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RESEARCH ARTICLE OPEN ACCESS

THE IMPACT OF ACTIVATED BLAST FURNACE SLAG ON THE MECHANICAL BEHAVIOR OF DUNE SAND FOR USE IN THE ROAD SECTOR

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ABSTRACT

The use of dune sand in the field of civil engineering, particularly in road technology, is a very interesting way of valorization. This material makes it possible to solve the problem of shortage of road materials which is based on the use of noble natural materials from quarries. It allows it to be valued as local material which is found in abundance in Algeria. This work makes it possible to achieve ecological, technical and economic objectives and results in a solution for sustainable development. It contributes to improve knowledge of the mechanical and rheological characteristics of dune sand treated with fine silt soil and blast furnace slag activated by lime. The study was carried out on formulations and mechanical tests (modified Proctor particle size distribution tests, CBR tests, shear strength tests, compressive strength tests, consolidation tests and hydraulic conductivity tests). The results obtained made it possible to improve the mechanical parameters of the studied formulations for use in pavement layers.

I. INTRODUCTION

It is known that the realization of large construction projects such as roads, highways, railways, dams, etc., aim to facilitate the development of agriculture, commerce and industry. These projects require a considerable quantity of materials with good characteristics and high load-bearing capacity. To be able to achieve these characteristics, it is necessary to look for materials from nature such as sand and quarry aggregates with high quality, which are becoming increasingly rare, and which cause the destruction of nature and the disturbance of the environment. Local materials can be a real alternative. They recycled materials from waste with poor characteristics which can be treated to improve their characteristics to use them in the field of construction. For this, the technique of treating these local materials with the aim of stabilizing them and improving their geotechnical characteristics is necessary. This can be achieved by using various types of artificial waste in construction works [1] such as recycled aggregates [2], plastic waste [3], fly ash, blast furnace slag [4-7], ceramic waste [8], [9] demolition waste [10], etc.

The local materials concerned by the treatment with the aim of stabilizing them are numerous, among these materials one can cite: dune sands, dredged sands (marine and river sediments), artificial and industrial waste, tuffs, clays, etc. Generally speaking, the improvement of the geotechnical properties of the soil is necessary when the structures are based on a soil presenting different problems such as expansive, deformable, liquefiable soils, fine dispersive silty sands, cohesionless sands, such as dune sands. The latter, for example, are problematic soil types that exist around the world and are susceptible to collapse under the most adverse conditions such as contact with water. To the bearing capacity of these sands can be undertaken by a variety of feature improvement techniques such as compaction, reinforcement, drainage and treatment by addition of natural, artificial and synthetic materials or a combination of physical and chemical methods [11]. Among the stabilization methods, chemical stabilization, experiments have been made with incorporating various natural and artificial materials into the soil. The most commonly used construction materials include lime, cement, and various pozzolanic materials widely used for the treatment and stabilization of soils in recent years [12], [13]. On the other hand, the use of artificial materials such as blast furnace slag remains neglected except for some work which is insufficient [5], [14], [15]. Dune sand comes from the gradual decomposition of rocks due to erosive agents such as wind [16], rain, etc. This local material is essential due to its abundance in nature (Sahara), it's almost zero extraction cost, and its apparent cleanliness, forms a response to the challenge of the depletion of natural resources in the world and presents itself as a local material of the future [5], [17]. Dune sands, known as eolian sands, are generally considered as unconventional materials.

They are considered to be of poor quality (high porosity, low bearing capacity, homometric grain size), giving insufficient mechanical performance. These materials are defined as non-standard and non-traditional soils, that is to say as materials that do not fully comply with the specifications in force in a country or region for standard use in road construction. However, it can be used successfully after having undergone particular treatment. Generally, these sands are suitable for construction because they consist of granular materials with a low content of fine particles, or even non-plastic, and have a relatively high permeability. Many research studies noted that dune sand is a material widely used as a stabilized material [18-23], with the aim of using it in civil engineering construction work, particularly in road engineering.

II. MATERIALS AND METHODS

II.1 MATERIALS

II.1.1 Dune sand and silt

The dune sand is from the Djelfa region located 300 km to the south of Algeria. It is a very fine sand, devoid of fine elements whose size is less than 80 µm. More than 90% of its components have dimensions ranging from 0 to 0.4 mm, which classifies it as D1. This type of soil, without cohesion and poorly graded [17], [24], is characterized by its permeability. It is therefore a very tight particle size. The grain size is very tight; almost 90% of the grains have a size between 0.1mm and 0.5mm. This leads us to assert that sand alone cannot have a sufficiently large compactness, and subsequently mechanical performances (resistance in compression and traction, lift, etc.) are not adequate. Treatment with hydraulic binders and the use of a granular corrector will certainly contribute to improve the characteristics of this material [17], [25]. It is worth mentioning that our sand is a siliceous sand, rich in SiO_2 (silica), and contains some limestone residues and magnetic species. In our research, we included sand from the dunes located approximately 57 km northwest of Djelfa, while silt is located approximately 60 km north of Djelfa.

