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SUSTAINABLE STABILIZATION OF LOESS SOILS USING MARBLE POWDER: IMPROVEMENT OF MECHANICAL PROPERTIES

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ABSTRACT

The instability of clayey soils poses a major challenge in geotechnical engineering, especially in arid regions where water infiltration causes a rapid loss of strength and cohesion. Due to the high cost and limited sustainability of conventional stabilization methods, this study evaluates marble powder (MP), a low-cost industrial by-product, as an effective stabilizer for collapsible soils in the Messaad region (Algeria). Soil samples were treated with 5%–20% MP and tested using unconfined compressive strength (UCS), direct shear, California Bearing Ratio (CBR), subsidence tests, and XRD/XRF analyses. The results revealed significant improvements with increasing MP content: UCS increased by 536.36%, CBR by 206.61%, and shear strength by 26.60%. Additionally, maximum dry density increased by 9.14%, while optimum moisture content decreased by 9.86%. XRF results showed higher CaO and lower SiO_2 and Al_2O_3 contents, while XRD confirmed the formation of calcite, which enhances bonding and soil stability. Overall, the study demonstrates that marble powder is an efficient, sustainable, and environmentally friendly material for improving the geotechnical behavior of collapsible soils.

I. INTRODUCTION

Geotechnical engineering frequently encounters the challenge of unstable soils that threaten the long-term performance and safety of civil structures. In arid and semi-arid regions, two types of problematic soils are particularly prevalent: expansive soils commonly found in Algeria and collapsible loess soils. Expansive soils exhibit volumetric changes due to cycles of wetting and drying, leading to cracking and structural deterioration. In contrast, collapsible soils, such as those in the Djelfa region, experience sudden settlement upon saturation, resulting in a significant loss of bearing capacity [1]. Traditional soil stabilization methods, including the use of lime and cement, are generally effective but often costly, short-lived, and environmentally taxing. The high carbon footprint and resource consumption associated with these materials have prompted increasing interest in more sustainable alternatives [2].

In this context, the reuse of industrial by-products offers a promising pathway toward environmentally responsible soil stabilization. Among these materials, marble powder (MP) a waste product generated by the marble industry stands out for its high calcium carbonate and metal oxide content, which can enhance both the mechanical and hydromechanical behavior of soils [3]. Several recent studies have demonstrated the potential of incorporating marble powder into clayey and collapsible soils. For instance, Nazir et al. (2020) [4] reported that the addition of up to 50% MP reduced the liquid limit by 35%, increased the maximum dry density by 6%, and improved cohesion by up to 314% under saturated conditions, while also reducing collapse potential [4]. Similarly, [5] observed a substantial reduction in the plasticity and swelling potential of clays, accompanied by enhanced shear strength [5].

More recently, research conducted in China confirmed that soil–marble powder mixtures with up to 60% substitution significantly increased unconfined compressive strength (UCS) and California Bearing Ratio (CBR), while enabling the development of a reliable predictive model for performance [6]. In Algeria, several alternative stabilizers have also been investigated. For example, the treatment of collapsible loess in southern Algeria with sodium silicate reduced collapse potential by more than 87% [7]. Likewise, the use of granulated slag has proven highly effective in improving the shear parameters of subsiding soils [8]. Building on these findings, the present study aims to assess the effectiveness of marble powder as a sustainable stabilizing agent for unstable soils in the Messaad region (Algeria), with particular emphasis on collapsible loess soils from the Djelfa area. Through a comprehensive series of laboratory and in situ tests, this research seeks to develop a sustainable, economical, and environmentally friendly solution that aligns with circular economy principles by valorizing local industrial waste.

II. STUDY AREA AND SAMPLING

The study was conducted in Messaad, located in the Djelfa province of Algeria, approximately 375 km south of Algiers. The region lies at the intersection of the Saharan Atlas and the central steppe (34.09°N, 3.30°E). It is traversed by National Road 89, a strategic 290 km highway connecting M'sila to the southern part of Djelfa. This heavily trafficked route is of particular importance for regional transportation but requires frequent maintenance due to the unstable nature of the underlying soils **Erro! Fonte de referência não encontrada.** Soil samples were collected from a quarry near Messaad (34°18'51"N, 3°37'01" E) Figure 2. A selective sampling approach was adopted to ensure the representativeness of key geotechnical parameters. Disturbed (remanaged) samples were extracted from depths shallower than 1.7 m to minimize organic matter content, while undisturbed samples were obtained using a manual auger for subsequent mechanical testing.

Grain size analysis classified the soil as clay loam (ML) according to the Unified Soil Classification System (USCS). The results are summarized in Table 2 and depicted in the grain size distribution curve (Figure). The investigated section corresponds to the terminal portion of the road, traversing loose clay soils highly susceptible to subsidence. These semi-saturated to dry soils, characteristic of arid environments adjacent to mountainous areas, exhibit strong sensitivity to moisture variations, resulting in settlement and deformation. The objective of this study is to evaluate the susceptibility of these soils to collapse and to propose effective stabilization measures. To achieve this, a comprehensive program of field investigations and laboratory tests was undertaken.

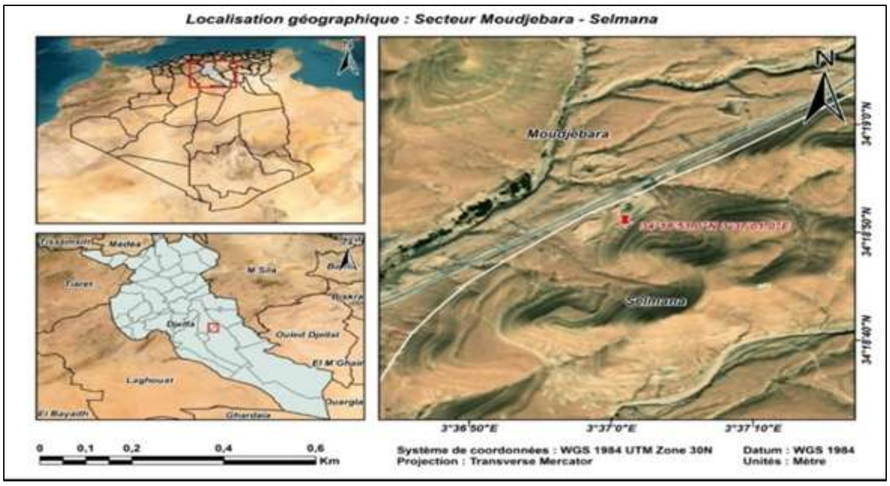

Figure 1: Location of sampling sites.
Source: Authors, (2026).

Figure 2: Natural ravines and collapses in RN89: PK 28+500.
Source: Authors, (2026).

