Journal of Engineering and Technology for Industrial Applications

ITEGAM-JETIA

Manaus, v.12 n.57, p. 696-704. January/February, 2026.

DOI: https://doi.org/10.5935/jetia. v12i57.2997

ISSN ONLINE: 2447-0228

RESEARCH ARTICLE OPEN ACCESS

USE OF DUNE SAND TREATED WITH HYDRAULIC BINDERS IN ROAD FOUNDATION LAYERS

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ARTICLE INFO

Article History
Received: November 24, 2025
Revised: December 20, 2025
Accepted: January 15, 2026
Published: February 28, 2026

Keywords:
Valorisation,
Dune sand,
binders,
Road,
Pavement layers.

ABSTRACT

Roads represent one of the main concerns in infrastructure development, and a significant part of the overall budget is dedicated to their construction, improvement, and maintenance. The realization of flexible pavements requires large quantities of high-quality materials such as aggregates and crushed sand. However, these materials are becoming increasingly difficult to obtain in the quantities needed, especially near construction sites. In order to create road layers that meet technical, mechanical, and durability requirements, it is often necessary to improve existing soils through the use of hydraulic binders, including lime and cement. This context led us to initiate our research, which provides an important opportunity to enhance and promote the use of a locally available material, namely dune sand, through appropriate treatment techniques based on hydraulic binders. At the same time, this approach helps address the growing shortage of noble materials traditionally used in pavement construction. By exploring alternative solutions and encouraging the use of local resources, our study aims to contribute to more sustainable, economical, and efficient practices in road engineering while responding to current and future challenges faced by the sector.

I. INTRODUCTION

The knowledge of ground stabilization in geotechnics has been well documented recently. Articles and manuals on stabilization techniques are available to students, practicing engineers and consultants in the field of geotechnics. During soil stabilization, the formation of dust due to aggressive binders is not a requirement. For this, soil studies have been carried out to find the solution to this problem. Companies have invested in research and development for several years already and are notably turning towards soil stabilization techniques using hydraulic binders. This method of soil modification uses lime and/or hydraulic binders to optimize soil properties [1] has undergone significant development recently. The use of materials such as lime, hydraulic binders and/or cements [2] in soil treatment facilitates the formation of fill and foundation layers. This type of treatment requires a good knowledge of the material to be treated. Road construction requires a large quantity of materials to create not only the road layers but also especially the embankments and the subgrade layers, to create the longitudinal profile. Two methods are used, either by adding aggregates, or by treating the soil in place. The aggregate supply technique requires the use of large quantities of trucks to, on the one hand, dump excess soil and on the other hand, transport aggregates to the site in large quantities.

The scarcity of aggregate resources and the nuisance generated by transport have encouraged decision-makers to valorize existing soils through treatment with hydraulic binders. Recently, in Algeria, a very consistent program was launched in terms of road construction. However, these types of initiatives require the use of large volume of high-quality materials [3],[4], which are not systematically available in the vicinity of the projects to create pavement layers with using hydraulic binders to treat the soil in place. This is the reason why it is interesting to promote local materials [5],[6] by a treatment technique. This permits to compensate for the deficit in noble materials, and to respond to economic and environmental concerns [7], [8]. The treatment of soils with hydraulic binders and lime is a process which improves the workability of materials. This treatment technique makes it possible to improve the physical and mechanical characteristics of soils after compaction. The advantages of this technique are well known in earthworks and are exploited for the construction of road, motorway, railway embankments, industrial platforms, etc. Soil treatment with hydraulic binders has become common practice in the field of road construction. This technique presents technical, economic and environmental advantages [7],[8].

Soil treatment makes it possible to save natural aggregate resources, limit the transport of materials and re-use existing soils, which are often too wet and not very supportive. Algeria is known for its sand dunes, which adorn postcards, are tourist destinations, but also which swallow up land and palm groves, and invade certain oases. However, this sand, which occupies almost the entire surfaceof the Algerian Sahara, is currently not valued for exploitation. Many researchers, in various scientific themes, seek to exploit this clean and abundant material. It couldbe used due to its high silica concentration. In the field of civil engineering, this sand also has significant economic and environmental importance for Algeria. Indeed, the growth in demand for sand for construction in Algeria, the inability of Algerian quarries to supply fine sand along with the planned cessation of using sea sand, which leads to a major ecological and tourist problem for Algeria, are all reasons for the valorization of this product. We are therefore interested in the valorization of this type of very abundant sand, which can exploit massively. The range of use of sands in the world is very wide, electronics [9-12], abrasive materials (sandpaper, files, discs, sandblasting, etc. for example.) [13-16]. Taking into account its particle size (medium to fine, naturally less than 1mm) [17-19], its morphology, its cleanliness and its hardness, we focused on its valorization in the layers of the roadways. Several studies have been carried out on the use of dune sand in road techniques [4], [17-25].