II.1.2 Blast furnace slag

The slag used in this study comes from the El-Hadjar steel factory in Annaba. It is a crushed and sieved slag at 0.1 mm, with a PH of 9.75, obtained by rapid cooling of the molten slag in water basins, which leads to the formation of the material. In our case the slag is activated by lime (calcium activation), and it is formed in the presence of water as a product of hydration of calcium silicate and tetracalcium aluminate which are responsible for the binding property.

II.1.3 Lime

The lime used in our research comes from the Saida region. It is a binder with a low content of basic components, including free lime (CaO), which gives our product its airy quality. The results of chemical, geotechnical and mechanical analyzes are summarized in Figures 1, 2. Figure 3 presents the X-ray diffraction patterns of dune sand and silt. Tables 1 and 2 illustrate the results of chemical, mechanical and physical analyzes of the used soils.

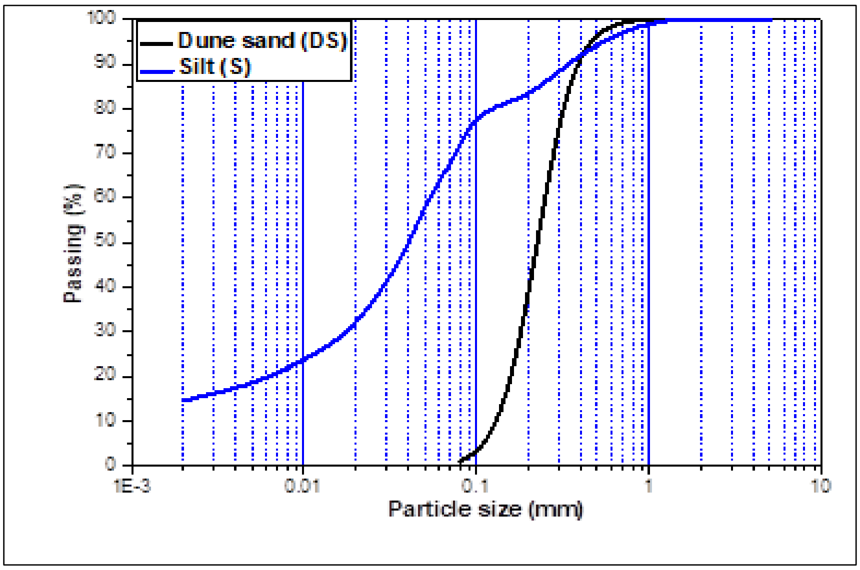

Figure 1: Grading curves of dune sand and silt.
Source: Authors, (2025).

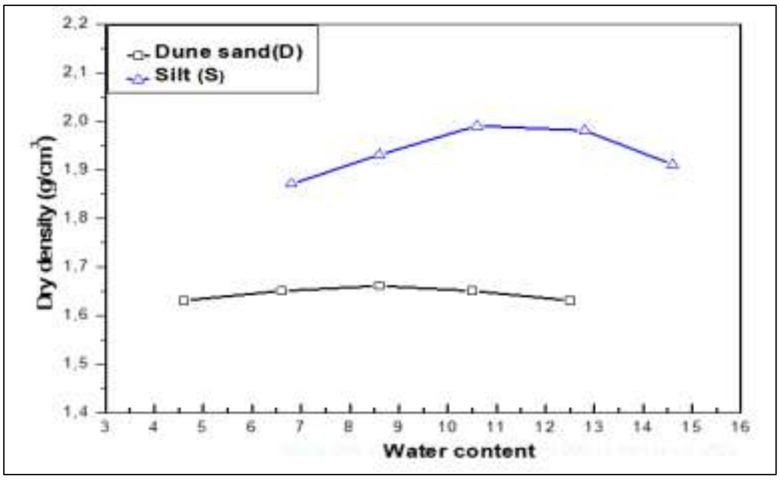

Figure 2: Proctor curves for dune sand and silt.
Source: Authors, (2025).

