Limestone Fines (LF), white in color, are obtained by crushing limestone rock. These fines consist of small particles derived from various geological formations. The main stages of crushing to obtain LF are as follows (Figure 3):

1) The rocks are broken using a hammer;

2) The stone volume is reduced using a crusher;

3) The resulting product is screened using a 0.5 mm sieve.

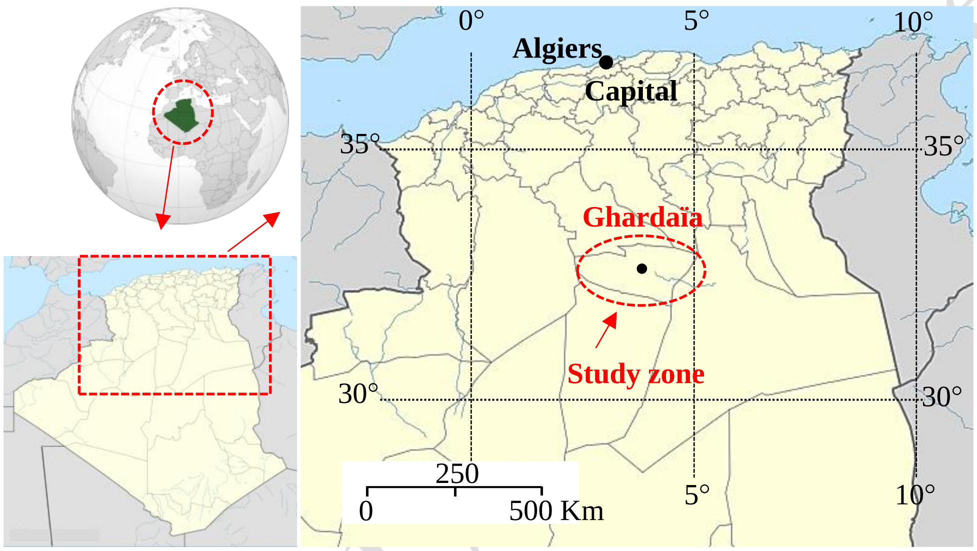

Fig. 1. Location of the studied area

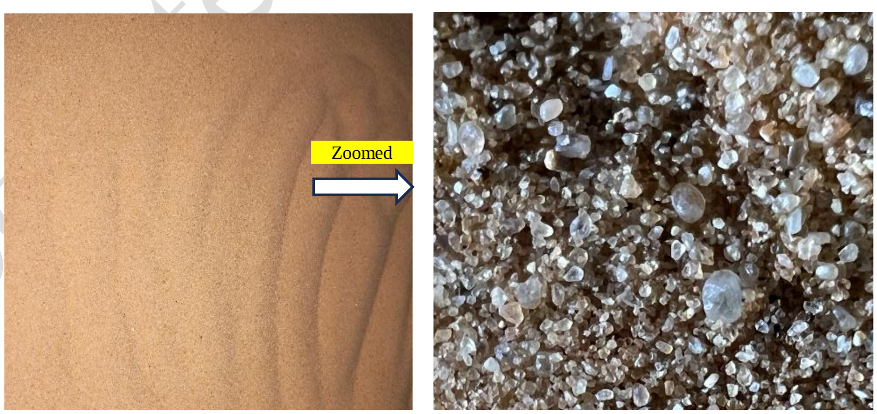

Fig. 2. Macroscopic and magnified views of dune sand

Fig. 3. Different stages of limestone rock crushing and grinding to produce limestone fines

Table 1 summarizes the results of the identification tests performed on the studied materials, along with the recommended threshold values from the following specifications.

1. **Saharan Road Technology (TRS) (Fenzy, 1966):** A local Algerian standard (French acronym for *Technique Routière Saharienne*) designed for arid environments. It emphasizes the use of locally available materials such as dune sand, tuff, and gravel, and addresses geoclimatic constraints including large thermal variations, aeolian sand movement, and minimal precipitation. This approach enhances infrastructure resilience, optimizes construction costs, and ensures long-term pavement performance in Saharan conditions.