II. MATERIALS AND METHODS

II.1 MATERIALS

II.1.1 Dune Sand

The sand used comes from the dunes of Djelfa, a region located 300 km south of Algeria. It is an extremely fine sand, free of particles smaller than 80 µm. More than 90% of its components have dimensions ranging from 0 to 0.4 mm [17-19], this abundant material is characterized as a permeable, incoherent soil, low resistance, low bearing capacity [26],[27] and poorly graded grain size. Our studied dune sand is located approximately 60 km northwest of Djelfa at a place named Zaafrane. The mineralogical analysis carried out on the dune sand samples and the particle size analysis are presented in Figures 1a and 1b and the chemical composition is given in Table 1. According to the chemical examination presented in Table 1, the dune sand is composed mainly of silica; it consists of a large proportion of SiO_2 (silica), while there are some traces of calcium and magnesium species. The X-ray examinations reveal a significant concentration of quartz, as well as traces of Illite and calcite. Table 2 summarizes the physical characteristics of the dune sand.

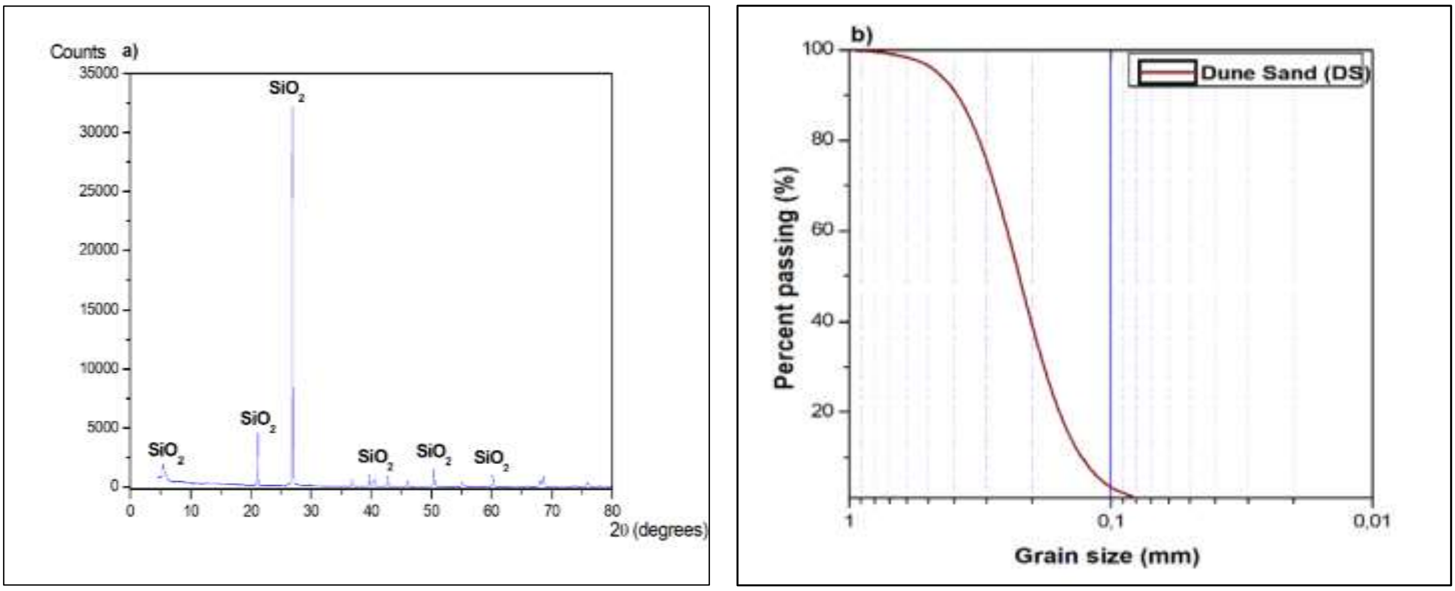


Figure 1: a) Mineralogical analysis of dune sand, b) Grain size analysis of dune sand.
Source: Authors, (2026).

Table 1: Chemical composition of dune sand.

SiO_2	CO_2	Fe_2O_3,Al_2O_3	$CaSO_4$,H_2O	NaCl	$CaCO_3$	H_2O
93.56%	1.49%	1%	Traces	0.29%	3.39%	0.24%

Source: Authors, (2026).

Table 2: Physical properties of dune sand.

Properties	Value
Apparent specific gravity (g/cm^3)	1.48
Bulk specific gravity (g/cm^3)	2.54
Propreties (%)	85
Fineness modulus	0.91
(d_{min}/D_{max}) (mm)	0/0.315
% Passing at 80 µm	1
% Passing at 2 mm	100
Coefficient of uniformity Cu	1.87
Coefficient of curvature Cc	1.10

Source: Authors, (2026).

According to the chemical examination presented in Table 1, the dune sand is composed mainly of silica; it consists of a large proportion of SiO_2 (silica), while there are some traces of calcium and magnesium species. The X-ray examinations reveal a significant concentration of quartz, as well as traces of Illite and calcite. Table 2 summarizes the physical characteristics of the dune sand.

II.1.2 Lime

The lime used in our study comes from Saida, which is characterized by a low concentration of oxide elements such as silicates SiO_2 and aluminates $A1_2O_3$ and a high concentration of basic elements such as free lime CaO. Its absolute density is between 2.2 and 2.4 g/cm3 and an apparent density (g/cm^3) as well as a specific surface area between 8000 and 12000 cm^2/g. Table 3 presents a summary of the chemical composition of the lime.