III. MATERIALS AND METHODS

The materials used in this study form the basis of the experimental program. Their prior characterization is essential to assess suitability for soil stabilization. The soil, collected from a quarry along National Route 89 near Messaad (Djelfa province), is classified as clayey silt (ML). Its geotechnical properties were determined in the laboratory before any treatment (Table 1). Marble powder, produced in large quantities during sawing and polishing operations notably from TamStones in Sidi Bel Abbès, the Société Nationale du Marbre in Felfla, and the Chlef marble factory in Aïn Defla is an abundant and inexpensive by-product. Although open-air storage can cause air pollution, its physicochemical characteristics make it a promising material for soil stabilization.

It is composed mainly of calcium carbonate ($CaCO_3$), with a high proportion of fine particles (<75 µm, 70–90%), a specific gravity of 2.65–2.70, and a plasticity index of zero (PI ≈ 0). Its high CaO content (50–56%) contrasts with the low proportion of secondary oxides (SiO_2, Al_2O_3, Fe_2O_3 <3%), moderate MgO (0.5–2%), and alkalis (Na_2O + K_2O <0.5%). Loss on ignition (LOI), linked to decarbonation, ranges between 40 and 45%. These properties confirm that marble powder is chemically stable and has low reactivity, making it effective in improving the geotechnical performance of soils, particularly when combined with hydraulic binders or silica- and alumina-rich additives [9], [10]. Recent studies support its effectiveness; for example, research on coffee husk ash [9] and nanomaterials (Al_2O_3, SiO_2) [10], [11] have shown similar reductions in plasticity and improvements in mechanical stability.

Figure 3: Marble waste in the Messaad (Djelfa) region—Algeria.
Source: Authors, (2026).

III.1 CHARACTERIZATION OF NATURAL SOIL

A series of laboratory tests were conducted to determine the geotechnical properties of the soil before mixing it with marble dust. The results are presented in Table 1.

Table 1: Geotechnical characteristics of loess (RN 89 : PK)268+500).

Désignations	Valeurs
Water content , W(%)	10.4
Specific weight Gs	2.65
Specific gravity of solid particles γ_s(kN/m^3)	27.0
Degree of saturation , Sr (%)	21.07
Saturation content w_{sat} (%)	35.03
Sand (%)	30
Silt (%)	52
Clay (%)	18
Coefficient of uniformity Cu	10.77
Coefficient of curvature Cc	5.49
Maximum dry density γd (g/cm^3)	1.75
Optimum water content w_{opt} (%)	14.2
collapse potentials CP (%)	10.01
Friction angle Φ (degree)	33.16
Cohesion,C(kpa)	11.00

Source: Authors, (2026).

III.2 CHARACTERIZATION OF MARBLE POWDER

The physical and chemical characterization of marble powder (MP) confirms its suitability as a stabilizing additive for fine-grained soils. Its composition is predominantly calcitic, with negligible plasticity, which makes it an effective complementary material in soil stabilization applications.

III.3 CHEMICAL AND MINERALOGICAL ANALYSES

To better understand the influence of marble powder incorporation on soil behavior, detailed chemical and mineralogical analyses were performed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) techniques.

III.3.1 X-Ray Diffraction (XRD)

XRD analysis of the natural soil as shown in the Figure 4. indicates a mineralogical composition dominated by calcite (52.1%), followed by dolomite (43.0%) and a minor proportion of quartz (4.8%). Following the incorporation of marble powder, the diffractograms Figures (5–8) reveal a slight but consistent increase in calcite content, reaching 53.3% for a 5% MP addition (Figure 5), while the proportions of dolomite (42.7–43.1%) and quartz (4.8–5.0%) remain largely stable. At higher MP dosages (10%, 15%, and 20%; Figures 6–8), this trend becomes more pronounced, with progressive intensification of the characteristic calcite peaks. This mineralogical stability, combined with the relative increase in calcite, suggests a gradual enhancement of interparticle bonding. Calcite thus plays a key structuring role by reinforcing intergranular contacts, leading to improved cohesion and mechanical stability in the treated soils.

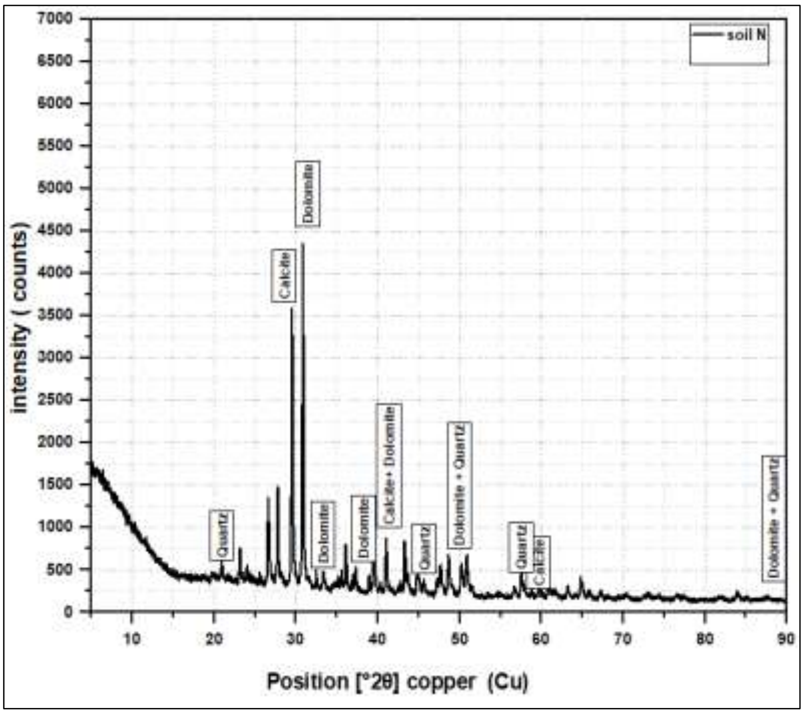

Figure 4: X-ray diffraction (XRD) of natural soil.
Source: Authors, (2026).

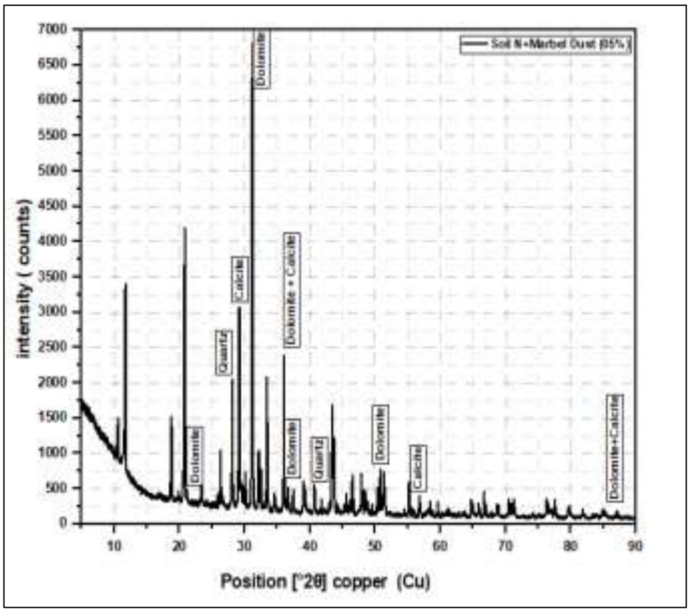

Figure 5: X-ray diffraction (XRD) of the soil treated with 5% marble powder.
Source: Authors, (2026).

