



RESEARCH ARTICLE

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STRUCTURAL STABILITY AND MECHANICAL BEHAVIOIR IMPROVEMENT OF LOESS SOIL TREATED WITH MARBLE WASTE- CEMENT HYBRID

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ABSTRACT

The stabilization of unstable Loess soil and the mitigation of industrial waste environmental impacts are achieved through a hybrid system integrating Waste Marble Dust (WMD) as a sustainable additive and 3% Portland cement as a hydraulic binder. Experimental investigations identified the 20% WMD blend as the optimal threshold for peak geotechnical stability; the Maximum Dry Density (γ_d) surged from 14.2 to 19.5 kN/m³, and the California Bearing Ratio (CBR) exhibited a structural surge from 5.14% to 97.16%. Cohesion (c) rose significantly from 11 to 152 kPa, while the Unconfined Compressive Strength (UCS) peaked at 279 kPa after 56 days of curing. Hydraulically, the permeability coefficient (k) significantly declined from 7.04×10^{-5} m/s in the natural state to 1.06×10^{-6} m/s in the stabilized matrix, reflecting superior microscopic densification and seepage resistance. At the mineralogical level, X-ray diffraction (XRD) analysis confirmed a fundamental phase transformation characterized by the consumption of unstable clay phases and the synthesis of calcium silicate and aluminate hydrates (C-S-H and C-A-H). The findings validate that the functional synergy between cementitious pozzolanic reactions and the WMD filler effect established a compact crystalline framework. Consequently, this hybrid approach transforms weak soil into a sustainable geotechnical composite with high structural integrity and durability, effectively fulfilling industrial waste recycling goals in infrastructure development.



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I. INTRODUCTION

In recent decades, Algeria has witnessed a strategic and qualitative leap in infrastructure development, with national investments intensified to achieve 100% coverage of the road network, highways, and basic facilities. This urban renaissance is a fundamental pillar for economic growth and regional connectivity. However, the execution of these major projects faces a highly complex geotechnical obstacle: the widespread presence of vast areas of collapsible loess soils. These aeolian deposits are known for their "metastable" open-fabric structure, exhibiting high apparent shear strength in their dry state but undergoing sudden and catastrophic volumetric reduction—known as hydro-collapse—upon exposure to wetting or saturation [1], [2]. This unstable behavior makes it exceedingly difficult to achieve the required standard compaction levels in road embankments and foundation engineering, leading to serious structural deformations, differential settlement, and premature failure of pavement layers [3], [4]. The fundamental mechanism of loess soil instability has been the subject of extensive scientific research. For instance, Abbeche et al. [5], [6], found that the saturation of loess soils with absorbed water leads to the dissolution and dispersion of internal cementing agents between soil particles, fundamentally altering the pore size distribution. Similarly, [7] attributed the collapse of remodeled loessial matrices to the inherent instability of pores within the aggregates.

Furthermore, the severity of this phenomenon increases due to external stresses; [8] observed that the collapse potential of loess soil becomes more pronounced with increasing vertical compaction loads. Since the rearrangement of internal pores upon contact with water is the primary catalyst for strength degradation, these collapsible loess soils usually need to be optimized and stabilized before they can be used as suitable foundation materials [9], [10]. To mitigate these risks, traditional chemical stabilizers such as cement and lime [11], [12] are commonly used to eliminate the collapsibility property. However, the reliance on these materials has come under increasing scrutiny; lime-treated foundations, for example, often show poor hydraulic stability and a high susceptibility to brittle failure under repeated traffic loads [13]. Moreover, cement production is associated with high energy consumption and substantial carbon dioxide emissions, necessitating a shift toward more sustainable and environmentally friendly alternatives. Solid waste accumulated in Algeria is present in large quantities, a portion of which remains unutilized, posing significant environmental challenges [14]. Among these wastes, waste marble dust (WMD)—a byproduct of the marble cutting and polishing industry—stands out as a promising candidate for soil improvement. The accumulation of marble dust in landfills not only leads to environmental degradation but also poses respiratory health risks due to its fine particulate nature. At the same time, highway construction creates a massive demand for stabilizing materials. If the use of bulk solid waste in highways can be realized, the environmental damage caused by marble production can be mitigated, helping to achieve the goals of high-quality economic development and environmental construction of highways [15], [16]. These waste materials can provide a synergetic platform for interaction with the loess soil matrix.