Table 3: Chemical composition of lime (%).

CaO	MgO	Fe_2O_3	AL_2O_3	SiO_2	SO_3	CO_2	$CaCO_3$
>73.3	<0.5	<2.0	<1.5	<2.5	<0.5	<5.0	<10.0

Source: Authors, (2026).

II.1.3 Cement

Chemical analysis of cement using a Scanning Electron Microscope (SEM) was carried out in the M'sila cement factory laboratory, the results are presented in Table 4.

Table 4: Chemical analysis of cement (%).

SiO_2	Al_2O_3	Fe_2O_2	CaO	MgO	SO_3	K_2O	Na_2O	Cl	CaO
19.70	4.52	3.49	62.15	1.79	2.27	0.49	0.25	0.02	1.00

Source: Authors, (2026).

II.2 METHODS

The research focuses on the impact of the incorporation of heavy substitutes, such as lime and cement, on the mechanical properties of the sand examined. The mixtures, which have been developed in this direction contains lime percentages of 4%, 6% and 8% and cement percentages of 5%, 7% and 9%. It is important to emphasize that these percentages were set in accordance with the guidelines of the standards concerning road networks [28] (GTR, 2000). The purpose of compaction is to densify the soil in place, to minimize its deformation and to optimize its bearing strength. Proctor standard compaction tests were carried out in accordance with the standard NF P94-093 [29] to determine the maximum dry density (MDD) and the optimum water content. Before being placed in the shear box, all mixtures underwent static compaction until an optimum Proctor was reached. The test is carried out at a rapid speed of 1 mm/min, which corresponds to an unconsolidated and undrained (UU) test in accordance with standard NF P 94-071-1[30]. It should be noted that the results regarding the optimum moisture content were also used to prepare the CBR and strength tests on the soil samples examined. Then, the CBR tests, shear strength, compressive strength and tensile strength were carried out in accordance with the standards NF P 94-078 [31], NF P 94-071-1 [30], standard EN 13286-53 [32] and standard EN 13286-42 [33], respectively, on the soil samples studied.

III. RESULTS AND DISCUSSIONS

III.1 EFFECT OF STABILIZERS ON THE PARAMETERS OF THE STANDARD PROCTOR COMPACTION TESTS

The obtained results are represented in Figures 2a and 2b. It is observable that the various additions seem to shift the coordinates of the Proctor modified (optimum moisture content and maximum dry density) to the right, by increasing the maximum dry density (MDD) and optimal water content (OMC) (Figures 4a and 4b). This trend of increasing the optimal water content becomes clearer for the case of cement mixtures. The densification of this material allowed us to note a dry density systematically higher than that of formulations based on cement. Lime mixtures result in an increase in dry density from 1.72 g/cm^3 to 1.81 g/cm^3. The optimum water content varies in the range of 5% to 7.8%. For cement-based formulations, the optimal water content varies in the range of 5% to 9.9% for a dry density between 1.72 g/cm^3 and 1.82 g/cm^3. The increase in density is attributed to the increase in the concentration of fine particles and their substitution by particles, which is the origin of the behavior observed in the various mixtures.