2. **Design Catalog for New Pavements (CTTP, 2001):** A national Algerian standard providing pavement design guidance based on traffic load classes and subgrade bearing capacity. It promotes the use of local materials while ensuring mechanical performance and durability, harmonizing design practices across diverse geotechnical and climatic contexts in Algeria.

3. **Technical Road Guide (GTR, 1992):** Published by LCPC-SETRA, it outlines best practices for the design, selection, and compaction of soils used in road embankments and

capping layers. It provides soil classification criteria, treatment methods, and quality control protocols to ensure long-term stability, load-bearing capacity, and durability of road earthworks.

Figure 4 illustrates the grading curves for both materials relative to the TRS discriminating envelopes (Fenzy, 1966). The grading curves of both materials are above the TRS spindle and fall within family III. Dune sand exhibits a uniform, well-graded particle-size distribution, with approximately 8% fines (< 80 µm). Limestone fines show a broader particle-size distribution, with about 45% sand and a high fines fraction (< 80 µm) of about 72%.

Table 1. Geotechnical characteristics and mechanical properties of the studied materials

	Materials		**Specifications**		
	DS	**LF**	**TRS**	**CTTP**	**GTR**
Grading analysis					
D_{max} (mm)	1	1	-	20-40	< 50
% < 0.425 mm	90	98	-	36-52	-
% < 80 µm	8	72	< 30	22-32	≤ 35
Uniformity Coefficient: C_u (%)	3.11	17.5	-	-	-
Curvature Coefficient:C_c (%)	0.89	0.55	-	-	-
Atterberg limits					
w_L (%)	17.7	19.7	-	< 40	-
w_L (%)	N.M	N.M	-	-	-
PI (%)	N.M	N.M	< 13	< 15	≤ 12
Sand equivalent (%)	65	-	-	-	-
Blue value	0.03	0.08	-	-	< 1.5
Modified Proctor Optimum (MPO)					
γ_{dmax} (kN/m^3)	1.82	2	> 1.7	-	-
w_{mpo} (%)	8.5	12	-	-	-
Bearing capacity					
CBR index (unsoaked) (%)	13	95	> 40	-	-
CBR index (soaked) (%)	08	45	-	-	-
UCS (MPa)	00	3.1	> 1.5	-	-
Chemical analysis					
Insolubles (%)	96	-	-	-	-
$CaCO_3$ (%)	00	90	-	≥ 45	-
$CaSO_4$; $2H_2O$ (%)	1	2	-	-	-
GTR Classification	D1	A1			

N.M: Not measurable

It can be noted that certain geotechnical properties of dune sand fall below standard requirements for road materials, particularly bearing capacity and strength, making it unsuitable under specification criteria. According to the American Association of State Highway and Transportation Officials (AASHTO) specifications, both dune sand and limestone fines are not suitable for use as a base layer. AASHTO requires a UCS exceeding 1.7 MPa for a stabilized subbase and at least 5.2 MPa for a stabilized base layer (Jamsawang et al., 2021). The following sections investigate whether incorporating limestone fines into dune sand can improve these properties.