When marble dust is incorporated, it acts as a "micro-filler," effectively filling the pores between soil particles and solving internal structural defects to improve soil quality [17], [18]. Many scientists have conducted extensive research on soil enhancement through the use of various industrial solid wastes, including slag and fly ash [19], [20] magnesium-activated slag [21], [13]. In addition, some studies have also shown that the incorporation of marble dust can significantly improve fracture resistance [22], unconfined compressive strength [16], [23] and hydrostatic stability [24], [25]. The resulting marble dust plays an important role in improving the mechanical skeleton and overall soil strength [26]. Given its mineralogical composition, marble dust has the potential to partially or fully replace lime as a stabilizing material to eliminate the collapsibility of loess soils [11], [12]. Considering the current low utilization rate of large quantities of marble waste produced in Algeria, this paper investigates a novel stabilization approach: the use of varying amounts of marble dust with a fixed, low-content dosage of cement to improve collapsible loess foundations. This "hybrid" stabilization strategy attempts to minimize cement consumption while maximizing the filler effect of marble dust. To evaluate this approach, a series of laboratory tests were designed, including the Standard Proctor test, California Bearing Ratio (CBR), Oedometer (consolidation) test, and Direct Shear test. This study not only evaluates the physical and engineering properties of the stabilized loess but also proposes optimal mixture proportions for practical field engineering applications [27], [15]. By bridging the gap between waste management and geotechnical engineering, this research provides a sustainable framework for constructing resilient infrastructure in loess-dominated regions.

Study Area and Sampling

The soil samples selected for this research were obtained from a national road rehabilitation project located in the southern part of the province, specifically in the Messaad region within the Djelfa district. This area represents a strategic transition zone between the Saharan Atlas and the central High Plateaus of Algeria. The sampling site was meticulously selected due to its direct proximity to National Road 89 (RN89), which serves as a vital transport artery.

The primary rationale for selecting this specific location stems from the persistent geotechnical challenges observed across several segments of this strategic highway. Despite its critical importance, the road suffers from recurring structural deformations and severe localized subsidence within the pavement layers. These issues have necessitated frequent and costly maintenance interventions, primarily attributed to the unstable and fragile nature of the loessial soil that constitutes the fundamental subgrade of the road in that region. Figure 1.

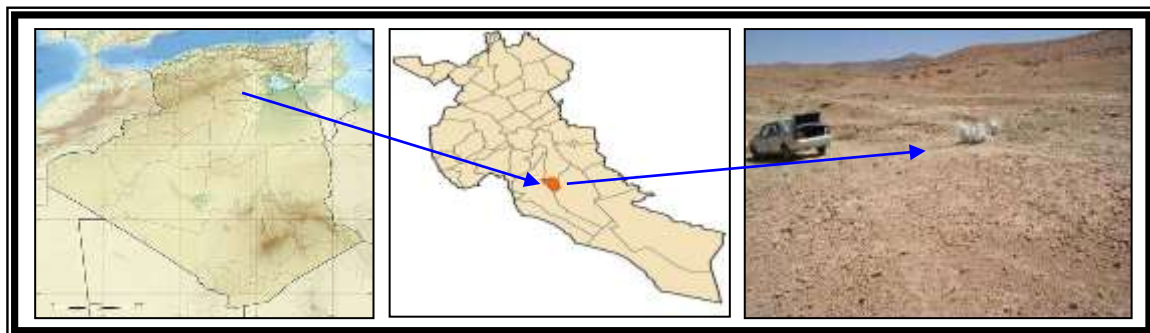


Figure 1: Map of the geographical location and Sampling point.

Source: Authors, (2026).

II. MATERIALS AND METHODS

II.1 MATERIALS AND CHARACTERIZATION

II.1.1 The Host Soil

This study focuses on natural loess soil extracted from the Djelfa region, characterized by its metastable structure and high collapsibility. To ensure representative field conditions and avoid surface organic contamination, samples were retrieved from depths ranging between 1.2 and 1.5 m. Figure 2.