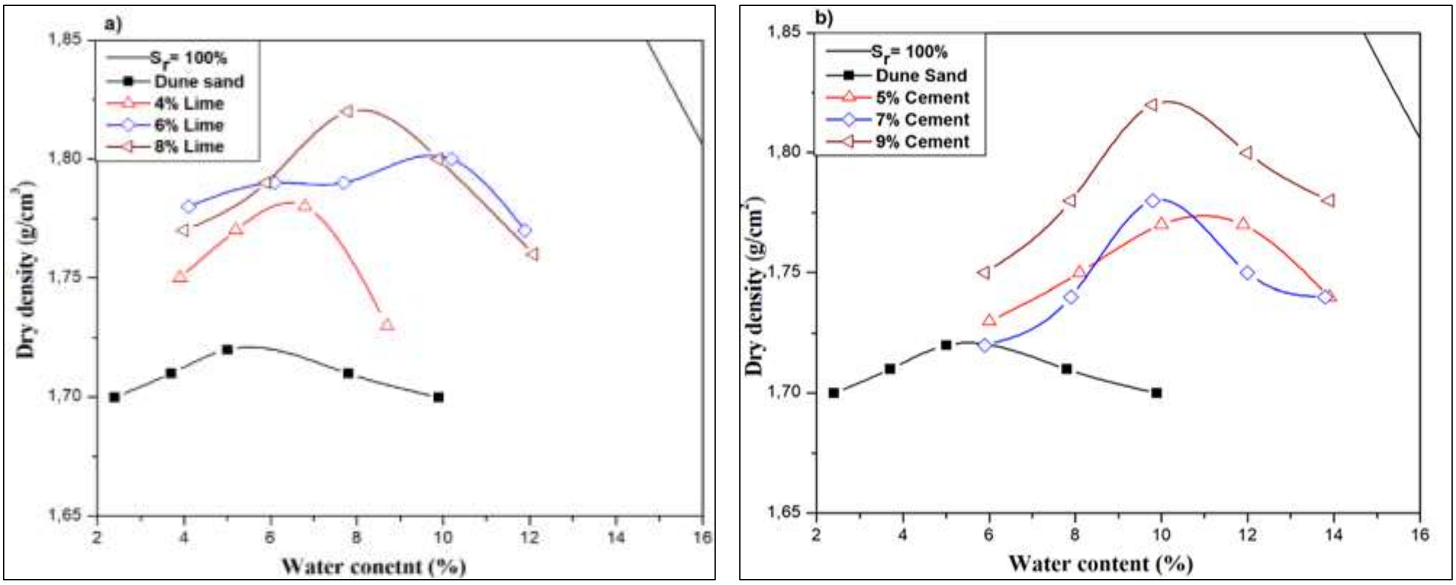


Figure 2: a) Modified Proctor of lime mixtures, b) Modified Proctor of cement mixtures.
Source: Authors, (2026).

III.2 EFFECT OF STABILIZERS ON THE CBR TESTS

To determine the CBR values at 95% of the optimum consists of punching into the CBR mold samples were made using various compaction energies (10 blows per layer, 25 c/c, 55 c/c), and at water content which corresponds to the optimal of the modified Proctor test. The aim being to obtain 3 castings with clearly different compactness (this compactness is respectively of the order of 90%, 95% and 100% of the maximum dry density of the modified Proctor). The material is then introduced according to the process of the modified Proctor test in 5 successive layers of equal thickness which will each be compacted with the same modified Proctor lady according to different compaction energies which are generally 10, 25 and 55 strokes per layer. According to the curves which represent the pressure of the piston as a function of its depression (Figure 3a and 3b), we determine the CBR index for each compaction energy.

This makes it possible to illustrate the change in dry density as a function of CBR index [γd = f(ICBR)] (Figure 4a and 4b). The final CBR index, determined graphically, is that which equals 95% of the maximum dry density of the modified Proctor test. Figure 5 a and b illustrates the variation of CBR at 95% for lime mixtures and cement mixtures. Figure5a show that lime improves the immediate bearing capacity from 8.28% to 13.45%for 4% lime. Beyond this value, we note a slight decrease to 12.32% for 8% lime. At the same time, in immersion, the lift improves from 6.45% to 12.10% for 6% lime then it drops to 9.5% for 8% lime. Just like lime, cement (Figure 5.b) showed a very significant increase in immersion lift of up to 162% in the case of 9% cement. This is obviously due to the cement setting. Unlike the lift in immersion, the immediate lift of cement shows values close to the values of lime where we note 26.5% for 5% cement then it drops to 21% for 9% cement.

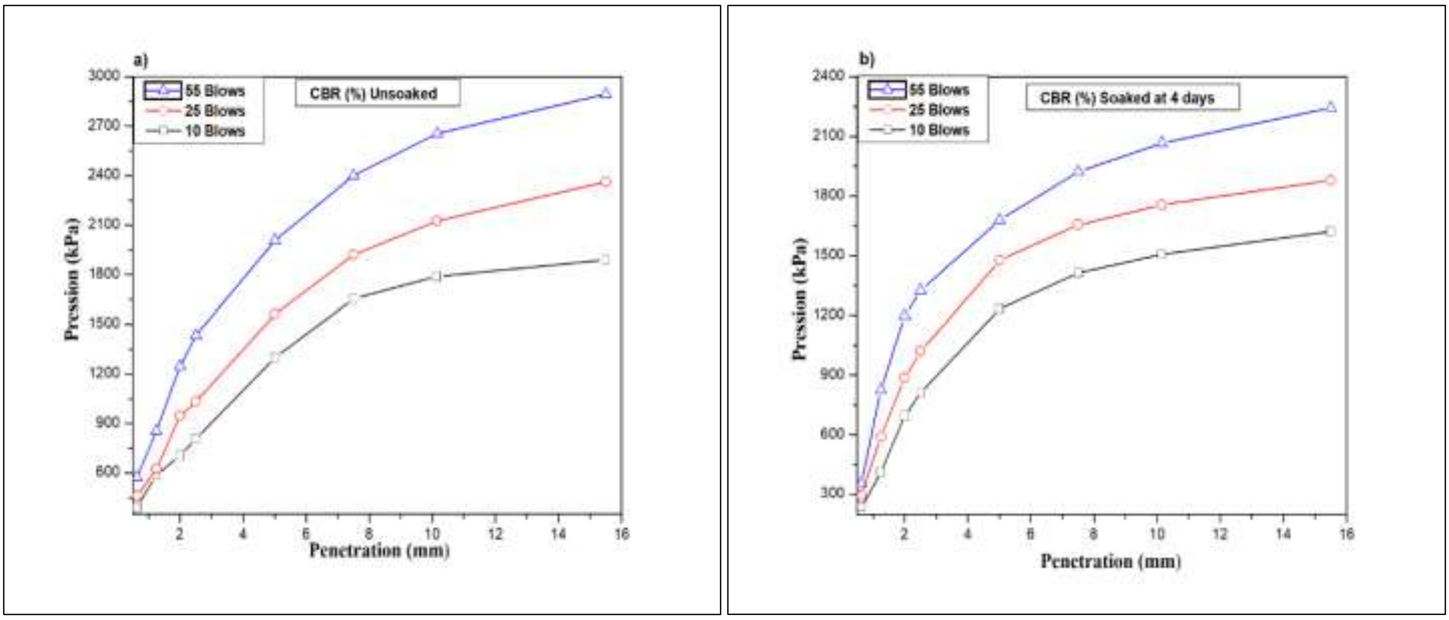


Figure 3: a) Variation of pressure according to the penetration (Unsoaked case), b) Variation of pressure according to the penetration (Soaked case).
Source: Authors, (2026).