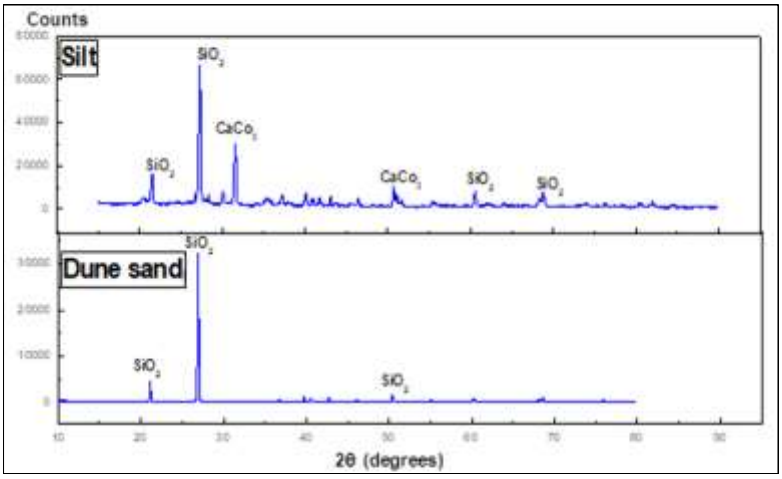

Figure 3: X-ray diffraction (XRD) of dune sand and silt.
Source: Authors, (2025).

Table 1: Chemical composition of the materials.

Material (%)	Dune sand	Silt	Blast furnace slag	Lime
SiO_2	93.56	78.02	30.12	2.15
Al_2O_3	0.99	25.2	15.45	0.58
$Fe_2 O_3$	0.56	2,33	0.72	0.26
CaO	2.45	10.34	45.80	68.52
MgO	0.13	0.36	3.82	0.41

Source: Authors, (2025).

Table 2: Physical and mechanical characteristics of the soil used.

Physical characteristics	Dune sand	Silt
Apparent density (g/cm^3)	1.49	1.37
Absolute density (g/cm^3)	2.57	2.26
< 80 µm (%)	/	73.61
% Passing at 80 µm	1	
% Passing at 2 mm	100	100
Coefficient of uniformity Cu	1.89	/
Coefficient of curvature Cc	1.10	/
Visual sand équivalent (%)	82	/
Sand equivalent test (%)	68	/
Blue value for 100g (VB)	0.05	0.92
Liquid Limit : LL (%)	/	33.6
Plastic Limit : PL (%)	/	17.9
Plastic Index : PI (%)	/	15.7
Optimum water content : W_{opm} (%)	8.7	11.4
Maximum dry density: γ_{max} (g/cm^3)	1.67	2.01

Source: Authors, (2025).

II.2 METHODS

The aim of this work is to valorize this abundant material (dune sand) in the road sector, by adding a grain size corrector (silt) and an activated hydraulic binder (blast furnace slag activated with lime), in order to improve its mechanical properties by replacing a fraction of large elements with fine elements (silt and activated blast furnace slag) by mass substitution. The formulations (dune sand + silt) are treated with percentages of blast furnace slag activated by a 1% lime percentage [5], [26]. The proportions of the chosen materials of the different formulations are given in Table 3.

Table 3: Proposed mixtures.

Formulation	Dune sand (%)	Silt (%)	Blast furnace slag (%)
F0	50	50	/
F1	50	40	10
F2	50	35	15
F3	50	30	20
F4	50	25	25

Source: Authors, (2025).

III. RESULTS AND DISCUSSION

III.1 PARTICLE SIZE DISTRIBUTION TESTS

According to (Schlosser 1988) [27], In order to obtain a uniform particle size distribution, two parameters of curvature and uniformity are applied in soil mechanics for sand-based formulations are to be fulfilled:

$$C_u = D_{60} / D_{10} > 6 \quad (1)$$

$$C_c = D_{30}^2 / (D_{60} \times D_{10}) \text{ compris entre 1 et 3} \quad (2)$$

The results of the particle size distribution tests are shown in Figure 4 and summarized in Table 4.

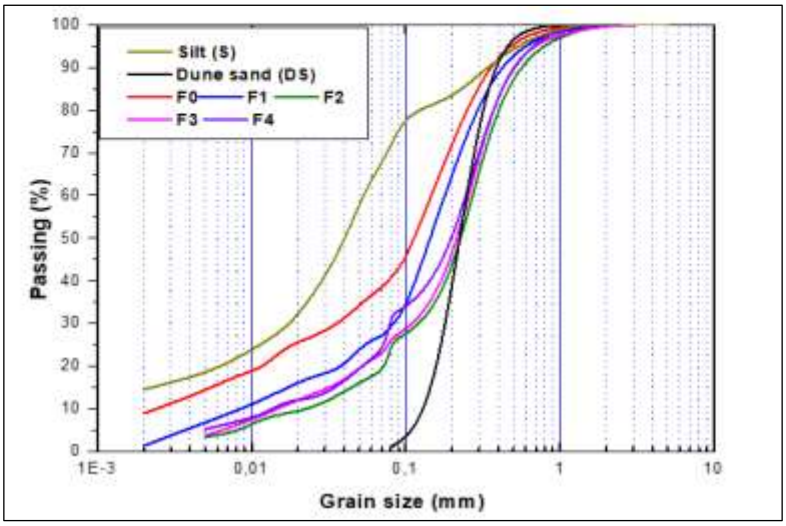

Figure 4: Grading curve for the mixtures.
Source: Authors, (2025).