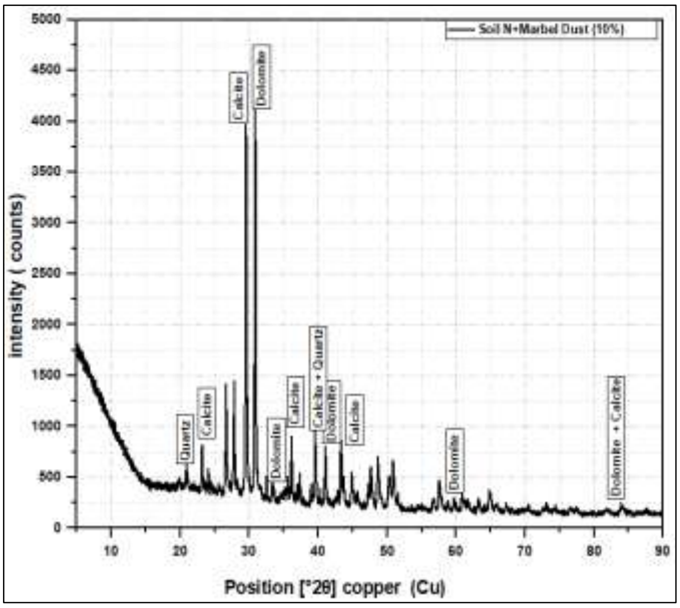

Figure 6: X-ray diffraction (XRD) of the ground treated with 10% marble powder.
Source: Authors, (2026).

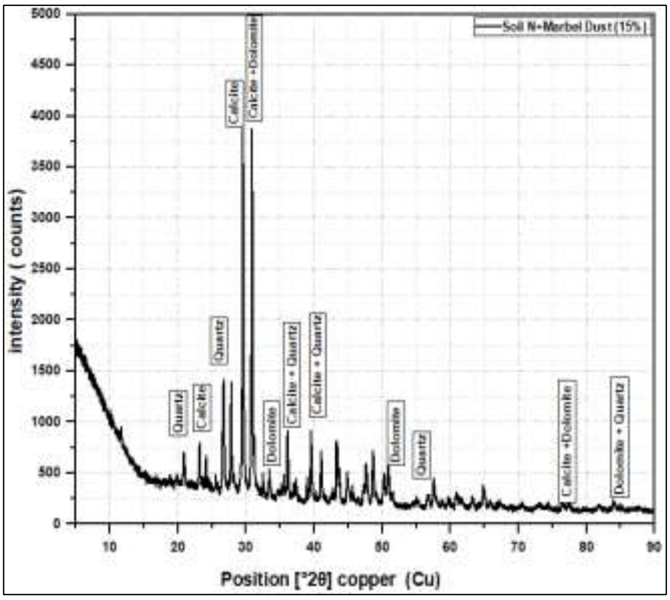

Figure 7: X-ray diffraction (XRD) of the ground treated with 15% marble powder.
Source: Authors, (2026).

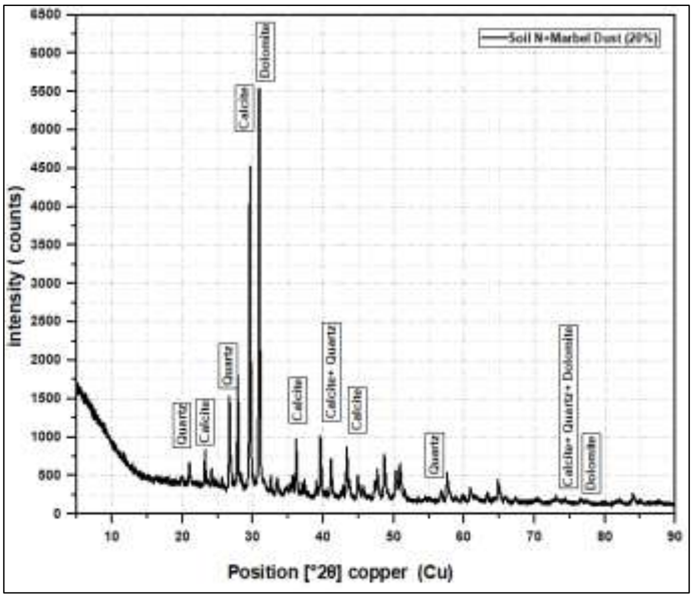

Figure 8: X-ray diffraction (XRD) of the ground treated with 20% marble powder.
Source: Authors, (2026).

III.4 CHEMICAL ANALYSIS BY X-RAY FLUORESCENCE (WDXRF)

The wavelength-dispersive X-ray fluorescence (WDXRF) results (Table *2*) reveal a marked increase in calcium oxide (CaO) content from 34.87% in the natural soil to 39.74% after the addition of 10% marble powder confirming the contribution of calcium carbonate and the activation of cementation mechanisms [1], [2]. Concurrently, the concentrations of silicate oxides exhibit a gradual decrease (SiO_2: 11.54% → 9.46%; Al_2O_3: 4.36% → 3.36%), indicating reduced susceptibility to moisture variations and improved structural stability [3].

In addition, the contents of sulfur trioxide (SO_3) and chloride ions (Cl^-) decrease by approximately 18% and 32%, respectively, reflecting a reduction in soluble salts that are often associated with geotechnical instability [4]. These compositional changes confirm that the incorporation of marble powder promotes the formation of stable carbonate phases, which enhance soil cohesion, reduce collapse potential, and improve overall mechanical performance. These findings are consistent with recent research on clayey soils treated under varying confinement conditions [12], which similarly demonstrated that fine mineral additives mitigate water sensitivity and enhance mechanical strength.

Table 2: XRF chemical composition of soil samples with varying marble dust contents.