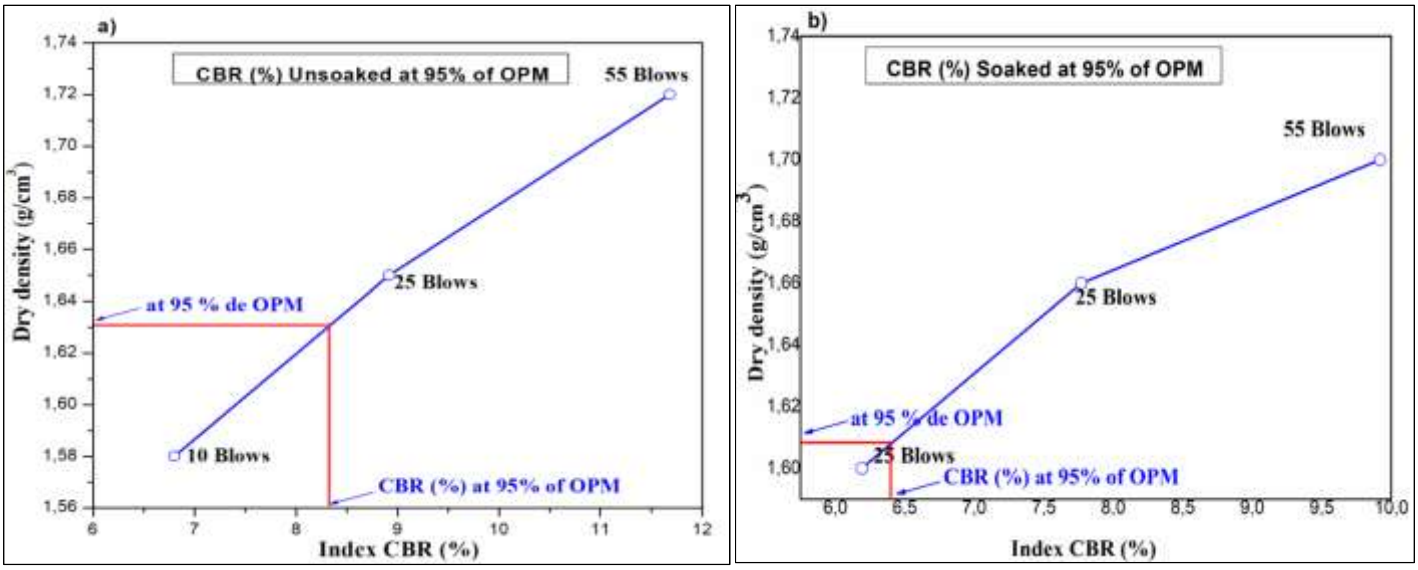


Figure 4: a) Variation of dry density according to the CBR Unsoaked index, b) Variation of dry density according to the CBR soaked index.
Source: Authors, (2026).

