

STUDY OF THE HYDROMECHANICAL BEHAVIOR OF COLLAPSIBLE SOILS IN THE GHARDAÏA REGION, ALGERIA.

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ABSTRACT

The rapid growth of the population has resulted in extensive land use and a notable expansion of construction activities on problematic soils. Arid and semi-arid regions in southern Algeria have witnessed significant urbanization and infrastructure development. These areas are generally characterized by unsaturated surface deposits and deep groundwater levels, allowing soils to remain unsaturated to considerable depths for long periods. Under the influence of climatic cycles and repeated wetting–drying processes, soils progressively develop their microstructure, hydraulic characteristics, and consequently their physical and mechanical properties. Recent studies have shown that soil-water retention curves (SWRC) are effective tools for characterizing the stress state of unsaturated soils, describing their hydromechanical behavior, and estimating their strength parameters. The aim of this research is to characterize these soils and examine the additional shear strength resulting from suction variations, as well as the influence of soil compaction on the collapse mechanism. Soil samples were collected from the Metlili Valley, an arid region located southwest of Ghardaïa. The findings reveal significant volumetric changes caused by suction reduction. Furthermore, an increase in suction enhances shear strength, mainly due to the rise in apparent cohesion associated with capillary effects.



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I. INTRODUCTION

Under the effect of population growth in recent decades, the arid and semi-arid regions in the South of Algeria have experienced significant urban development and the construction of civil engineering structures. The soils in most of these regions are superficial unsaturated aeolian deposits, unconsolidated, and characterized by a well-developed pore space over a significant depth. Such deposits are known as collapsible soils [1-4] that exhibit significant volume reductions due to the simultaneous variation of their water content and matric suction resulting from repeated climatic cycles of wetting and drying. This phenomenon of alternating variations in moisture and suction can cause multiphysical problems for civil engineering structures [5–8]. It is therefore important to properly understand these phenomena and to implement resilient geotechnical design measures and approaches for reliable risk prevention [9-11]. A Previous research work [12], [13] has highlighted the effect of initial suction on the mechanical properties and strength parameters of unsaturated soils, particularly in the arid and semi-arid climatic context. Several authors have emphasized that the hydromechanical behavior of unsaturated soils is very complex under the combined effect of suction and water content. The effect of the initial state of unsaturated collapsible soils on their mechanical behavior and strength parameters, particularly in terms of density, water content, and matric suction, has been studied by several researchers [14-17], among others. The analysis of the matric suction properties of unsaturated collapsible soils in the study area remains one of the most significant factors in research on their hydromechanical behavior. More recent studies have indicated that the linear correlation between shear strength and matric suction is not relevant for all soil types and for the entire suction range [18]. In this study, a set of laboratory tests were carried out on soil specimens to analyze the simultaneous effect of the variation of matric suction, compaction state, and water content on the collapse potential and the mechanical characteristics of the tested soils.

The obtained results highlight the relationship between matric suction and collapse potential, as well as the parameters affecting shear strength.

II. MATERIALS. EQUIPMENT AND TESTS

II.1 STUDY AREA

The studied soil was extracted from the Metlili region, located 45km south of the city of Ghardaia in the Northern Algerian Sahara at 32.17°N latitude and 3.32°E longitude, with an average site elevation of 454 meters Figure 1. Climate is considered one of the important factors in the formation and evolution of the soil's geotechnical characteristics. Indeed, the seasonal fluctuations in temperature and precipitation in the studied area illustrate its marked desert climate, characterized particularly by low and irregular rainfall. Given the climatic conditions, the study region is classified as an arid zone according to its aridity index, which is a useful indicator for characterizing this phenomenon.

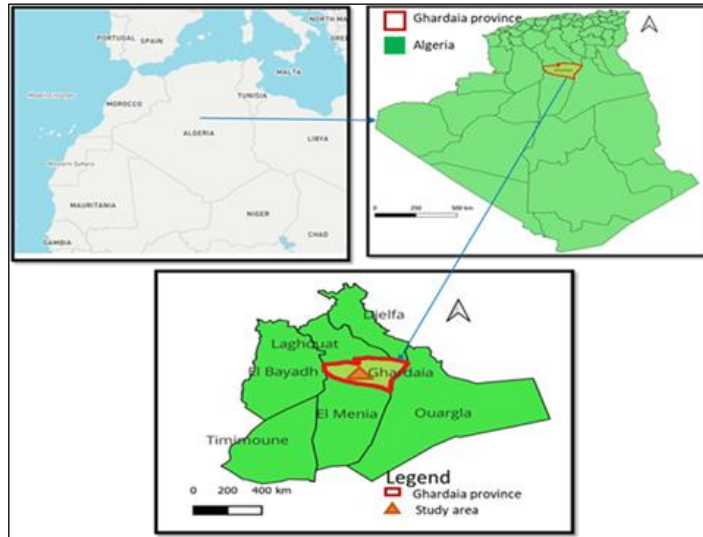


Figure 1: Localization of the study area map of Ghardaia, Algeria.