	SOIL N T	SN- M 5%	SN- M 10%	SN- M 15%	SN- M 20%
Na_2O	0.8094	0	0	0	0
MgO	5.0029	4.6643	4.1149	5.1237	3.9825
Al_2O_3	4.3606	4.0785	3.827	4.1425	3.3619
SiO_2	11.546	11.317	10.722	10.701	9.4598
P_2O_5	0.0727	0.0858	0.0806	0.0716	0.0663
SO_3	0.7258	0.7005	0.6643	0.6482	0.591
Cl	0.2037	0.1803	0.1743	0.1707	0.1379
K_2O	1.7052	1.7243	1.6899	1.5712	1.4873
CaO	34.877	37.542	39.738	36.997	38.992
TiO2	0.1325	0.127	0.2027	0	0.0993
MnO	0.0188	0.0223	0.0278	0.0183	0.023
Fe_2O_3	1.0992	1.2271	1.3133	1.3977	1.152
ZnO	0	0.0043	0	0	0
Br	0	0.0028	0.0043	0.0037	0.0028
Rb_2O	0	0.0031	0.0049	0.0037	0.0038
SrO	0.0488	0.0561	0.0598	0.0657	0.0527
ZrO_2	0.0024	0.0039	0.0046	0	0
CO_2	40.62	39.25	38.09	37.5	39.24

Source: Authors, (2026).

IV. EXPERIMENTAL METHODS

IV.1 PREPARATION OF SOIL–MARBLE POWDER SAMPLES

The marble powder (MP) percentages selected for this study—5%, 10%, 15%, and 20%—were chosen based on previous research demonstrating that this range is particularly effective for improving the geotechnical properties of fine soils stabilized with industrial residues. [11] reported that incorporating 5-20% fine additives into expansive soils results in substantial gains in both mechanical strength and overall stability. Similarly, several recent studies have confirmed that increasing the proportion of marble powder significantly decreases the plasticity index and swelling potential of clayey soils, thereby enhancing their suitability for road construction and shallow foundations [9], [10], [12] found that a 15% MP dosage yielded the most favorable California Bearing Ratio (CBR) value (~8%), accompanied by a marked reduction in plasticity an observation that supports the dosage levels adopted in this study.

At higher concentrations, Umar and Lin (2024) [6] observed a considerable improvement in bearing capacity, with the CBR increasing from approximately 10.4% to 22.9% and the unconfined compressive strength (UCS) rising from 170 to 661 kN/m² after 28 days of curing. These results confirm the effectiveness of marble powder in enhancing mechanical performance. Boukhatem et al. (2024) [13] further demonstrated that combining marble powder with lime reduces the void ratio and increases soil density while promoting certain pozzolanic reactions. Similarly, [14], [15] reported that the use of calcium carbide residue improves the mechanical properties of fine soils through stabilization mechanisms comparable to those achieved with marble powder. In a related study. [16], [17] showed that combining lime with digestates derived from rice waste provides a sustainable and efficient method for clay soil stabilization, supporting the broader use of industrial and agro-industrial by-products.

X-ray diffraction (XRD) analysis of the marble powder revealed a crystalline structure dominated by calcite ($CaCO_3$), with intense peaks around 29.4° 2θ, characteristic of this carbonate mineral. Secondary reflections observed between 23° and 48° 2θ confirmed the presence of dolomite ($CaMg(CO_3)_2$) and, to a lesser extent, quartz (SiO_2). These stable and inert mineral phases indicate that marble powder primarily acts as a mineral filler rather than as a pozzolanic material. Scanning electron microscopy (SEM) analyses showed angular particles of varying sizes with sharp edges, promoting better interlocking with soil grains. Elemental mapping confirmed high calcium and magnesium contents consistent with the carbonate nature of the material. This morphology, combined with the fine particle size, reduces intergranular voids and increases the maximum dry density during compaction.

Although marble powder does not exhibit strong pozzolanic activity, its high carbonate content and favorable physical characteristics make it an effective additive for physical soil stabilization mainly through densification, improved compactness, and reduced plasticity. These findings are consistent with recent research on the use of industrial residues and nanomaterials in the treatment of fine soils, which highlights not only significant gains in strength and improved durability of stabilized mixtures [9-12], Umar & Lin (2024) [6], Boukhatem et al. (2024) [13], but also the emergence of new sustainable approaches incorporating industrial and agricultural by-products [14], [16], Hanafi et al. (2025) [18].

IV.2 EXPERIMENTAL PROGRAM AND ASSESSMENT OF SUBSIDENCE POTENTIAL

A comprehensive experimental program was conducted to evaluate the influence of marble powder on the geotechnical behavior of the studied soils, with particular emphasis on their susceptibility to subsidence. The first stage involved granulometric analysis of the natural soil, which is essential for identifying the open, loose structure characteristic of subsidence-prone soils particularly loess typically distinguished by high porosity and low dry density [15], [17]. The second stage focused on quantifying the subsidence potential using a subsidence susceptibility index derived from single and double oedometer tests [19], [20], conducted in accordance with ASTM D5333-03 [21], [22]. This procedure measures volumetric deformation in response to progressive saturation, providing an accurate assessment of soil reactivity during water infiltration [23]. Together, these two components grain-size characterization and evaluation of collapse susceptibility constitute a robust methodological framework. They enable a rigorous comparison of soil properties before and after marble powder treatment, facilitating the assessment of both microstructural and mechanical improvements.

IV.3 GRAIN SIZE DISTRIBUTION OF NATURAL SOIL

Grain size analysis of the loess samples Figure shows a predominance of silt (52%), followed by sand (30%) and clay (18%). The uniformity coefficient (C_u = 10.77), derived from the grain size curve, indicates a high susceptibility to subsidence (Ayadat and Belhouari). A second value (C_u = 10.77) further confirms the presence of a transitional interval conducive to collapse phenomena. These results characterize the natural soil's behavior and highlight its pronounced susceptibility to subsidence. To assess potential improvements and mitigate this risk, a subsequent series of analyses was conducted on soil stabilized with marble powder.

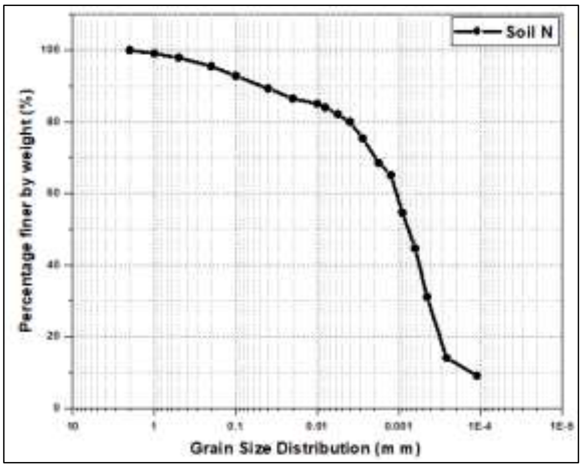

Figure 9: Grain size distributions curve for tested soil.
Source: Authors, (2026).