Table 4: Results obtained from particle size tests.

Formulations	Uniformity coefficient (Cu)	Curvature coefficient (Cc)	Percentage of particles < 80 µm (%)
Dune sand (DS)	1.50	0.93	01
Silt (S)	/	/	71.71
F0	61.71	4.06	41.46
F1	17.8	3.595	32.81
F2	15.1	3.03	27.06
F3	18.07	1.76	26.78
F4	11.18	2.498	33.02

Source: Authors, (2025).

By aiming for dense and compact formulations, the two Schlosser criteria must be respected, for sandy mixtures. According to the results shown in Figure 4 and Table 4, all the formulations meet the criteria with an advantage for the two formulations F3 and F4. This appears to be mainly related to the incorporation of large particles of ground slag from blast furnaces that fortify the soil, and to a physicochemical reaction resulting from water adsorption and ion exchange between the slag and the smaller clay particles to generate larger particles.

III.2 COMPACTION TESTS

The compaction characteristics are very important in most civil engineering construction projects using soil as a construction material such as road projects, highways and airport runways. Therefore, the study of the impact of the stabilizer on the compaction curve is of great importance. Figure 5 and 6 illustrates the compaction results.

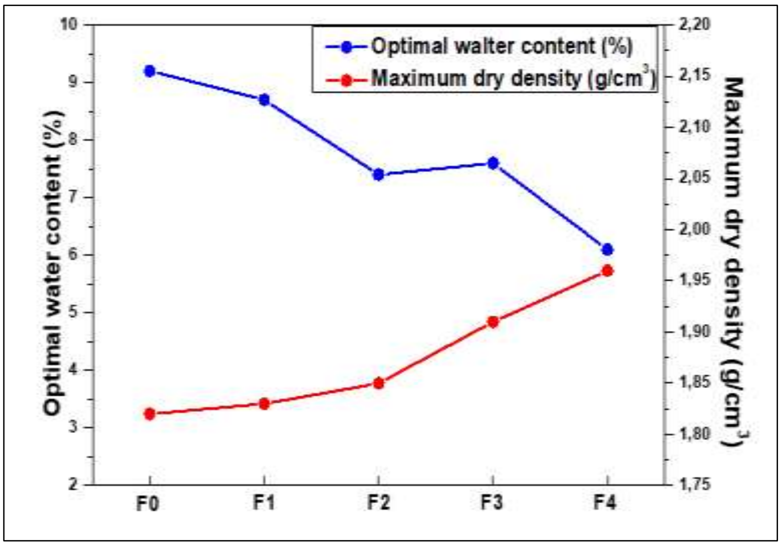

Figure 5: Modified Proctor curves of the different mixtures.
Source: Authors, (2025).

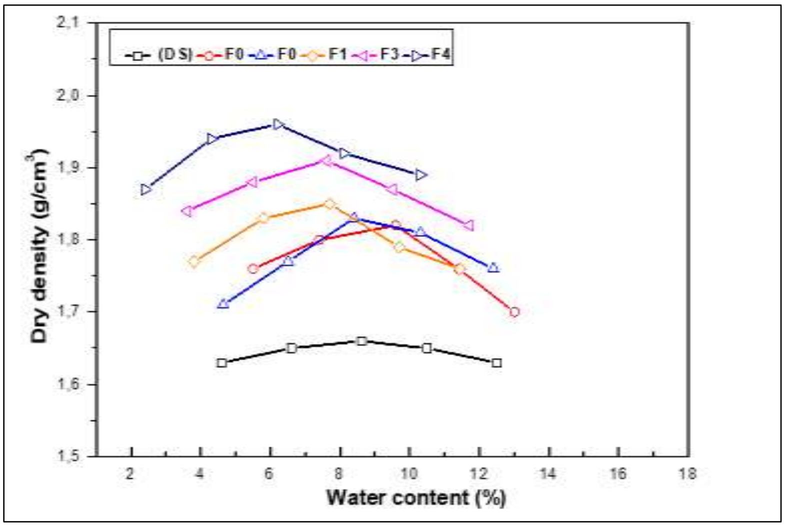

Figure 6: Variation of maximum dry density and optimum water content for the mixtures.
Source: Authors, (2025).