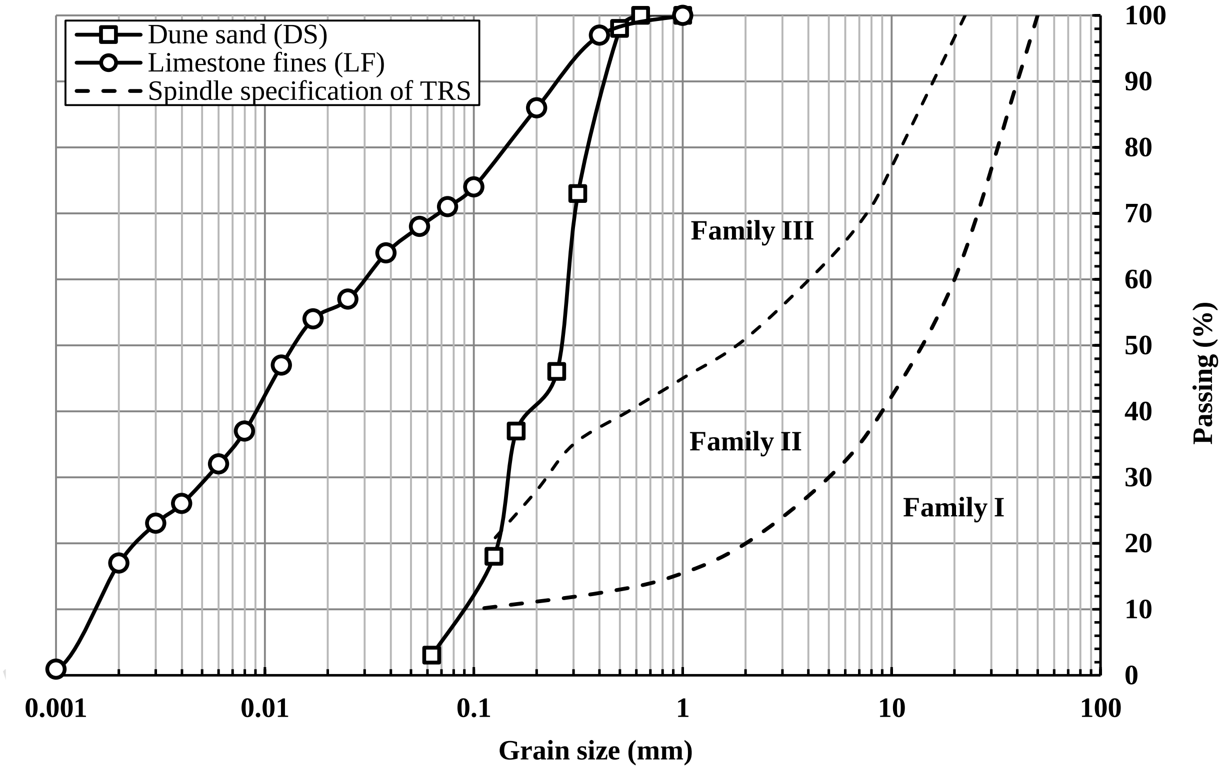

Fig. 4. Grading curves of dune sand and limestone fines

3. Methods

To obtain an optimal mixture of dune sand (DS) and limestone fines (LF) with the best physical and mechanical properties, several proportions were evaluated: 100% DS + 0% LF, 90% DS + 10% LF, 80% DS + 20% LF, 70% DS + 30% LF, 60% DS + 40% LF, 50% DS + 50% LF, and 0% DS + 100% LF. The experimental program focused on assessing the influence of LF addition on the geotechnical characteristics and mechanical behavior of dune sand.

3.1 Geotechnical characteristics

This step was essential before considering the use of these materials in pavement construction. The parameters selected were those defined by the referenced standards (TRS, CTTP, and GTR), including maximum dry density, optimum water content, and soaked/unsoaked California Bearing Ratio (CBR) index. Compaction characteristics and bearing capacity, which indicate immediate stability, were determined using the Modified Proctor test (ASTM D1557) and the CBR test (ASTM D1883).