IV.4 ASSESSMENT OF SUBSIDENCE POTENTIAL

The subsidence potential of the natural soil was evaluated using oedometer tests, which quantify the tendency of the material to undergo sudden compression upon water infiltration. The settlement index obtained serves as a key indicator of the soil's susceptibility to structural instability. According to the criteria proposed by [24], soil is classified as non-settling when the uniformity coefficient (Cu) is ≤4%, transitional when 4% < Cu < 12%, and clearly settling when Cu ≥ 12%. For the soil studied (RN89, PK 268+500), the value of Cu=10.77% places it firmly in the category of subsidence-prone soils, confirming its high vulnerability to saturation. These findings align with several recent studies, which report that loess soils and metastable wind-blown deposits are highly prone to collapse when moistened [22], [24–26].

Furthermore, experimental and numerical investigations have validated the use of the subsidence index as an effective predictive tool for unstable behavior, while emphasizing its integration into multi-criteria approaches that consider soil particle size, suction, and microstructure [27], [28]. The results obtained in this study corroborate these observations and underscore the necessity of stabilization treatments such as the incorporation of marble powder to reduce subsidence susceptibility and enhance the geotechnical durability of the soils under investigation.

IV.5 EVALUATION OF COMPRESSIBILITY TESTS

Compressibility tests performed on the natural soil allowed the calculation of the collapsibility index (Cp), a widely used parameter for quantifying the susceptibility of loess soils to subsidence. According to the classification of Jennings and Knight (1975), Cp values are categorized from "non-subsiding" to "very severely subsiding" soils, depending on the magnitude of settlement under applied stress. For the soil studied, a vertical load of σ = 200 kPa resulted in Cp = 10.01%, placing it in the "troubled" category. This indicates a significant potential for subsidence, which could compromise the stability of foundations. These findings are consistent with recent research confirming the relevance of the Cp index as a diagnostic tool for loess soils, particularly in semi-arid regions where the open soil structure is highly vulnerable to water infiltration [29–33]. The combined use of particle size analysis, Atterberg limits, and compressibility testing provides a robust framework for assessing subsidence behavior. This evaluation is an essential preliminary step

IV.6 EVALUATION OF DIRECT SHEAR STRENGTH

The direct shear test conducted on the natural soil indicated very low cohesion (c = 11 kpa)) and a moderate angle of internal friction (φ = 33.16°). These results suggest that the soil's overall strength is primarily governed by friction, with cohesion contributing minimally to its mechanical behavior. This pattern is typical of loess soils, whose open structure, low active clay content, and sandy-to-silty grain size distribution lead to reduced cohesion and internal friction generally ranging between 30° and 35°. Several studies have highlighted this behavior.

For example, [24], [33] reported that loess soils in Algeria exhibit negligible cohesion but relatively high internal friction, reflecting their fragile structure while maintaining granulometric properties conducive to frictional resistance. Recent research further confirms that the shear strength of loess soils is strongly influenced by factors such as degree of saturation and initial density [30], [34], [35]. Therefore, the relatively high friction angle observed in this study aligns with the silty and slightly clayey nature of the soil, but it does not offset the soil's susceptibility to subsidence when saturated.

IV.7 GENERAL METHODOLOGY

The methodology followed in this study, illustrated in Figure 10, involves the preparation and characterization of the materials—subsiding soils from Djelfa and marble powder derived from industrial waste—followed by the preparation of soil–marble powder mixtures with varying additive ratios (0–20%). Standardized laboratory tests were then conducted to evaluate the behavior of these mixtures. The investigations focused sequentially on: Compaction properties: including modified Proctor tests, maximum dry density, and optimum moisture content. Mechanical performance: assessed through unconfined compressive strength (UCS), California Bearing Ratio (CBR), and direct shear tests. Hydromechanical behavior: evaluated via subsidence susceptibility measurements.

This integrated approach allows for a systematic assessment of the influence of marble powder on the geotechnical properties of the studied soils and facilitates the identification of optimal proportions for sustainable stabilization.

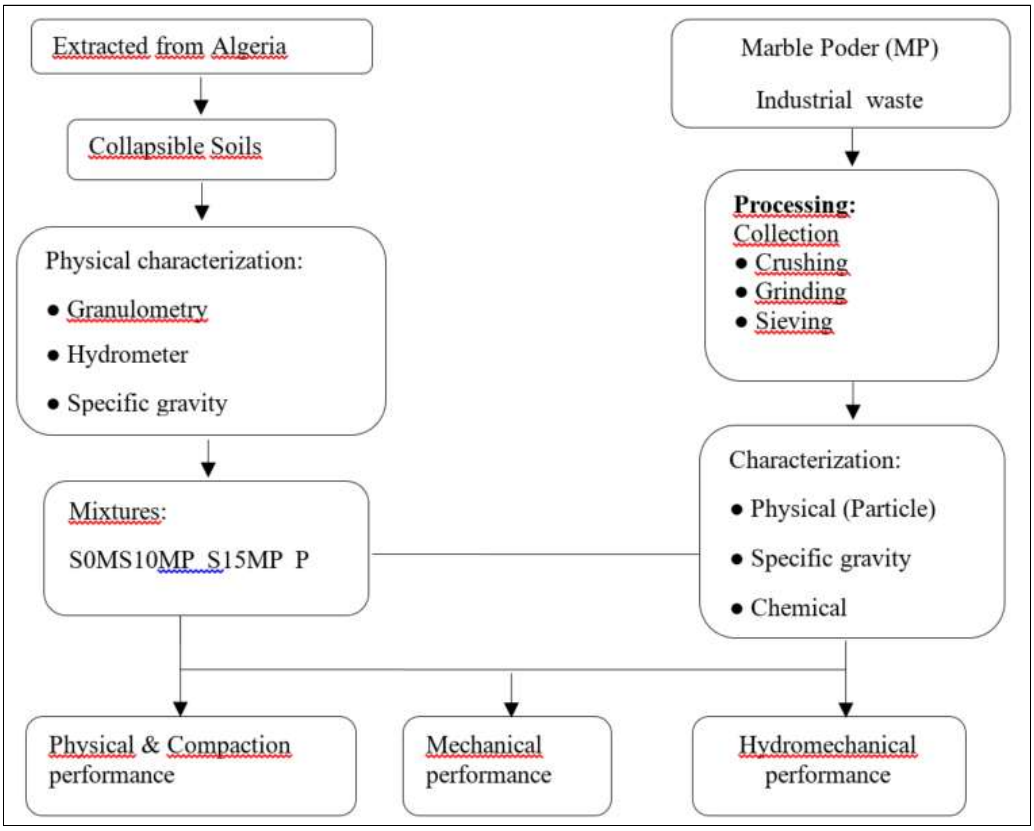

Figure 10: Experimental methodology for stabilizing collapsible soil with marble powder.
Source: Authors, (2026).