As shown in Figure 6, the formulations tend to decrease the optimal water content and increase the maximum dry density. Regarding compaction, the ideal water content of dune sand decreases from 8.7% to 6.2% for the F4 rate (which represents a decrease of 30%). The maximum dry density for the F0 mixture increases from 1.67 g/cm³ to 1.83 g/cm³, an elongation of 9%, while for the F4 mixture it increases by 15% with an optimal of 6.2%, reaching a maximum dry density of 1.97 g/cm³. This change is seen as a sign of improved compaction properties of the stabilized soil. The increase in dry density is explained by the fact that agglomerated and flocculated soil particles occupy a larger space.

As for the increase in optimal water content, this is due to the activated slag, which requires more water for its immediate reaction in the drying process by absorption and evaporation, as well as for the ion exchange process generated by the reactions between the activated slag and the minerals of the fine soil thus causing the flocculation and agglomeration of the minerals of the fine soil particles, this improvement in the compaction characteristics was confirmed by specific density measurement tests, the results of which obtained in (Figure 7) show the increase in the specific density of the different mixtures measured, where an increase was recorded ranging from 2.58 g/cm^3 for the F0 mixture up to 2.64 g/cm^3 for the F4 formulation case, thus making the soil more compact. Similar observations have been reported previously by other authors [28].

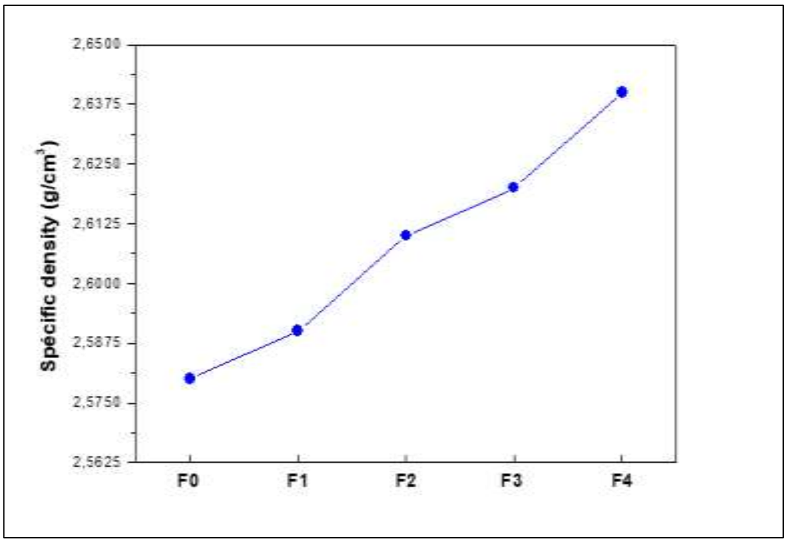

Figure 7: Variation in specific density for the different mixtures.
Source: Authors, (2025).

III.3 BEARING CAPACITY TESTS (CBR)

The CBR index represents the measurement used to determine the resistance of a material to the weight of construction equipment moving directly over its surface. In association with the Modified Proctor test, punching measurements on the compacted specimens are carried out in order to estimate the CBR Index. To do this, CBR tests were carried out on the analyzed compositions, compressed in CBR matrices, according to the adjusted Proctor conditions, in accordance with the NF P94-078 standard [29]. The objective of this test is to examine the capacity of the soil to support traffic and to evaluate the stability of our formulas. The test involves striking combinations of densified slag sand at a rate of 56 strikes per level in a CBR mold, using humidity levels corresponding to the optimal level of the modified Proctor test. Figure 8 shows the evolution of CBR index unsoaked and soaked (4 days).

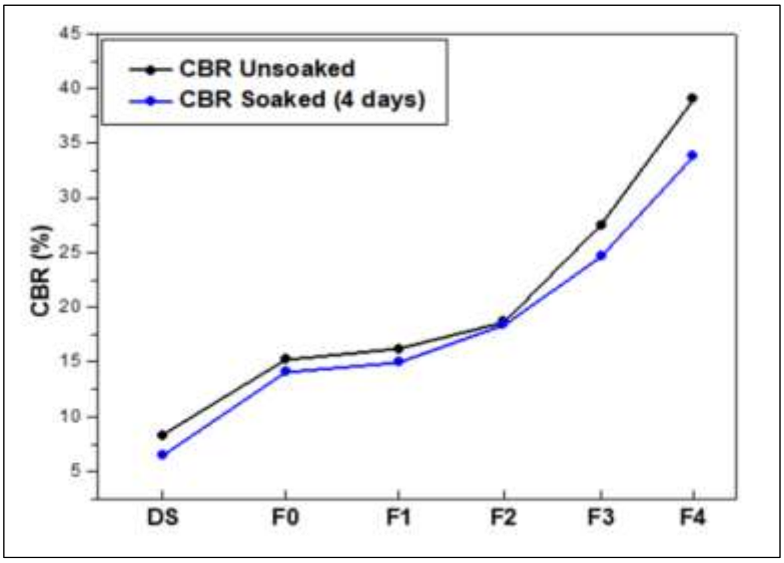

Figure 8: Variation of CBR index (Unsoaked and soked) for the different mixtures.
Source: Authors, (2025).