3.2 Mechanical behavior

The effect of LF incorporation on the mechanical properties of DS was investigated using Unconfined Compressive Strength (UCS) tests in accordance with ASTM D2166. The UCS serves as an index for evaluating the cohesion of compacted materials (Ishola et al., 2025). The two natural soils were first air-dried, then blended in various mass proportions and mixed thoroughly by hand until a uniform color was obtained. For each mixture, specimens were compacted at the Modified Proctor Optimum (MPO). Compaction was performed statically in cylindrical molds with a diameter of 50 mm and a height of 100 mm, at a loading rate of 1.27 mm/min. After demolding, specimens were oven-dried at 55 °C for 48 hours in accordance with TRS standards

(Cherrak et al., 2015). Each specimen was then subjected to a compressive load at a rate of 0.2 mm/min until failure. The reported results represent the average of three individual tests.

4. Result and discussion

4.1 Compaction characteristics

Figure 5 presents the Modified Proctor curves for dune sand (DS), limestone fines (LF), and the various DS-LF mixtures. The solid grain density (Gs) values measured for DS, LF, and the mixtures ranged from 2.67 to 2.71. Given this small variation, a Gs value of 2.7 was adopted to plot the saturation curve for all mixtures. The effect of LF incorporation on the optimum characteristics derived from the Modified Proctor curves is shown in Figure 6.

The Proctor curve of DS is relatively flat, indicating that dry density shows little sensitivity to water content up to the optimum. This suggests that the fine particles of DS exhibit low water sensitivity. In contrast, the Proctor curve of LF shows a steep slope, reflecting a high sensitivity of dry density to changes in water content up to the optimum. The optimum water content for LF is relatively high compared to conventional road materials. The addition of LF leads to the following effects:

- DS densification: The maximum dry density increases linearly with the LF percentage. This occurs because LF progressively fills the interparticle voids in the coarse sand matrix, resulting in denser packing and improved particle interlocking. The presence of non-plastic fines also enhances gradation, decreases air void content, and improves compaction efficiency.
- Increase in optimum water content, evidenced by a shift of the curves to the right.
- Greater sensitivity of maximum dry density to variations in optimum water content.

For all materials, the maximum dry density exceeds the minimum threshold required by TRS standards. A potential limitation of this approach should be noted. While LF were primarily considered in this study as inert fillers to improve the physical properties of the DS matrix, their chemical composition, mainly calcium carbonate, may induce reactivity under certain field conditions. In particular, delayed or insufficient compaction in the presence of moisture could cause partial cementation or crust formation due to carbonation or weak cementitious bonding. Such effects may not appear in controlled laboratory conditions but could influence field performance of the mixtures.