Source: Authors, (2026).

Geological studies indicate that the study area is incised into the Turonian limestone massifs and is characterized by four geological layers: Quaternary, Turonian, Cenomanian, and Albion. The Quaternary corresponds to the alluvial deposits covering the Metlili Valley. The Quaternary alluvium consists of sands, pebbles, and clays lining the valley floor with a thickness ranging from 20 to 30 meters. The Cenomanian is characterized by variegated clays that range in color from brown and grayish to greenish. These clays are plasticized and sandy at the base, with gypsum present. The Albion is made up of fine to medium yellowish sands, Figure 2.

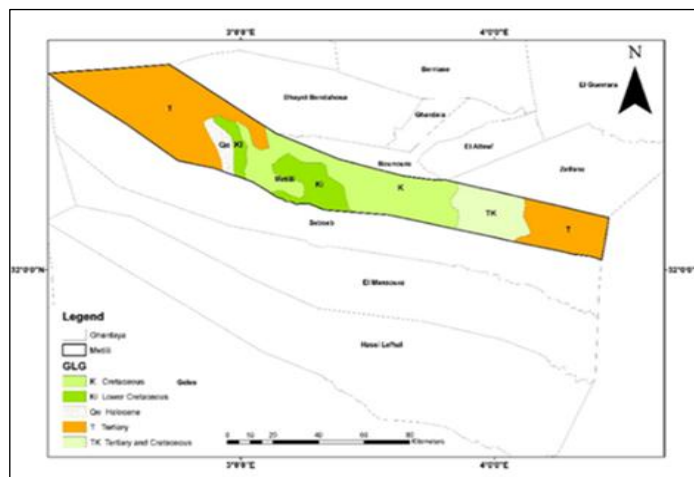


Figure 2: Simplified geological map of Ghardaia, Algeria.

Source: Authors, (2026).

II.2 MATERIALS

Samples of the studied soil were collected from three different experimental sites at depths ranging from 1.5 to 2 meters in their natural state. For the physical characterisation of the soil, an initial series of traditional tests was carried out in the laboratory to measure the specific gravity of solid particles (G_s), natural water content (w_n), methylene blue value (MBV), Atterberg limits (PL, LL, PI), particle size distribution, and standard Proctor compaction. These tests indicate that the soil exhibits low plasticity properties, the studied soil can be classified as sand loam. The details of geotechnical properties can be found in Table 1.

Table 1: Properties of soils used in this study.

Property	Value
Initial Moisture Content , w_n (%)	4.5
Spécific Gravity , G_s	2.66
Liquid Limit, LL(%)	24
PlasticLimit ,PL (%)	17
Maximum Proctor Test, γ_d (Mg /m ³)	1.82
Optimum Moisture Content, w_{op} (%)	10.5
Clay fraction (%)	6.5
Silty fraction (%)	38.5
Sandy fraction (%)	55
Calcium carbonate CaCO ₃ (%)	22.5
Methylene bleu valueMBV	0.42
USCS Classification	SM-SC

Source: Authors, (2026).

Particle size analysis allows for the quantitative determination of the soil particle distribution based on size categories. The studied soils belong to class (A1) according [19]. These materials are characterized by a percentage passing greater than 35% through the 80 μ m sieve. The methylene blue absorption value is less than 2.5, and the plasticity index is less than 12. The predominance of the sand fraction (55%), the relatively high fines content (45%), and Atterberg limits positioned in the transition zone of the Casagrande chart (PI = 7% and LL = 25%) indicate that this soil is classified as SM–SC according to the USCS system. The particle size distribution curves of the samples are presented in Figure 3.

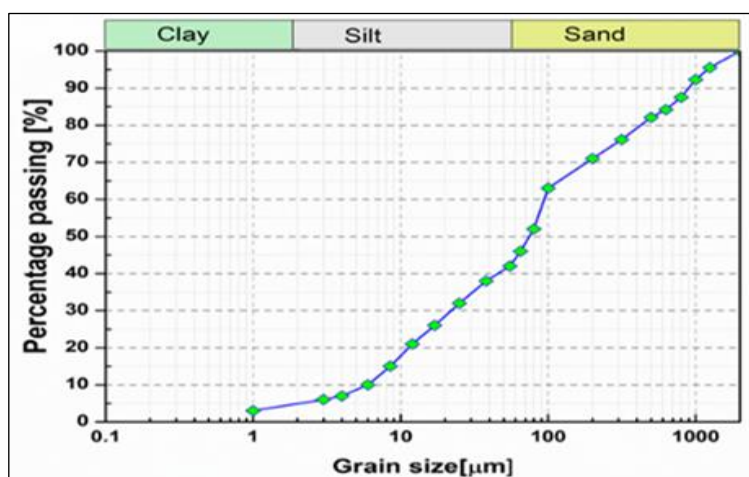


Figure 3: Grain size distribution of studied soil.