It is clear from Figure 8 that the progressive incorporation of blast furnace slag leads to an increase in the lift of the formulations, hence the stability of the latter. For the CBR values obtained for the different mixtures, we note an increase ranging from 8.3% in the case of single dune sand up to 15.2% in immediate CBR and 6.46% CBR in immersion for the F0 formulation. This immediate CBR value of untreated dune sand multiplies more than three times in formulation F3, i.e. (27.5%) and will become 24.63% in Immersion CBR. The major lift is recorded in F4 formulation of which we note 39% for the case of immediate CBR and 33.8% in the case of immersion. The increase in the CBR index for the various mixtures is due to the change in particle size following the incorporation of correctors (silt) with lime-activated slag. This phenomenon is mainly related to the formation of reinforced contact bridges between the grains, as well as the increase in the number of large particles and the reduction of fine particles, thus promoting the flocculation of clay particles, according to cation exchange mechanisms.

III.4 SHEAR STRENGTH AND COMPRESSIVE STRENGTH TESTS

When constructing linear earthworks, load-bearing capacity and strength are of crucial importance. It is essential to ensure that these structures withstand the expected external loads, during or after construction, without undergoing deformations or fractures that could cause significant harm to people or property. Therefore, our research aims to enhance our tests with shear and simple compression strength assessments. The direct shear test is an experimental method used in geotechnics to measure the resistance of a soil to deformation and sliding when subjected to shear stress. This resistance is a crucial parameter for understanding how the soil will behave under applied loads, such as those from buildings, roads or other civil engineering structures. The direct shear test provides essential information on the mechanical properties of the soil, including the angle of internal friction (φ) and cohesion (C), which are key parameters for geotechnical modeling and structure design. The experiment used to establish these parameters is the direct shear test, an unconsolidated and undrained test case cited by the American standard NF P94-071-1 [30].

In this research, the unsaturated state (with constant water content) was used as the test condition. The usual restrictions of employees to carry out these tests are: $\sigma 1=100$ kPa; $\sigma 2=200$ kPa; $\sigma 3=300$ kPa. The shear speed used is 1mm/min. Figure 9.a and b respectively show the intrinsic curves of the different mixtures being studied. For the tests the compressive strength, cylindrical specimens with dimensions φ=100mm, H=100mm were prepared according to standard 13286-53 [31] for the different formulations. The mixture is statically compacted with OPM according to standard EN 13286-41 [32] in a double piston mold making it possible to homogenize the stress over the entire height of the specimen. These samples were kept away from humidity in bags at a temperature of 20 ±2 °C for different curing periods of 7, 14, 28, 60 and 90 days until the date of the test. Figure 9 shows the intrinsic curves of the studied mixtures. Figure 10 shows the evolution of the simple compressive strength as a function of the age of the different mixtures.

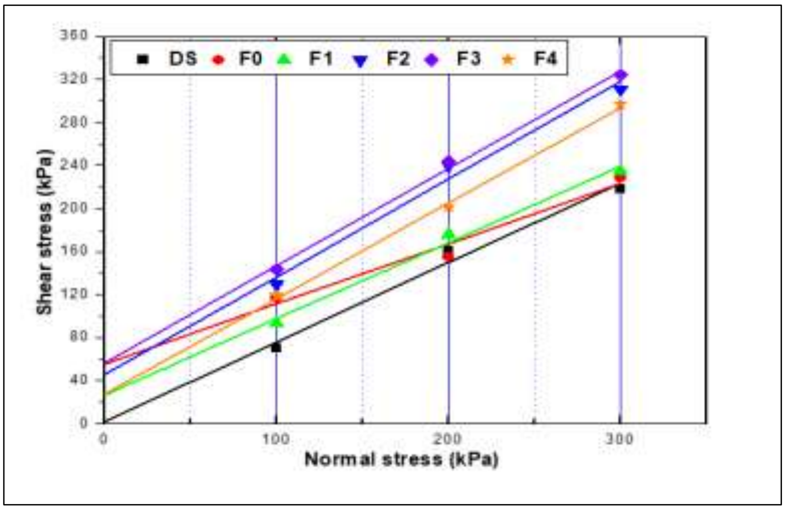

Figure 9: Intrinsic curves of the different formulations.
Source: Authors, (2025).