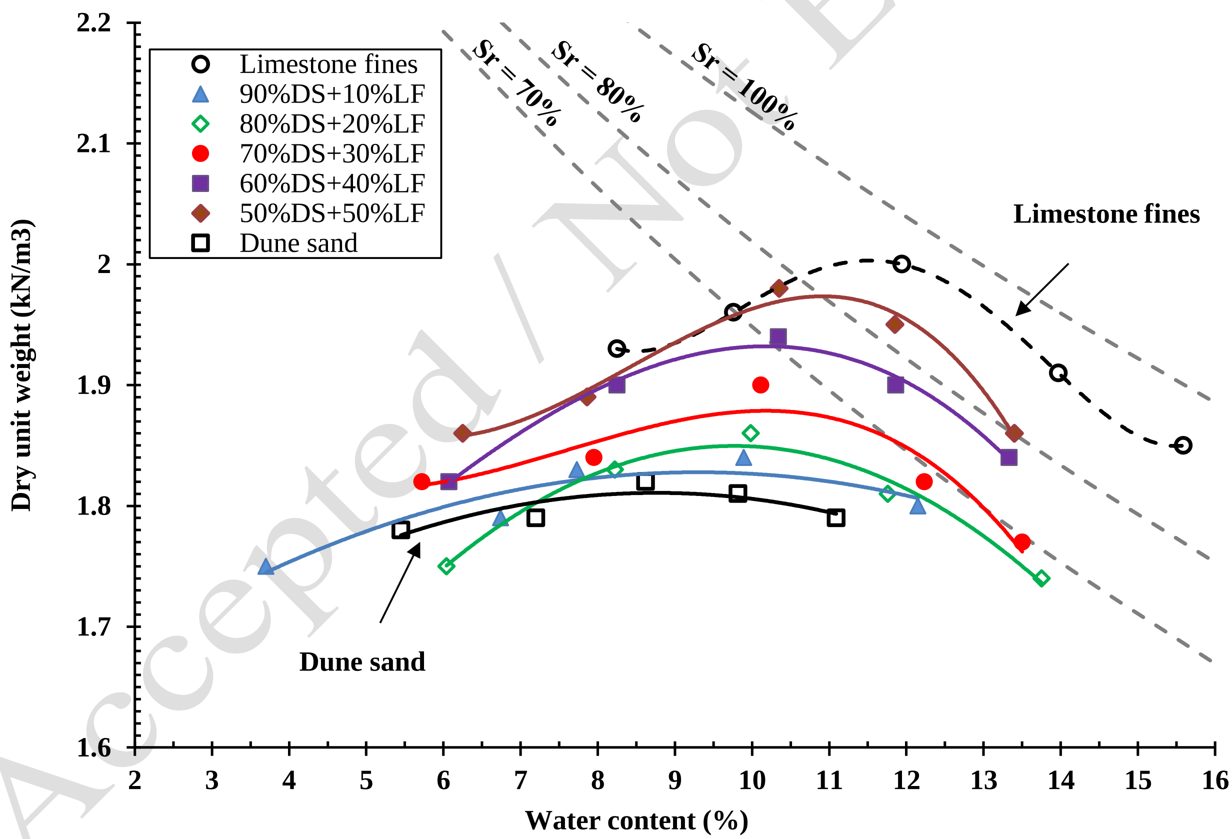

Fig. 5. Modified Proctor curves of DS, LF, and different DS-LF mixtures

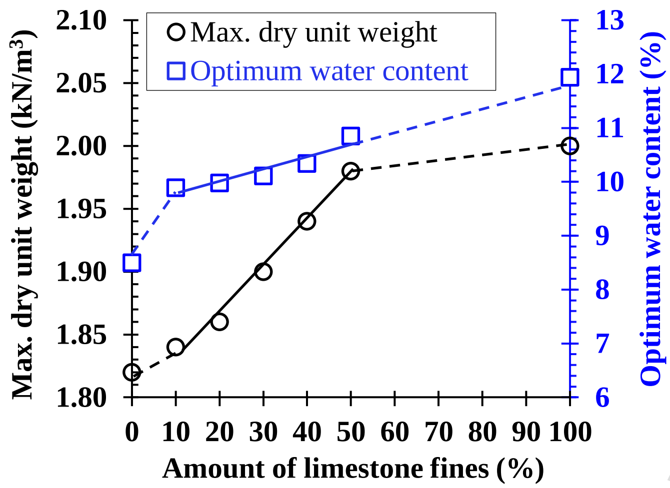

Fig. 6. Evolution of compaction characteristics with LF content

4.2 bearing capacity

The bearing capacity test is a penetration test conducted on a compacted soil specimen under predefined density and water content conditions. It is expressed as a California Bearing Ratio (CBR) value, which is proportional to the force required for a piston to penetrate the soil to depths of 2.5 mm or 5 mm. This test evaluates the load-bearing capacity of road materials. The test was performed on the different mixtures, both immediately after compaction and after 4 hours of soaking. The Immediate Bearing Index (IBI) corresponds to the unsoaked CBR value measured on a specimen compacted under the optimum conditions of the Modified Proctor test. The soaked CBR value, obtained after 4 hours of immersion, reflects the material's performance under unfavorable hydric conditions (presence of water).

Figure 7 shows the variation of CBR values with LF content. The following observations can be made:

- The addition of LF significantly improves the CBR index, especially the unsoaked CBR. For example, when the LF content increases from 0% to 30%, the CBR rises from 13 to 44, representing a gain of 240%.