Source: Authors, (2026).

Mineralogical analyses were conducted on the studied soil using a BRUKER-binary V3 X-ray diffractometer with $K\alpha$ radiation (1.5406 Å), operating at 35 kV and 30 mA, with an angular detection range (2θ) from 5° to 90°. This analysis aimed to identify the crystalline structure and mineralogy of the samples. The results of this X-ray analysis are presented as diffractograms (XRD) shown in Figure 4.

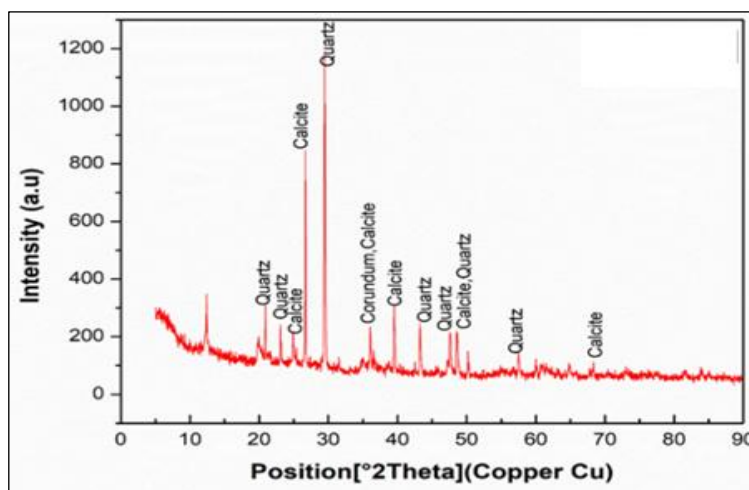


Figure 4: X-ray diffraction pattern of studied soil for mineralogical composition.

Source: Authors, (2026).

The position and intensity of characteristic diffraction peaks enable the identification of different crystalline phases in the studied material, which is primarily composed of quartz. Quartz, known for its chemical stability, promotes a granular texture and increased permeability whereas showing low water retention. The substantial presence of quartz is confirmed by the particle size distribution, indicating a high percentage of sand in the material. Calcite notably influences the chemical and mechanical properties of the soil, enhancing cementation and cohesion. Corundum and other minerals are present in minor proportions. To identify and quantify the chemical elements of the studied soils, a geochemical analysis was performed using an X-ray fluorescence spectrometer (XRF). The results of this analysis are also presented in Table 2.

Table 2: Chemical composition of the studied soil.

Major elements		Trace elements	
Oxydes	Content (%)	Oxydes	Content (ppm)
SiO ₂	51,45	MnO	59.6
Al ₂ O ₃	21,73	SrO	42,5
CaO	10,58	ZrO ₂	28.4
Fe ₂ O ₃	9,41	Cr ₂ O ₃	28.3
K ₂ O	2,13	V ₂ O ₅	27.1
MgO	2,04	ZnO	15.8
TiO ₂	1,69	Rb ₂ O	10.8
Na ₂ O	0,33	NiO	7.4
So ₃	0,32	Nb ₂ O ₅	5.2
P ₂ O ₃	0,18	Y ₂ O ₃	3.4

Source: Authors, (2026).

The obtained results show high proportions of silicates (SiO₂) 50.4%. The strong presence of quartz is confirmed by the granulometric distribution, which indicates a high percentage of sand in the material. Aluminum oxide (Al₂O₃) 21.7%, calcium carbonate (CaO) 10.6% and iron oxide (Fe₂O₃) 9.41. There is a relative chemical richness in potassium oxide (K₂O) 2.13%, titanium oxide (TiO₂) 1.7%, which are detrital chemical elements originating from basement rocks, and relatively low contents of magnesium oxide (MgO) 2.04%.

II.3 PERFORMED TESTS

The experimental program included collapse tests, shear tests, and suction tests. The selection of low water contents and moderate compaction energy for investigating collapsible soils is designed to replicate the loose, metastable structure characteristic of natural conditions in arid regions. This methodological choice is substantiated by the fact that such soils typically exist in a partially saturated state, wherein matric suction exerts a critical influence on their apparent structural stability. The experimental procedure and the parameters selected for each test series, as well as the specific characteristics of each category are detailed in Figure 5.