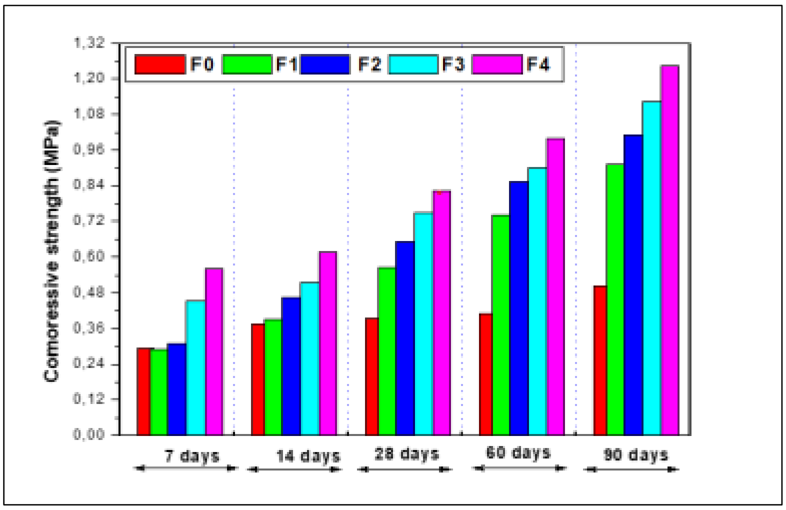

Figure 10: Variation in compressive strength for different mixtures.
Source: Authors, (2025).

According to the results depicted in Figure 9, the cohesion values for the various mixtures are all higher than those of untreated dune sand. One can see that the cohesion value increases from 1.67 kPa (dune sand) with an angle of friction from 36.49° to 55 kPa with an angle of friction of 29.24° for the mixture F0. The cohesion decreases then to 26.71 kPa with an angle of friction of 35.28° in the case of mixture F1. For the F2 and F3 it increases by marking the values (45.1 kPa and 55.93 kPa) and friction angles of 42.30° and 42.12° respectively. It falls then into F4 mixture of which we noted a cohesion of 27.2kPa and a friction angle of 41.66°. It is clear that the silt, active blast furnace slag, has brought a benefit to the dune sand by filling the voids existing between these grains, and offering much higher cohesion values than that of untreated dune sand. The maximum cohesion value was noted in the F3 mixture (50 dune sand+30% silt+20% lime). As for the compressive strength (Figure 10), it is noted that a large amount of additive causes a rapid increase in this resistance, thus promoting its improvement. The increase appears considerable for mixtures F3 and F4, with measurements of 0.90 MPa and 1.12 MPa respectively for a curing time of 60 days, and 1.01 MPa and 1.24 MPa for a period of 90 days for these two mixtures.

The consolidation test is a fundamental test for soils in order to determine the compressibility parameters (the compressibility index Cc and the swelling index Cg). Consolidation tests were carried out on similar samples using a ring of diameter (Φ=50 mm) and height (H=20 mm) for the different mixes. The specimens are drained at the top and bottom and kept saturated during the oedometric test. The samples were prepared according to the modified Proctor protocol (at maximum dry density and maximum water content) for the two tests. Figure 11 shows the loading-unloading curves for the different mixtures. Figure 12 presents the evolution of the hydraulic conductivity k (m/s) (permeability).

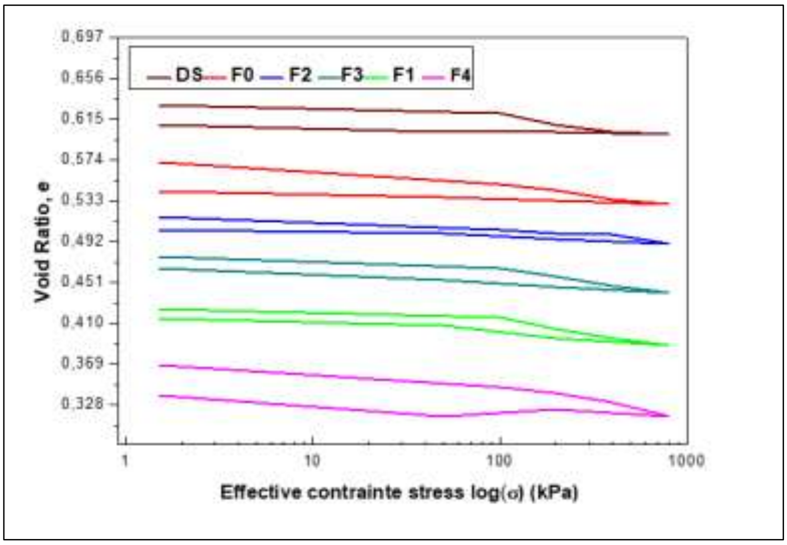

Figure 11: Consolidation curves of the plane *(e- $\log\sigma'_v$)* of the mixtures.
Source: Authors, (2025).