- Soaked CBR values are consistently lower than unsoaked values. A reduction of 52% was observed for raw LF and 38% for raw DS, confirming the water sensitivity of both materials.
- The sensitivity to water increases with higher LF content. The reduction in soaked CBR compared to unsoaked CBR rises from 38% to 52% as the LF proportion increases from 10% to 50%.

These results indicate that a limestone fines content of 30% or more satisfies the TRS requirement for unsoaked CBR (> 40).

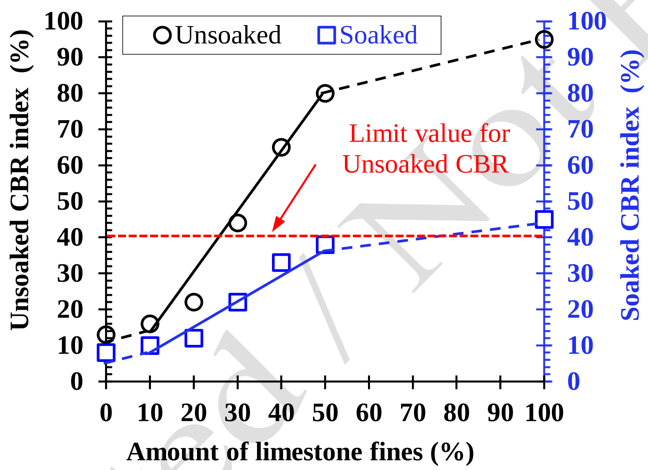

Fig. 7. Evolution of soaked and unsoaked CBR index as a function of LF content

4.3 Unconfined compressive Strength

The Unconfined Compressive Strength (UCS) test is one of the most widely used laboratory methods in pavement engineering and soil stabilization (Chhabra et al., 2024; Ghanbari et al., 2022). It is an index for assessing the cohesion of compacted materials (Kumar et al., 2025; Scheuermann et al., 2024). Introduced for local materials by Fenzy (1966), the UCS test is generally performed on Saharan soils using the fraction smaller than 5 mm.

Figures 8a and 8b illustrate the evolution of UCS and water content, respectively, as a function of curing duration. The following observations can be drawn:

- The curves have comparable shapes.
- Compressive strength develops in two phases:
  - Phase 1 (0-7 days): Rapid hardening occurs, proportional to the amount of LF added. During this phase, water content decreases sharply.
  - Phase 2 (7-28 days): Hardening slows down, and the rate of water loss decreases.
- For any given curing period, UCS increases with higher LF content.
- Loss of water is favorable to strength gain.

These results confirm the beneficial effect of LF addition on UCS and emphasize the crucial role of moisture control in ensuring long-term performance, particularly in arid and semi-arid regions such as the Sahara.