V. RESULTS AND DISCUSSIONS

This section aims to analyze and discuss the results of the experiments in order to highlight the effect of adding marble powder on the geotechnical properties of the soil under study, through a methodological comparison between the behavior of natural soil and that of stabilized mixtures. The discussion begins with a presentation of the results of the chemical analysis of both the soil and the marble powder, with the aim of explaining the changes in mechanical properties depending on the chemical composition of the materials used, particularly the presence of calcium-rich compounds in the marble powder.

Next, the effect of the addition on the mechanical properties, especially compressive strength, is examined, in addition to other parameters such as maximum dry density, optimum moisture content, and deformation properties. This integrated approach analysis to link mechanical results to chemical background, contributing to a deeper understanding of the mechanism of action of marble powder and evaluating its effectiveness as a soil conditioner from a scientific and practical standpoint... Chemical and mineralogical analyses To better understand the effect of adding marble powder on soil behavior, detailed chemical and mineralogical analyses were performed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) techniques.

V.1 EFFECT OF MARBLE POWDER ON COMPACTION PROPERTIES

The influence of varying proportions of marble powder (MP) on soil compaction properties was evaluated using modified Proctor tests in accordance with ASTM D698. Mixtures containing 0%, 5%, 10%, 15%, and 20% MP were prepared, and the results were plotted Figures (11–13) to illustrate the relationship between water content and dry density. The results indicate that increasing the marble powder content leads to a significant rise in maximum dry density compared to the unsterilized soil, which had a value of 1.75 g/cm³. Specifically, maximum dry density increased by 5.71%, 6.86%, 8%, and 9.14% for MP contents of 5%, 10%, 15%, and 20%, respectively, with the highest value reaching 1.91 g/cm³. This improvement is primarily due to the filling effect, whereby fine marble powder particles occupy the voids between larger soil grains, reducing porosity and enhancing overall compactness [1], [25].

In addition, the higher specific gravity of marble powder, combined with particle rearrangement and flocculation, contributes to improved densification and cohesion in the stabilized soil. Conversely, the optimum moisture content (OMC) exhibited a decreasing trend with increasing MP content. The reductions relative to the natural soil were 2.11%, 0.7%, 0.7%, and 9.86% for 5%, 10%, 15%, and 20% MP, respectively. This decrease is attributed to the low plasticity and low water absorption of marble powder, which reduces the amount of water required for effective particle lubrication [6], [25]. Additionally, the increased specific surface area of the mixture promotes more uniform water distribution, further lowering the OMC. These findings are consistent with previous studies, including those by [36-38], which reported that marble powder incorporation enhances maximum dry density, reduces plasticity, and favorably influences the compaction behavior of fine soils.

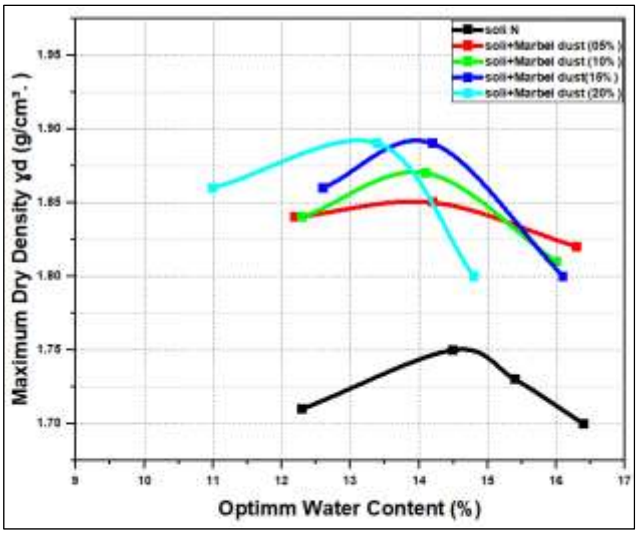

Figure 1: Influence of marble dust on Optimum parameters of proctor test.
Source: Authors, (2026).

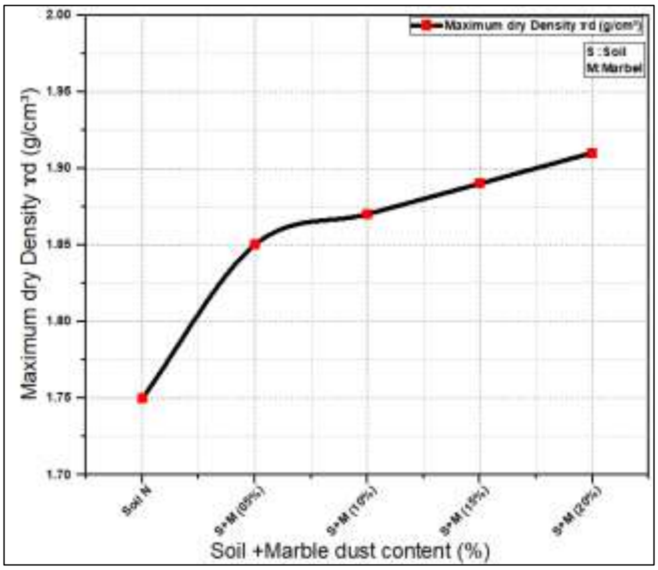

Figure 2: Influence of marble dust on maximum dry density.
Source: Authors, (2026).

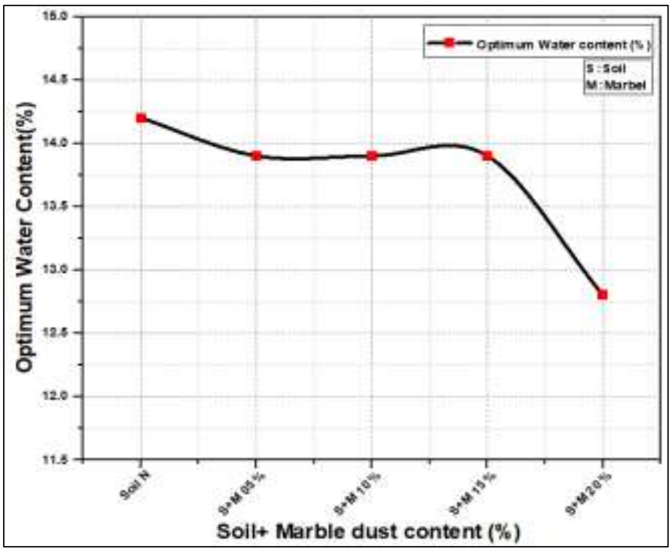

Figure 3: Influence of marble dust on Optimum Water Content (%).
Source: Authors, (2026).