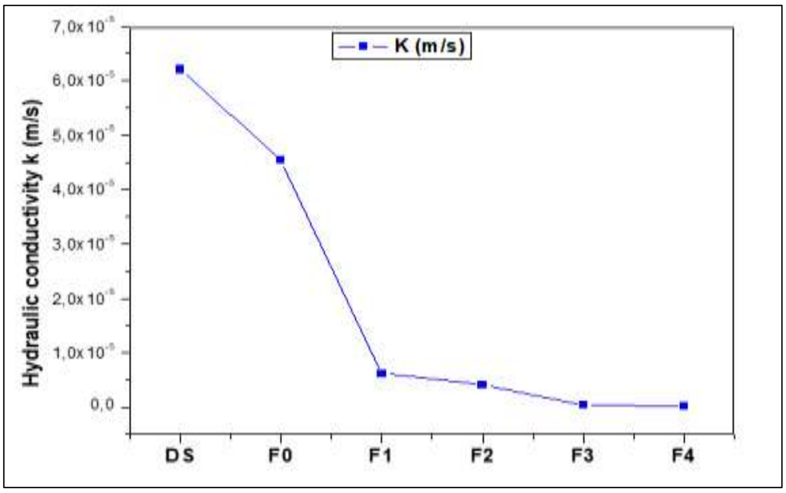

Figure 12: Variation of hydraulic conductivity according to the different mixtures.
Source: Authors, (2025).

It is noted that, according to our results obtained in Figure 10, the compression index of the F4 mixture is Cc=1.06x10^{-1} equal to that of the base mixture F0. This allows us to specify that the additions do not have an influence on the compressibility (settling) of the base mixture F0. On the other hand, we note that the swelling index of the base mixture F0 (Cg=6.5x10^{-3}) is slightly higher than obtained on F4 mixture (Cg= 1.4x10^{-3}).

The obtained results for the hydraulic conductivity (Figure 11) show that the hydraulic conductivity k varied proportionally to the vacuum index and inversely to the percentages of activated slag added. The permeability k decreases from 6.2x10^{-5} (m/s) for untreated dune sand to 4.53x10^{-6} (m/s) in F0 formulation. This reduction reached 3.12 x10^{-7} (m/s) and 1.34x10^{-7} (m/s) respectively for the F3 and F4 mixtures. This confirms that the fine elements have indeed filled the existing voids between the grains of dune sand, making it a dense and coherent compact material.

IV. CONCLUSION

The present work is performed with the aim to a more in-depth knowledge of dune sand and its integration among road materials. The results are generally satisfactory and confirm the physical role of the elements (silt and activated blast furnace slag) which consists of filling the voids between the grains of the mixture. This filling increases the compactness of the mixture and consequently its mechanical resistance. The main findings are:

- The use of dune sand alone cannot be considered, but it could be mixed with other materials which improve its mechanical characteristics.
- The particle size analysis test allowed us to choose the formulations which meet the stability before compaction ($Cu \geq 6$ and $1 \leq Cc \leq 3$) on which we will carry out the Modified Proctor tests to test their stabilities after compaction.
- The additions (silt and activated furnace cap slag) increase the maximum dry densities and decreased the optimal water content proportionally to the increase in percentages.
- The improvement in the CBR lift of the formulations demonstrates their resistance to punching, which allows them to better resist loads induced by traffic.
- The mechanical strengths (shear resistance and compressive strength) obtained for the treated dune sand are improved to be beneficial for a high-performance pavement structure in both intense and moderate traffic. These formulations will lead to the design of thinner pavements allowing considerable savings in materials.
- Consolidation and hydraulic conductivity tests show the compactness and densification of the formulations obtained by minimizing voids and subsequently having more stable formulations

V. AUTHOR'S CONTRIBUTION

Conceptualization: Ali Smaida.
Methodology: Ali Smaida and Hayet Cherfa
Investigation: Khalil Latreche, Abderrahmane Hamadi and Hadi Koribi.
Discussion of results: Ali Smaida, Hayet Cherfa and Smail Haddadi.
Writing – Original Draft: Ali Smaida.
Writing – Review and Editing: Ali Smaida.
Resources: Hayet Cherfa and Smail Haddadi.
Supervision: Ali Smaida.
Approval of the final text: Ali Smaida, Hayet Cherfa and Khalil Latreche.

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