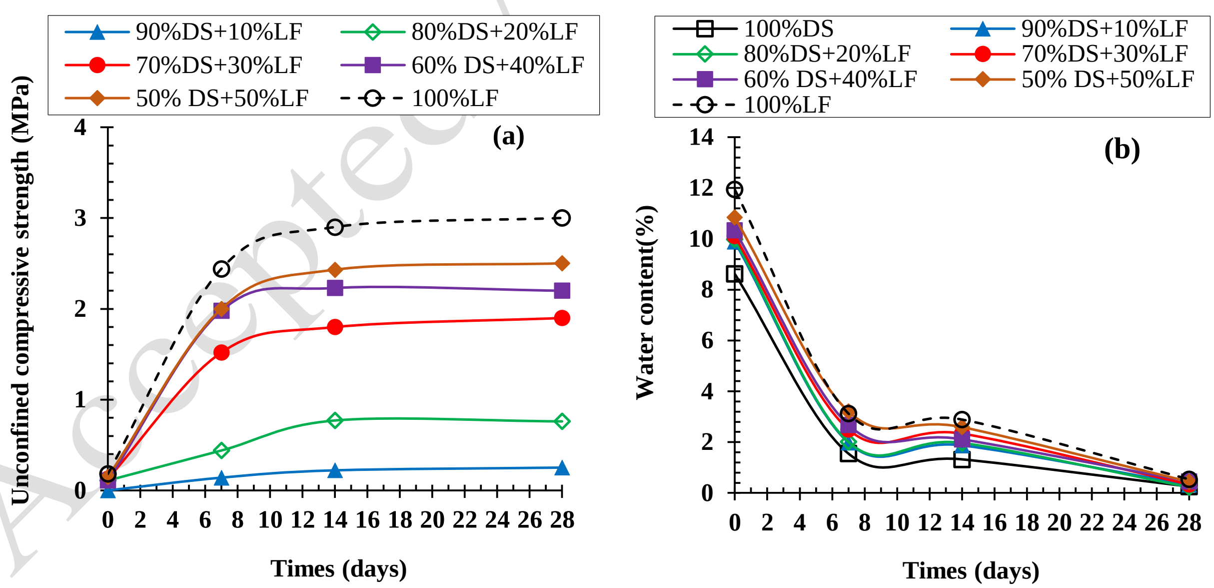

Fig. 8. Variation of (a) UCS, and (b) water content as a function of curing duration

To analyze the stress-strain behavior of the mixtures, Figure 9 presents axial stress versus axial strain. Mixtures with low LF content exhibit ductile behavior with low strength. Starting from 30% LF, a distinct strength peak appears, becoming more pronounced as LF content increases. This trend indicates a transition from ductile to brittle behavior as LF content rises. The transition can be attributed to higher dry density from improved compaction, as LF enhances particle packing and may promote interparticle bonding, which is typically associated with brittle responses.

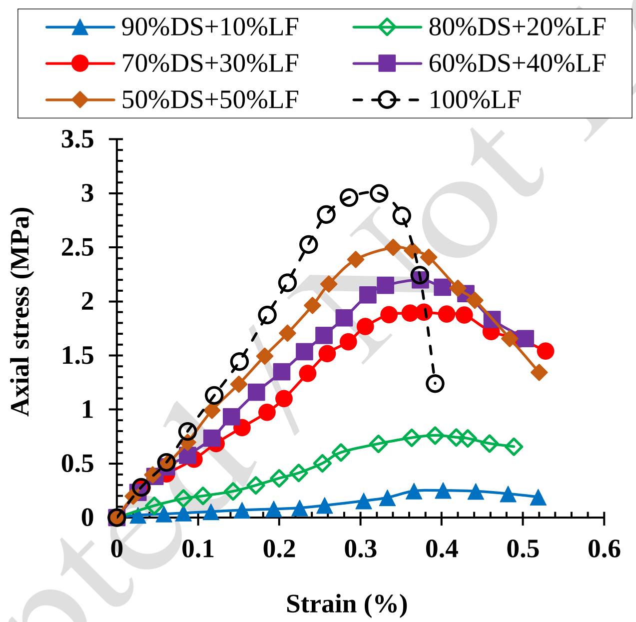

Fig. 9. Evolution of axial stress versus axial strain of DS-LF mixtures

Figure 10 shows UCS values at 28 days of curing (UCS28) for mixtures with varying LF proportions. Mixtures containing 30% or more LF achieve compressive strength values above the limits required by TRS standards, making 30% the optimal threshold for mechanical performance. Mixtures with less than 30% LF fail to meet the standard and are therefore unsuitable for engineering applications. The increase in strength with LF content results from improved cohesion and void filling between sand particles, leading to higher density and strength. Thus, a mixture containing 30% LF can be considered optimal, both technically and economically. According to AASHTO specifications, this composition is suitable for use as a subbase layer (UCS > 1.7 MPa).