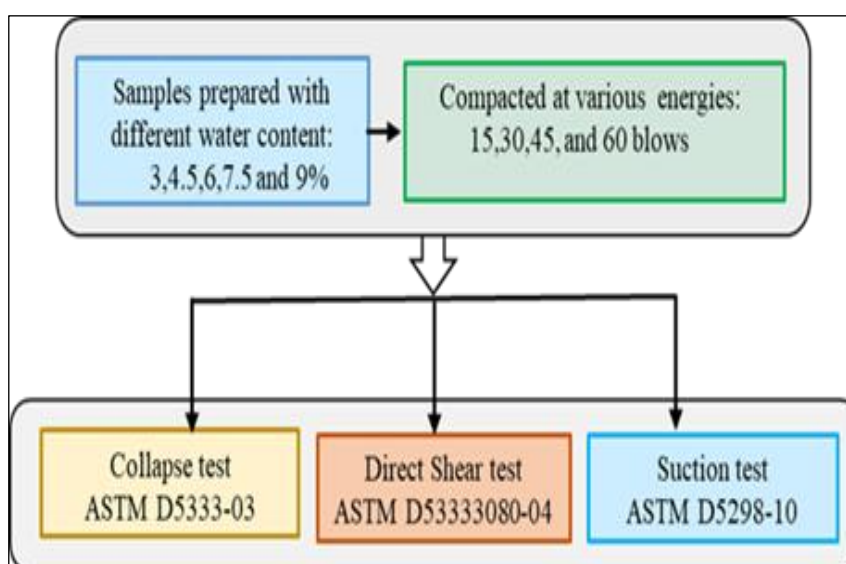


Figure 5: Flowchart of the tests.

Source: Authors, (2026).

The samples of the studied soil are prepared in the laboratory from soil extracted from various sampling sites, presented in block form. The samples are dried in an oven, crushed with a wooden hammer, and then sieved using a 2 mm sieve. To achieve the desired water content, demineralized water is carefully mixed with the samples in different proportions corresponding to the water content values ($w = 3\%$, 4.5% , 6% , 7.5% , and 9%), taking into account the amount of water content lost during preparation. The mixture is then left to cure at a constant temperature and humidity for 24 hours to ensure a homogeneous distribution of moisture.

Then, the soil mixture is poured into an oedometer mold 60 mm in diameter and 20 mm in height and compacted in a single layer using a compaction hammer at different compaction energy levels (15, 30, 45, and 60 blows corresponding to 69, 138, 207, and 276 kJ/m³). The apparatus used for the compaction procedure, designed in the laboratory, is shown in Figure 6. It consists of a disk whose diameter is slightly smaller than that of the ring, fixed to a guide rod, and a disk-shaped hammer.

The hammer weighs 132 g and slides along the rod, falling from a height of 20 cm to strike the disk, thus compacting the material in the oedometer ring. The compaction energy E_c applied to the specimen, which is the work of the mass M (kg) falling from a height h (m), is given by the equation:

$$E_c = \frac{MghN}{V} \quad (1)$$

With M : mass of the hammer, g : acceleration due to gravity, h : drop height of the hammer, N : number of blows, V : Volume of the mold in m³.

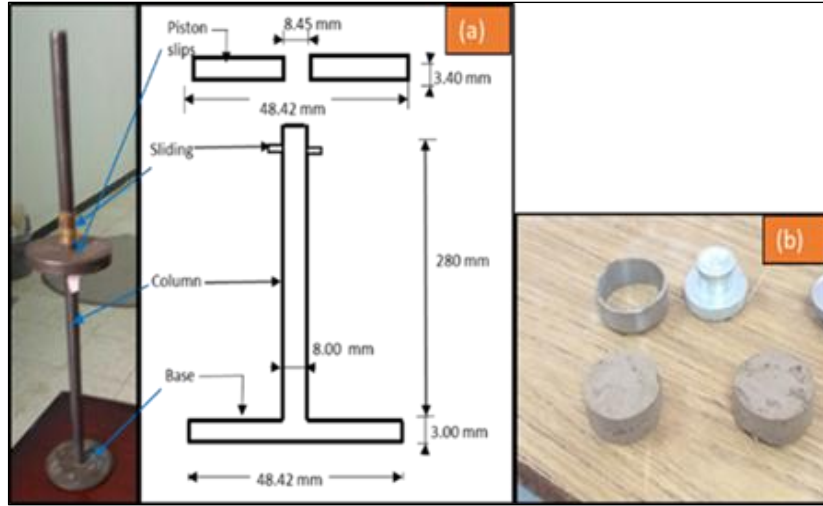


Figure 6: Compaction procedure of the samples: (a) Compaction hammer, (b) Compacted samples.

Source: Authors, (2026).

II.3.1 Collapse Tests

The collapse tests are conducted according to the specifications [20]. The vertical load is applied in the following successive stages: 25, 50, 100, and 200 kPa. To estimate the collapse potential (C_p), the sample is flooded for 24 hours. The collapse potential is determined by measuring the difference in axial deformation at a vertical stress of 200 kPa after and before immersion. Then, the loading is increased to the value of 400 kPa. During the test, the settlements are recorded at 15s, 30s, 1min, 2min, 5min, 10min, 30min, 1h, and 24h. The collapse potential is calculated for each test using the expression.

$$C_p = \frac{\Delta e_c}{(e_0 + 1)} 100\% \quad (2)$$

With $\Delta e_c = e_1(200 \text{ kPa, unsaturated}) - e_2(200 \text{ kPa, flooded})$, and e_0 : initial void ratio

II.3.2 Shear Tests

Experimental shear tests were conducted on soils samples at various suction and confinement pressures of 100 kPa, 200 kPa, and 300 kPa, in accordance with [21] under drained conditions. A shear box with dimensions of 60 mm x 60 mm with a thickness of 25 mm was used for the tests, which were conducted at a constant low shear rate of 0.3 mm/min throughout the experiment.