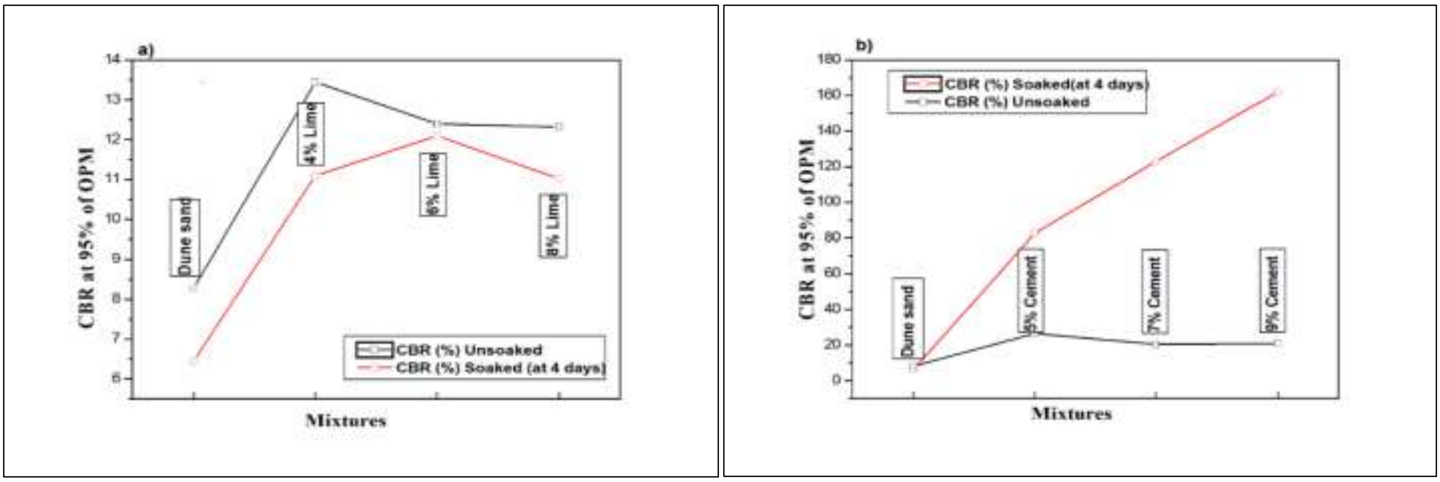


Figure 5: a) Variation of CBR index (unsoaked and soaked) according to the percentage oflime, b) Variation of CBR index (unsoaked and soaked according to the percentage of cement.
Source: Authors, (2026).

III.3 EFFECT OF STABILIZERS ON THE SHEAR STRESS TESTS

The test is intended to evaluate the mechanical characteristics of a soil, that is to say the cohesion C, the friction angle Φ and the shear resistance τ_{max} at the moment of rupture. The cohesion of a soil is the property that makes it possible to oppose the sliding of the grains which compose it and to resist a shear force, that is to say to oppose the sliding of a layer, this allowing exposure to the danger of landslides to be limited. The used test to determine the parameters is the unconsolidated undrained direct shear test (U.U) in accordance with standard NF P 94-071-1. The samples of the dune sand-lime, dune sand-cement mixtures were placed between two half-boxes, which have the ability to move relative to each other. In addition, a piston makes it possible to exert a stress normal to the shear plane. The samples of the sand-binder mixtures are sheared at their compaction water contents. The standard constraints applied during these tests are as follows:

σ1 = 100 kPa; σ2 = 200 kPa; σ3 = 300 kPa. The shear speed used is 1mm/min.

The mechanical parameters of the mixtures are determined by graphically representing the Coulomb lines (intrinsic curves) in an orthonormal coordinate system, where the abscissa axis indicates the vertical stresses (σi) and the ordinate axis the maximum shear stresses (τimax). The slopes of these lines represent the tangents of the internal friction angles Φ of the sand-binder mixtures, on the one hand. On the other hand, the cohesions C are obtained by the intersection of these lines with the ordinate axis. The values of the angle of friction and cohesion are obtained analytically according to Coulomb's law:

$$\tau = C + \sigma \, tg(\Phi) \qquad (1)$$

Figure 6a and 6b show the intrinsic curves of the dune sand-lime and dune sand-cement mixtures. Figure 7 and 8 present the variations of the cohesion of the mixtures and the variation of the friction angle depending on the binders added. The dune sand-lime and dune sand-cement mixtures show an increase in cohesion ranging from 2 kPa to 81 kPa for 6% lime and 46 kPa for 5% cement. Beyond these contents, we observe a slight decrease in cohesion, which becomes around 24 kPa for 8% lime and 15 kPa for 9% cement. However, the function of cement is to strengthen the structure of the sand by binding the particles together, thanks to the setting of the binder; on the other hand, the dune sand-cement mixture becomes less flexible and risks cracking quickly under traffic. However, it is necessary to choose a proportion of cement which improves the bearing capacity without making the mixture too stiff once it has hardened. Unlike cohesion, the friction angle shows a decrease to 32° for 5% cement and to 21° for 6% lime followed by an increase to 40° for 9% cement and to 27° for 8% lime. It is evident that all the dosages of hydraulic binders analysed demonstrate an increase in cohesion which is inversely proportional to the friction angle.