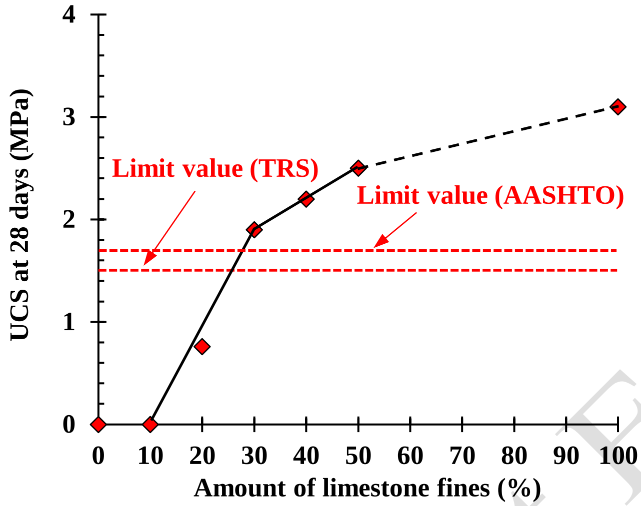

Fig. 10. UCS variation at 28 days as a function of LF content

4.4 Soil classification

Table 2 presents the classification of the DS-LF mixtures according to the Unified Soil Classification System (USCS) (ASTM D2487-06, 2006). Raw dune sand (DS) is classified as SP (Poorly Graded Sand), reflecting its uniform grain size distribution. With the addition of only 10% LF, the classification shifts to SM (Silty Sand), showing the strong influence of LF on soil behavior. This classification remains unchanged up to 50% LF. Limestone fines (LF) alone are classified as ML (Inorganic Silt of Low Plasticity), which is typical of non-plastic, fine-grained particles. This progressive transition in USCS classification demonstrates the substantial impact of LF on the gradation characteristics of the mixtures. Such changes directly affect geotechnical properties, including workability, compaction behavior, and strength development.

Table 2. Unified Soil Classification System (USCS) of DS-LF mixtures

100%DS	**90%DS +10%LF**	**80%DS +20%LF**	**70%DS +30%LF**	**60%DS +40%LF**	**50%DS +50%LF**	**100%LF**
SP	SM	SM	SM	SM	SM	ML

(Poorly graded sand)	(Silty sand)	(Silty sand)	(Silty sand)	(Silty sand)	(Silty sand)	(Inorganic Silts of low plasticity)

5. Conclusion

This study investigated the potential utilization of dune sand from the Ghardaïa region in Saharan road engineering. The research examined the effect of incorporating limestone fines into dune sand in order to improve its geotechnical and mechanical properties. The results showed that the addition of limestone fines significantly enhances maximum dry density, optimum water content, California Bearing Ratio (CBR) indices, and unconfined compressive strength (UCS).

The optimal formulation was determined to be 70% dune sand and 30% limestone fines, which provides a balance between technical performance and economic feasibility. This mixture achieved an optimum moisture content (w_{mpo}) of 10.11%, a maximum dry density (γ_{dmax}) of 1.9 kN/m^3, CBR values of 44% (unsoaked) and 22% (soaked), and a 28-day UCS of 1.9 MPa. These results demonstrate that the proposed mixture satisfies the requirements for subbase materials and is suitable for application in Saharan road construction. The valorization of dune sand in this way offers a low-cost and environmentally sound solution that supports sustainable development policies.

Further research is necessary to deepen the understanding of the mechanisms involved. Microstructural investigations using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) should be conducted to identify potential cementitious formations in dune sand-limestone fines mixtures. Long-term and fatigue performance studies are also recommended, both for untreated mixtures and for those treated with binders such as cement, lime, or fly ash, or reinforced with fibers. Comparative studies with conventional high-grade materials, such as treated gravels, as well as detailed mineralogical analyses, will provide additional insight into the behavior of these mixtures and confirm their suitability for large-scale application.

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