II.3.3 Suction Tests

The suction tests conducted in this study used a laboratory method with Whatman filter paper grade No. 42, which allows for measuring matric suction values of up to about 100 MPa, following the specifications in [22]. The wet samples were prepared by adding a specific percentage of distilled water based on their weight. A set of filter papers was dried in an oven for 24 hours before testing. The suction measurement involves placing three filter papers between two soil samples. This setup is designed to prevent contamination of the central filter paper, which is used for measuring suction and has a slightly smaller diameter than the outer two filter papers. To reach hydraulic equilibrium, the assembly is wrapped in plastic film and then kept in a glass desiccator for 15 days. The experimental procedure is illustrated in Figure 7.

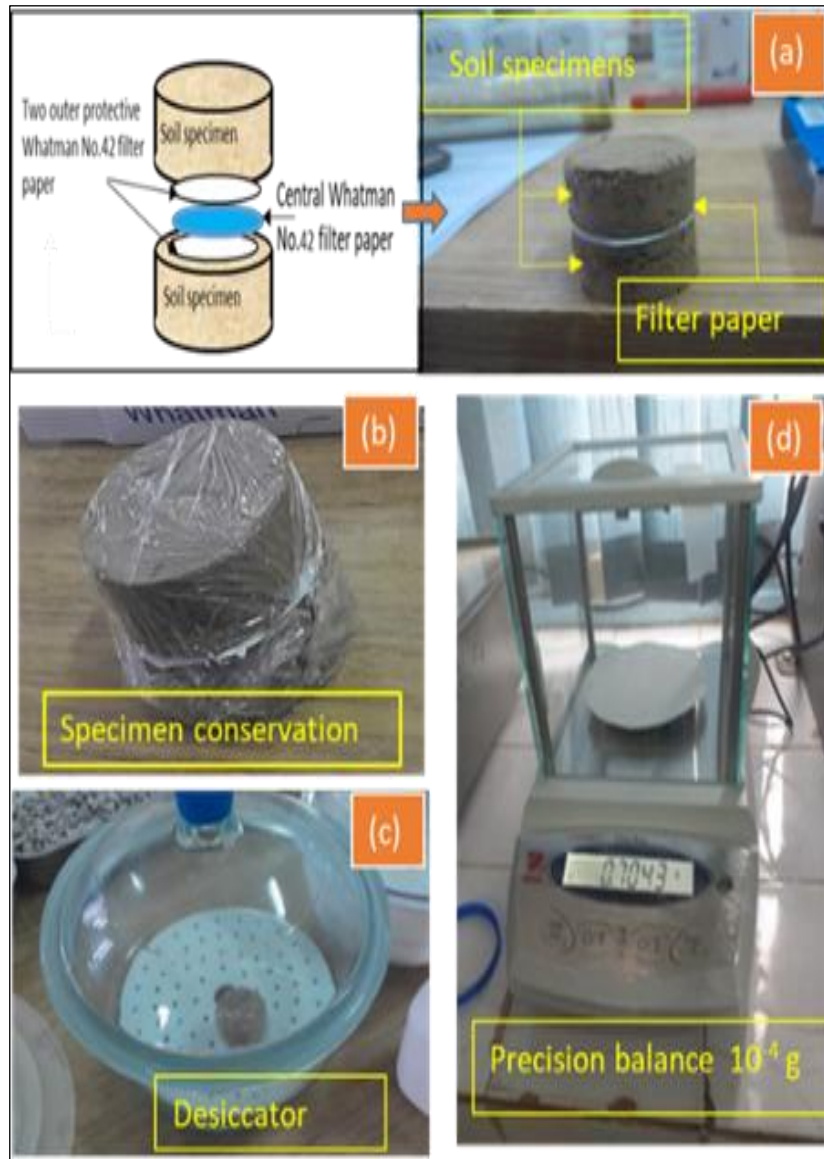


Figure 7: Experimental procedure for suction measurement suction using the filter paper Whitman 42: (a) filter paper interposed between two soil samples, (b) soil samples wrapped in plastic film, (c) suction equilibrium phase, (d) measurement of the weight of the filter paper loaded with moisture.

Source: Authors, (2026).