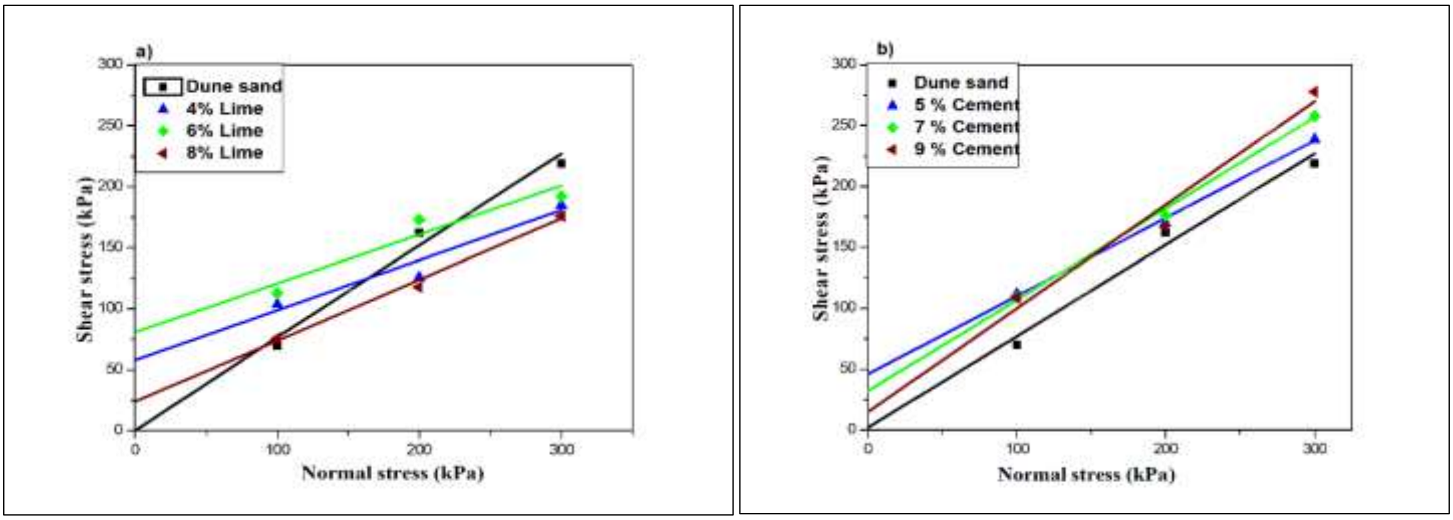


Figure 6: a) Intrinsic curves of lime mixtures, b) Intrinsic curves of lime mixtures.
Source: Authors, (2026).

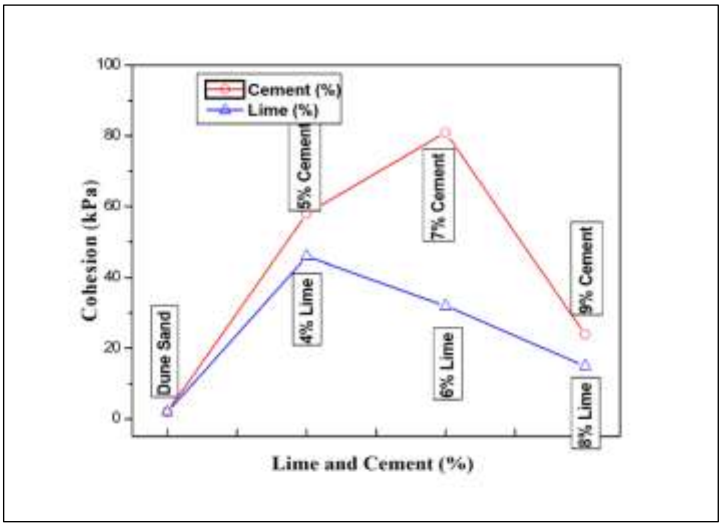


Figure 7: Evolution of the cohesion according to the binders added.
Source: Authors, (2026).

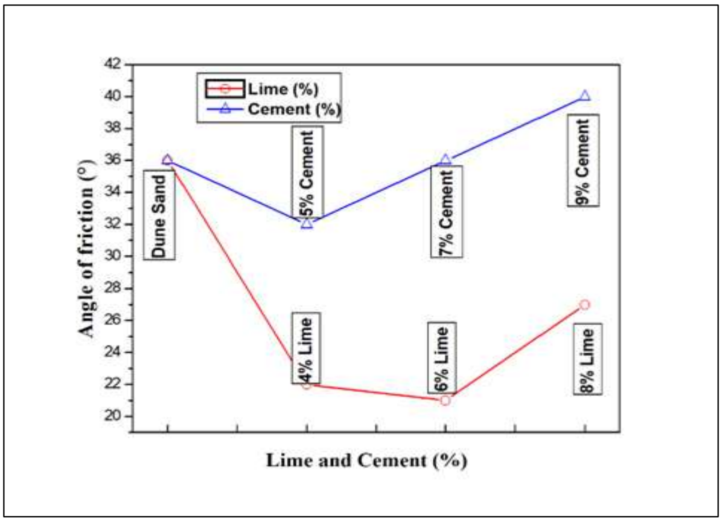
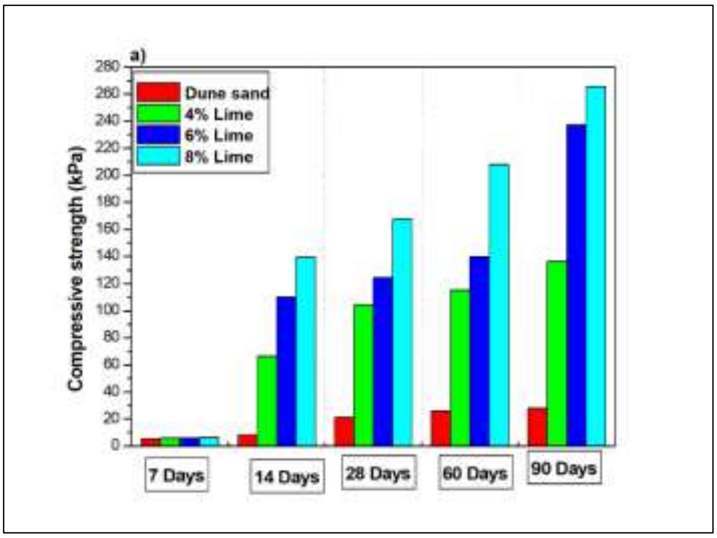


Figure 8: Evolution of the angle of frictionaccording to the binders added.
Source: Authors, (2026).