V.2 EFFECT OF MARBLE POWDER ON THE CALIFORNIA BEARING RATIO (CBR) AND DRY DENSITY OF SOIL

To evaluate the behavior of stabilized soil under water exposure, the effect of varying marble powder (MP) proportions (0%, 5%, 10%, 15%, and 20%) on the California Bearing Ratio (CBR) and dry density (ɣd) was investigated. CBR tests were conducted on samples immersed for 96 hours to simulate prolonged water exposure, such as during sustained rainfall or subsoil infiltration. This saturation period allows the soil to fully absorb water, revealing its potential for settlement and strength reduction, while ensuring comparability with standard recommendations and literature data. CBR values were determined at 95% of the maximum dry density obtained from modified Proctor tests. The results are presented in Figures 14 and 15. The data show a clear positive correlation between marble powder content and soil CBR values.

Specifically, increasing MP content from 0% to 20% raises the CBR from 5.14% to 15.76%. This improvement is attributed to several mechanisms: Void Filling Effect: Fine marble particles occupy the interstitial spaces between larger soil grains, increasing soil density and reducing total void volume. This limits water absorption and enhances post-immersion stability and strength, as reflected by the corresponding increase in dry density (ɣd) with higher MP content. Minimum Acceptable Threshold Achieved: With the addition of 10% MP, the CBR value (10.07%) surpasses the typical minimum requirement for road sub-bases (approximately 8%). This indicates that an appropriate proportion of marble powder can effectively improve the bearing capacity of weak soils, making them suitable for pavement layers.

Increase in Dry Density: The gradual rise in dry density with increasing MP content contributes directly to higher CBR values, as denser soils generally exhibit greater resistance to deformation. Reduction in Expansion Upon Immersion: Although specific expansion measurements were not recorded, the 96-hour immersion CBR test reflects the impact of water absorption on soil durability. Filling voids with marble powder likely reduces permeability and limits expansion, helping maintain higher durability after water exposure. In summary, the addition of marble powder simultaneously enhances soil density and bearing capacity after immersion, providing an effective solution for strengthening weak soils intended for pavement applications.

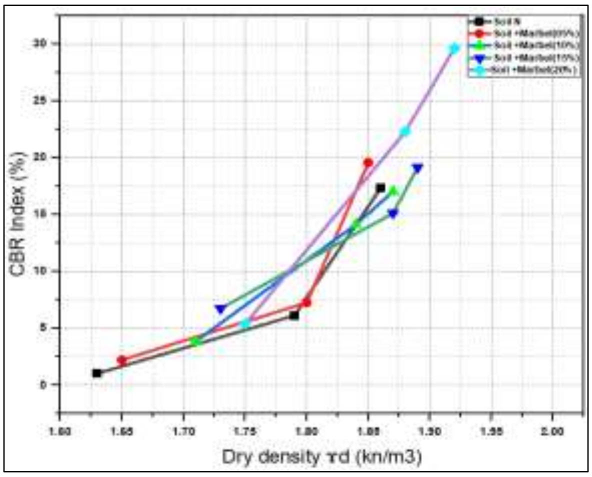

Figure 4: Influence of Maximum Dry Density (MDD) on CBR Index.
Source: Authors, (2026).

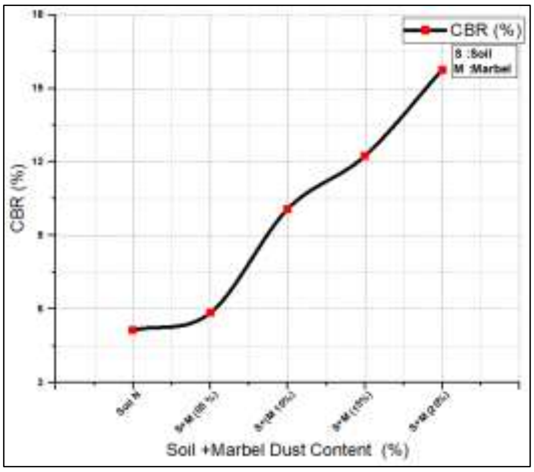

Figure 5: Influence of marble dust on CBR index (%).
Source: Authors, (2026).

V.3 EFFECT OF MARBLE POWDER ON THE DIRECT SHEAR PROPERTIES OF SOIL

Direct shear tests were conducted on both treated and untreated soil samples. The treated samples were prepared with varying marble powder (MP) contents of 5%, 10%, 15%, and 20% by dry weight, while untreated control samples (0% MP) were also tested. Different vertical stresses were applied to the samples, and the maximum shear stress was recorded to establish the Mohr-Coulomb failure envelope. From this envelope, the internal friction angle (φ) and cohesion (c) were determined for each mixture.

V.3.1 Internal friction angle (φ)

The results Figure *6* show a slight decrease in the internal friction angle with increasing marble powder content. The measured values are 32.12°, 32.12°, 32.18°, 29.17°, and 29.12°, compared to 33.16° for the untreated soil. In relative terms, these represent reductions of approximately 3.1%, 3.1%, 3.0%, 12.0%, and 12.2%, respectively. This decrease can be attributed to the modification of soil grain surfaces caused by the introduction of fine, relatively smooth marble powder particles. These particles reduce interlocking and friction between coarser grains, resulting in slightly lower resistance to sliding along the shear plane. However, the reduction remains minor across the tested proportions, indicating that marble powder has a negligible effect on the internal friction angle [18], [26].

V.3.2 Cohesion (c)

In contrast, a significant increase in soil cohesion was observed with higher marble powder contents Figure *6*: Effect of marble dust content on shear strength parameters (internal friction angle ϕ and cohesion c). Cohesion values increased from 11 kPa in the untreated soil to 17, 48, 62, and 70 kPa for 5%, 10%, 15%, and 20% MP, respectively, corresponding to relative increases of approximately +55%, +336%, +464%, and +536%. Cohesion, representing the soil's shear strength in the absence of vertical stress, is therefore greatly enhanced by marble powder addition. This increase reflects the strengthening of intermolecular forces in the soil, which can be attributed to two main mechanisms: (i) Filling of Interstitial Voids: Fine marble powder particles occupy void spaces, reducing porosity and increasing grain contact surfaces. (ii) Bridge Formation Between Grains: Marble particles can form bonds between soil grains, improving shear strength under low stress and increasing apparent cohesion. These results indicate that, unlike the internal friction angle, which remains relatively stable, marble powder substantially increases cohesion, thereby enhancing the overall mechanical strength of the soil.