When equilibrium is achieved between the filter paper and the soil, the gravimetric water content of the central filter paper is measured, from which the matric suction is calculated using the calibration curve described by “(3)” and “(4)”, as the suction measurement device

$$\text{Log}_{10} S(\text{kPa}) = 5.327 - 0.0779w_f \quad w_f > 45.3 \quad (3)$$

$$\text{Log}_{10} S(\text{kPa}) = 2.412 - 0.0135w_f \quad w_f > 45.3 \quad (4)$$

Where S is the matric suction, w_f is the gravimetric water content of the filter paper in percentage. The hydro-mechanical behavior is influenced by its water retention characteristics. In this study, the soil-water retention behavior is modelled using the semi-empirical van Genuchten equation [23] as expressed in the (5) below:

$$\theta_w = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha S)^n]^m} \quad (5)$$

Where :

θ_w : is volumetric water content, θ_r : is residual volumetric water content, θ_s : is saturated volumetric water content,

S : is soil suction, α : is scaling parameter inversely proportional to the mean pore diameter (cm^{-1}), n , m : are the shape parameters of the soil water characteristic. $m = (1 - 1/n)$.

III. RESULTS AND DISCUSSIONS

III.1 COLLAPSIBILITY

Figure 8 illustrate the results of collapse tests conducted on sample soils at different water contents, suction values, and compaction energies.

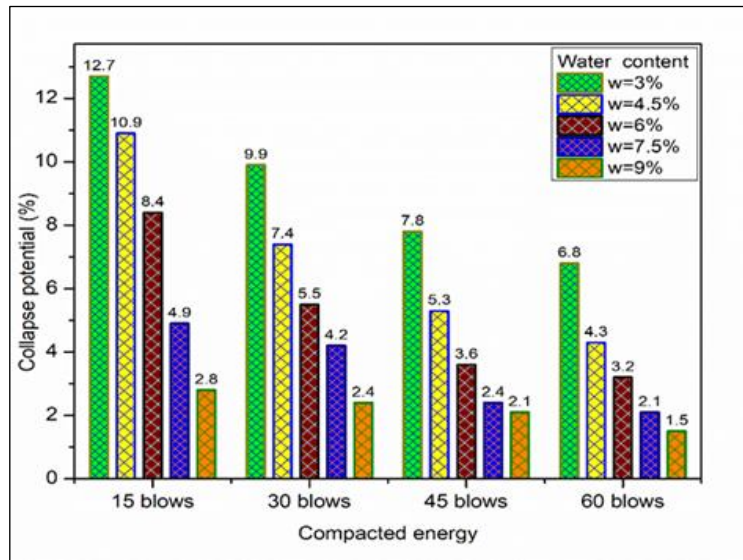


Figure 8: Effect of water content and compaction energy on collapse potential.
Source: Authors, (2026).

The collapsibility test results show that water content and compaction energy have a crucial effect on the C_p . This potential decreases from 12.7% to 2.8% for the soil compacted under 15 blows, from 11.4% to 2.4% for soil compacted under 30 blows, from 7.8% to 2.1% for soil compacted under 45 blows and from 6.8% to 1.5% for soil compacted under 60 blows. The results indicate that the collapse potential increases as water content and compaction energy decrease. The maximum C_p value is obtained is $C_p=12.7\%$, corresponding to the lowest water content, $w=3\%$ and compaction energy of 15 blows. This is explained by the structural instability of the soil, leading to a high C_p . However, the low $C_p=1.1\%$ at the highest water content, $w=9\%$, compacted under 60 blows. Under these conditions, the soil is not susceptible to collapse. Figure 9 explicitly shows the effect of suction and compaction energy on the C_p . It is observed that the magnitude of C_p decreases with increasing compaction energy, whereas it increases with higher suction levels, which typically develop during dry periods.

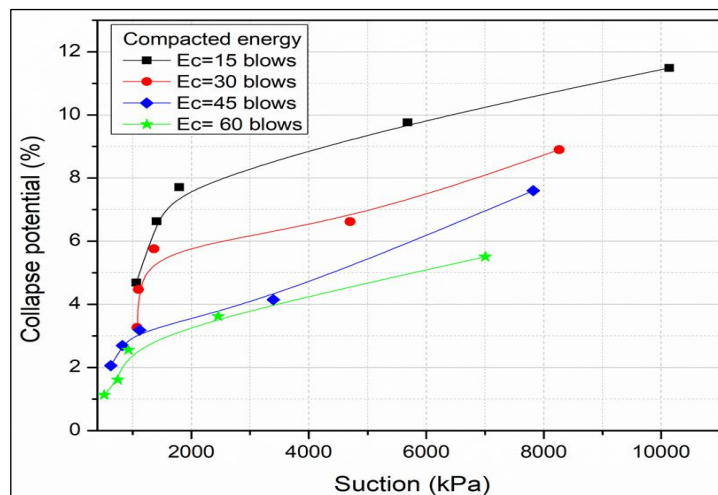


Figure 9: Effect of suction and compaction energy on collapse potential.
Source: Authors, (2026).