III.4 EFFECT OF STABILIZERS ON THE COMPRESSIVE AND TENSILE STRENGTH TEST

In accordance with standard 13286-53, the series of cylinders with dimensions φ = 100 mm and H = 100 mm was set up for the various mixtures. The mixture was arranged in a uniform layer in a double piston mold and then statically compressed until the optimum dry density and moisture content were reached, established according to the modified Proctor method in accordance with EN 13286-41. Following their preparation in accordance with standard EN 13286-53[32], the samples were kept in bags at 20 ± 2 °C until testing. The different mixtures were tested on days 7, 14, 28, 60, and 90. The tensile tests were performed on cylindrical samples for the different mixtures. The tensile tests were carried out on cylindrical specimens of the same dimensions in accordance with standard EN 13286-42 [33] by measuring the indirect tensile strength, but the specimens were compacted and preserved in the same way until the date of the test (at 90 days). Figures. 9a and 9b show the progression of compressive strength over various curing times and binder ratios. The compressive strength capacity following curing time demonstrates a moderate growth up to 265.59 kPa for a curing duration of 90 days (Figure 9a) for 8% lime mixture.

It is clear from the results that lime does not act as a good stabilizer on sandy material since only the role of grain size corrector is predominant. For the case of cement (Figure 9b), the results are greater than those obtained with lime and go up to 2734.25 kPa and 2973.41 kPa respectively for mixtures with 7% and 9% cement for a curing duration of 28 days and at 3425.26 kPa and 3845.68 kPa for a cure duration of 90 days. This lets us notice that the increase in compressive strength is less significant from 28 days to 90 days, which explains the rapid hydration of the cement for the first period (28 days). Figures 10a and 10b illustrate the variation of the tensile strength depending on the binders incorporated. The tensile strength generally increases with the percentage of binder added. According to Figure 10a, lime has low values before 8% lime, value for which the resistance becomes more significant. For the case of cement, we notice an increase in the tensile strength up to the respective values of 398.23 kPa and 538.75 kPa corresponding to the percentages of 7% and 9% respectively for a curing duration of 28 days. It is clear that cement mixtures give better tensile strength compared to those obtained with lime mixtures.



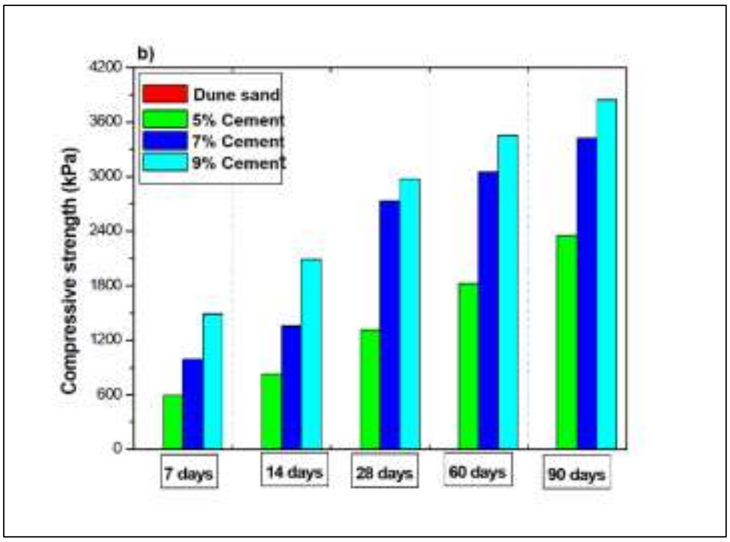


Figure 9: a) Evolution of the compressive strength according to the percentage of lime, b) Evolution of the compressive strength according to the percentage of cement.
Source: Authors, (2026).

In order to valorize dune sand, taking into account the environmental and economic aspects, the work focused on materials formulation techniques by adding hydraulic binders: lime and cement. The aims set were to examine the impact of the incorporation of percentages of fines (hydraulic binders) on the improvement of the mechanical characteristics of the dune sand treated. The results obtained from the present study show that the use of hydraulic binders and lime acts, in a very significant way, on improving the mechanical properties of this treated material. The following main conclusions can be drawn:

- Hydraulic binders such as lime and cement have a very positive effect on the mechanical performance of dune sand-based mixtures for use as pavement bases.
- Lime is less effective in improving mechanical characteristics than cement.
- Lime as a stabilizer is more suitable for fine soils (silt and clay) than for grainy soils (sand). It acts as a grain size corrector rather than a stabilizer.
- The addition of increasing quantities of hydraulic binder demonstrated a trend towards a permanent increase in the optimal water content.
- The use of hydraulic binders improves the tested mechanical performance (tensile and compressive strength).

IV.AUTHOR'S CONTRIBUTION

Conceptualization: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Methodology: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Investigation: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Discussion of results: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Writing – Original Draft: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Writing – Review and Editing: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Resources: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Supervision: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.
Approval of the final text: Ali Smaida, Dif Fodil, Khalil Latreche, Smail haddadi, Hayet Cherfa.

V ACKNOWLEDGMENTS

This research was funded by the laboratory of Laboratory Environment, Water, Geomechanics and Structures, (LEEGO), USTHB, Algeria and Civil Engineering and Sustainable Development Laboratory (LGCDD), University of Djelfa, Algeria.

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