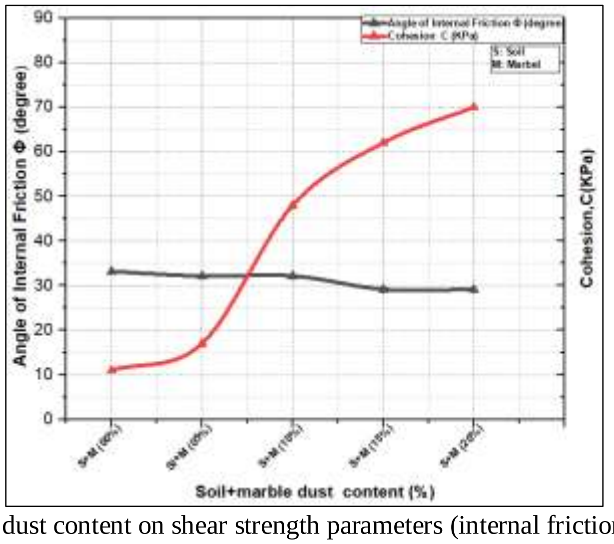

Figure 6: Effect of marble dust content on shear strength parameters (internal friction angle ϕ and cohesion c).
Source: Authors, (2026).

V.4 EFFECT OF MARBLE POWDER TREATMENT ON SLUMP POTENTIAL

The effect of marble powder (MP) addition on the slump potential (CP) of collapsible soils was evaluated. The untreated soil exhibited unstable behavior when immersed in water, with a CP value of 10.01%, classifying it as "beginning of severe problems" according to the Jennings and Knight scale (CP > 5) [9], [39]. This study aimed to determine the effectiveness of marble powder in improving soil stability and reducing susceptibility to settlement. Four soil samples treated with 5%, 10%, 15%, and 20% MP were tested using standard oedometer tests under a constant vertical stress of 200 kPa. The CP values and their reduction relative to the untreated soil are presented in Figures 17 and 18: (i) 5% MP: CP decreased to 6.18%, a reduction of 37.92%.

Despite this improvement, the soil remains classified as "beginning of severe problems" (CP = 6.18 > 5). (ii) 10% MP: CP dropped to 2.05%, a 79.24% reduction, improving the classification to "moderate problems" (1 < CP ≤ 5). (iii) 15% MP: CP further decreased slightly to 2.01%, a 79.60% reduction, maintaining the "moderate problems" classification. (iv) 20% MP: CP reached the lowest value of 1.42%, an 85.01% reduction, with the soil still classified as "moderate problems". These results demonstrate that increasing marble powder content progressively reduces the collapsibility of subsiding soils. This improvement can be attributed to several mechanisms: the filling of voids by fine marble particles, enhanced internal friction between grains, and minor particle interactions that contribute to increased cohesion [13], [14], [15].

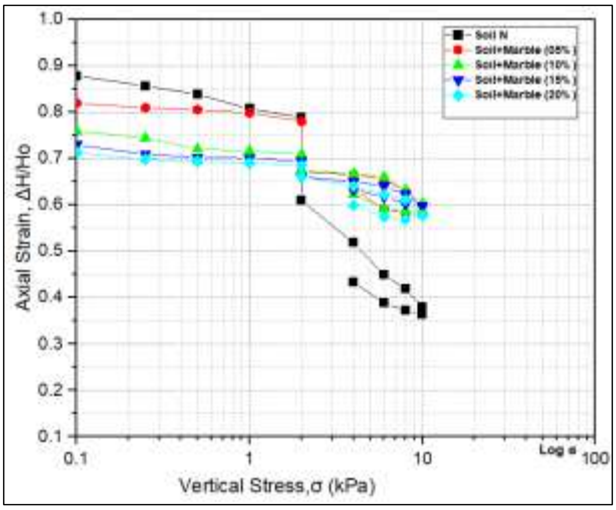

Figure 7: Collapse potential curves for marble dust – soil mixture.
Source: Authors, (2026).

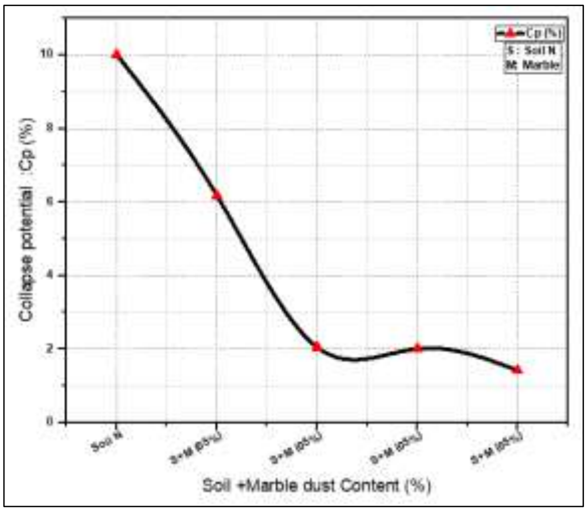

Figure 8: Influence of marble dust on collapse potential Cp (%).
Source: Authors, (2026).

VI. CONCLUSIONS

The results of this study confirm the effectiveness of marble powder (MP) as an innovative and sustainable stabilizer for improving the physical and mechanical properties of subsiding soils. The main findings are as follows:

- ✓ Improved Compaction Properties: Addition of up to 20% MP increased the maximum dry density and decreased the optimum moisture content, indicating enhanced compaction behavior.
- ✓ Strength and Bearing Capacity Enhancement: At 15% MP, the soil exhibited higher cohesion and resistance. The California Bearing Ratio (CBR) increased significantly, demonstrating that treated soils can be effectively used for road foundation layers.
- ✓ Reduced Settlement Potential: Oedometer tests showed a decrease in settlement potential with increasing MP content, attributed to void filling and higher density, which improves resistance to subsidence.
- ✓ Optimization of Dosage: Results indicate that 10% MP may suffice to meet minimum road sub-base requirements. Emphasizing however, that the optimal dosage should be determined based on economic considerations, soil characteristics, and project specifications.
- ✓ Overall Improvement in Stability: MP treatment significantly reduces the susceptibility of subsiding soils, improves hydromechanical behavior, and limits the risk of differential settlement.
- ✓ Reduced Permeability and Improved Durability: Permeability decreased progressively with increasing MP content, reaching a reduction of over 90% at 20% MP. This limits water infiltration, reduces subsidence risk, and enhances long-term durability for civil engineering applications.
- ✓ Enhanced Soil Cohesion: Cohesion increased substantially, from 11 kPa in untreated soil to 70 kPa with 20% MP, improving shear strength and overall stability.
- ✓ Sustainable and Environmentally Friendly Solution: The use of marble powder valorizes an abundant industrial by-product while minimizing environmental impact.
- ✓ Improved Resistance to Moisture-Drying Cycles: Incorporation of MP also helps mitigate cracking and differential settlement caused by repeated wetting and drying.

Outlook:

- ✓ For future applications, it would be relevant to study the combined effect of marble powder with other binders (such as cement or lime) to further optimize soil stability and strength.

Additional studies on long-term behavior and cyclic loading could complement this approach and ensure the durability of structures built on these treated soils.

VII. AUTHOR'S CONTRIBUTION

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