III.2 EFFECT ON SUCTION SHEAR PARAMETERS

As for the shear tests, Figures 10 and 11 show that the results yielded low cohesion values, ranging from 12.5 kPa to 26 kPa, due to the low plasticity of the silty sand. For a suction range between 1196.6 kPa and 9678.5 kPa, cohesion varies from 12.6 kPa to 21.5 kPa, representing an increase of approximately 68%. Similarly, for suctions varying between 510 kPa and 6830 kPa, the increase in cohesion is about 35%. This behavior is explained by the enhancement of capillary attraction forces between particles, which gives the soil a more rigid structure and greater strength in the unsaturated state. The influence of suction on the internal friction angle remains limited and is scarcely noticeable, with a variation magnitude between 0.5° and 1.0° .

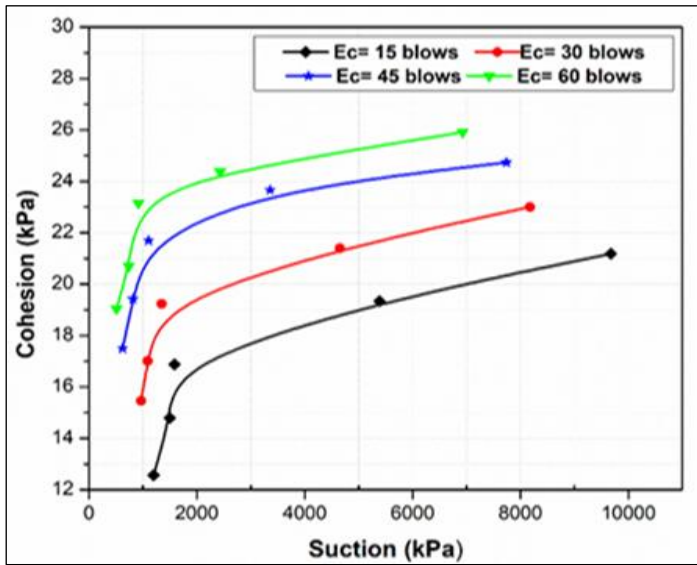


Figure 10: Effect of suction and compaction energy on cohesion.
Source: Authors, (2026).

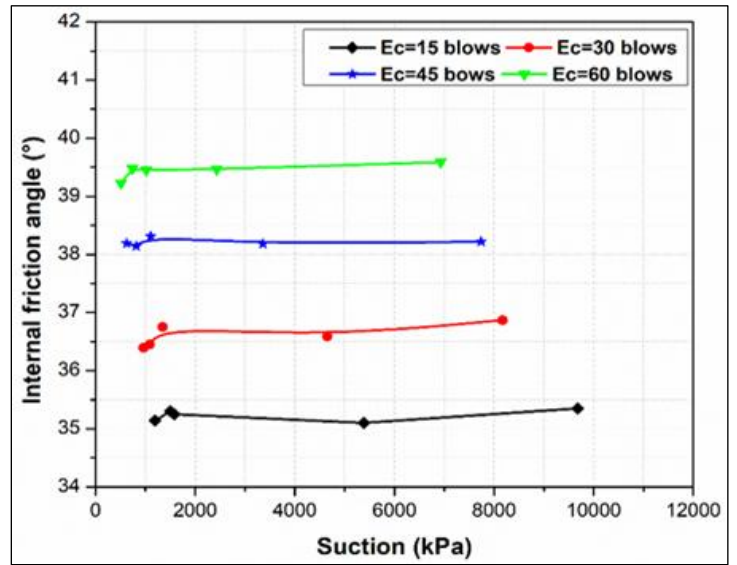


Figure 11: Effect of suction and compaction energy on friction angle.
Source: Authors, (2026).

III.3 SOIL WATER RETENTION BEHAVIOR

The analysis of the soil water retention curve (SWRC) according to the van Genuchten model was performed using the RETC (REtention Curves) software [24]. The water contents predicted by the RETC program are evaluated against the measured values Figure 12.

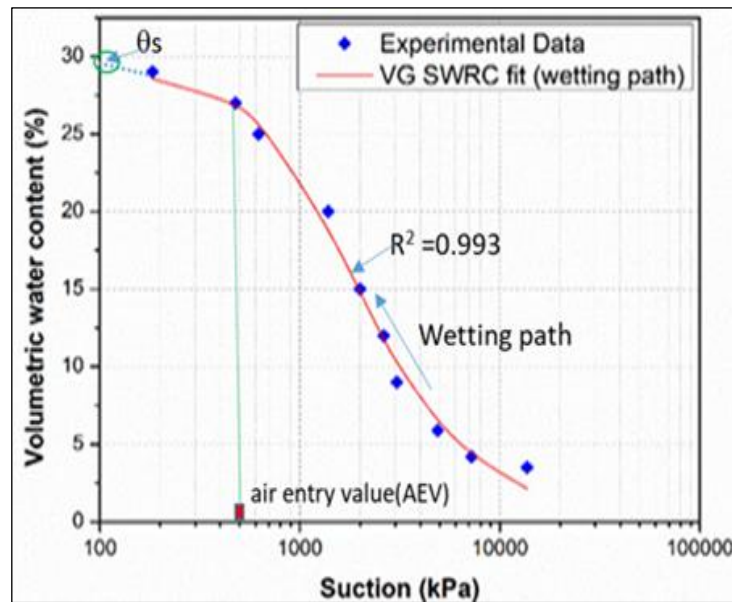


Figure12: Soil-water retention curve.
Source: Authors, (2026).

The evaluation of the fitting performance using the van Genuchten model is provided by the statistical indicators, specifically the coefficient of determination $R^2=0.993$, and the root mean square error $RMSE=0.009$. Figure 13 illustrates a strong correlation between the experimental values and the results obtained from the model. The parameters of the Van Genuchten model are used to characterize the hydraulic properties and texture of the soil. The parameter α is related to the air-entry pressure. Lower values of α correspond to higher air-entry pressures (AEV). For the soil studied, $\alpha = 0.008 \text{ cm}^{-1}$, which corresponds to an air-entry pressure of 500 kPa. The parameters n and m describe the pore-size distribution, reflected in the slope, and the overall shape of the soil water retention curve, respectively.

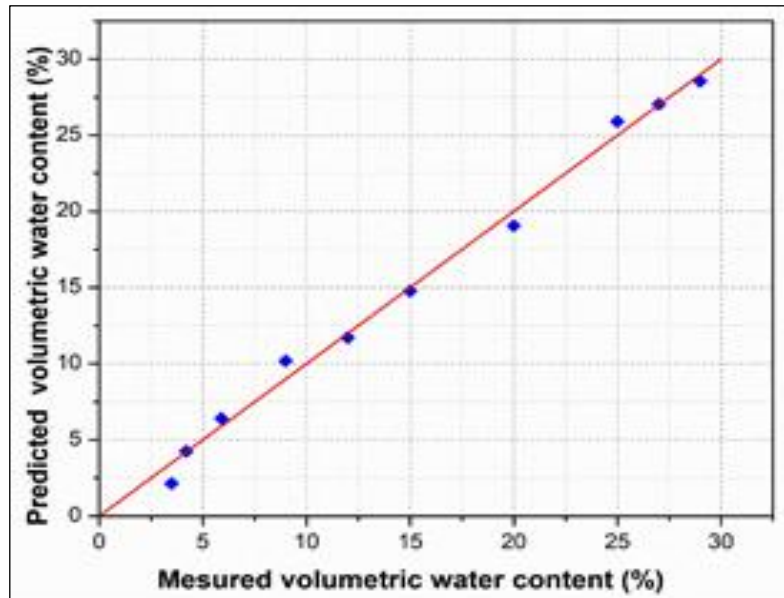


Figure13: Predicted versus measured values of the volumetric water content of the studied soil.
Source: Authors, (2026).

The van Genuchten parameters for the soil modelled in this study are provided in Table 3.

Table 3: Van Genuchten parameters.

Parameter	value
θ_s (%)	28.8
θ_r (%) _a	0.06
α (1 /cm)	0.008
n (-)	2.09
m (-)	0.47

Source: Authors, (2026).

IV. CONCLUSIONS

This experimental research offers insights into the characterization and analysis of the hydromechanical behavior of an unsaturated collapsible soil from the Metlili area in Ghardaïa Province (southern Algeria). The study aims to address existing gaps in knowledge regarding the natural soils of the region. The study also provided information on the behavior of a sandy loam soil with low plasticity under different moisture conditions. The obtained results confirm the effect of suction and capillary stresses on the assessment of the shear strength of unsaturated soils, by varying the compaction state and the interactions between soil particles. Specimens exhibiting high suction and compacted under moderate energy levels recorded the maximum values of collapse potential C_p . This behavior is attributed to the presence of a porous structure and weak interparticle bonds. The study revealed that the internal friction angle was not significantly affected by suction. However, an increase in the apparent cohesion of the soil is observed with an increase in suction. The collapse and shear tests conducted on unsaturated samples with different suction values allowed for the characterization of the collapse and shear properties of the soils studied at different suction levels. The hydraulic behavior of the studied soil, as described by the van Genuchten model, constitutes a relevant tool for hydromechanical studies of unsaturated soils, as it establishes a continuous relationship between water content and matric suction. It represents the different wetting phases, from conditions of high suction to the saturated state.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Ali Fernane, Samir Benmoussa and Laouar Mohamed Salah.

Methodology: Ali Fernane and Laouar Mohamed Salah.

Investigation: Ali Fernane and Laouar Mohamed Salah.

Discussion of results: Ali Fernane, Laouar Mohamed Salah and Samir Benmoussa.

Writing – Original Draft: Ali Fernane.

Writing – Review and Editing: Ali Fernane and Laouar Mohamed Salah.

Resources: Ali Fernane and Laouar Mohamed Salah.

Supervision: Samir Benmoussa.

Approval of the final text: Ali Fernane, Samir Benmoussa, and Laouar Mohamed Salah.

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