A dual sampling methodology was implemented: disturbed samples were collected for physical identification, compaction (Proctor), and CBR tests, while undisturbed samples were carefully extracted using hand augers. Maintaining the original structural fabric and natural void ratio in the undisturbed samples is critical for ensuring the reliability of subsequent oedometer (consolidation) and direct shear test results. In the laboratory, the soil underwent thermal drying at 105°C to dissipate natural moisture, followed by manual crushing and sieving through a 2 mm mesh. These preparatory procedures aimed to obtain a homogeneous powder, ensuring a uniform particle distribution when subsequently blended with the additives (waste marble dust and cement). This standardization facilitates an accurate characterization of the soil's geotechnical properties in its raw state.



Figure 2: Process of host soil from extraction to sieving.

Source: Authors, (2026).

II.2 THE ADDITIVES

A. Waste Marble Powder (MP)

The marble powder utilized in this research is an industrial by-product derived from the cutting and polishing processes of natural marble. This material was selected for its distinct physical properties, functioning as a non-plastic mineral filler. Due to its high fineness, it optimizes the grain-size distribution of the loess soil by filling the macro-interstitial voids, thereby increasing the dry density and reducing the overall porosity of the soil matrix. Chemically, it is predominantly composed of calcium carbonate (CaCO_3), providing physical stability to the mixture while offering an eco-friendly alternative to traditional stabilizers.

B. Cement

Cement is a basic hydraulic binder with widespread use in the global construction sector. Cement types are varied to meet different construction requirements, and Ordinary Portland Cement (OPC) is the most common, as Portland Limestone Cement (MATINE) (NA442 CEM II/B-L 42.5 N) was used in this research due to its durable properties. Cement is used in a wide range of construction projects, from small residential units to large infrastructures such as bridges and dams. In this research work, cement was exploited as an additive to Loessian soil to modify its properties [28].

II.3 GENERAL METHODOLOGY

The experimental strategy of this research follows an integrated analytical approach designed to evaluate a hybrid stabilization system tailored for road pavement construction. This system utilizes Waste Marble Dust (WMD) and a low-content Cement dosage to transform unstable loess into a high-bearing capacity structural layer. The laboratory program focuses on critical parameters for highway engineering:

- **Compaction Characteristics:** Modified Proctor tests were utilized to optimize dry density, ensuring the structural stability required for pavement layers.
- **Pavement Bearing Capacity (CBR):** Soaked CBR tests (96-hour immersion) were conducted to evaluate the subgrade performance under saturation. This phase is crucial for determining the reduction in pavement thickness and improving the overall structural number of the road.
- **Structural Mechanical Performance (R_c):** Compressive Strength (R_c) was monitored to ensure the material can withstand vertical traffic stresses and resist permanent deformation (rutting) over the long term.
- **Shear Integrity:** Direct shear tests established the cohesion (c) and friction angle (ϕ) necessary to guarantee the lateral stability of the road embankment and shoulders.
- **Hydraulic Durability :** Permeability testing was performed to ensure the stabilized matrix acts as a semi-impermeable barrier, protecting the road structure from moisture-induced damage and enhancing its service life.

II.4 GRAIN SIZE DISTRIBUTION OF NATURAL SOIL

The particle size distribution results, as illustrated in Figure 3, elucidate the physical characteristics of the studied loess soil. The silty fraction represents the dominant component at approximately (52%), while the remaining proportions are distributed between sand (30%) and clay (18%). Analysis of the gradation curve yielded a coefficient of uniformity (C_u) of 10.77%. This value positions the soil within the critical transitional range ($4\% < C_u < 12\%$), which is widely associated in geotechnical literature (Ayadat and Belhouari) [3] with a high potential for structural collapse.

This granular composition, combined with the observed non-uniformity, confirms the inherent instability of the soil in its raw state, thereby justifying the imperative need for stabilization to reinforce the internal matrix against external stresses and hydraulic variations.

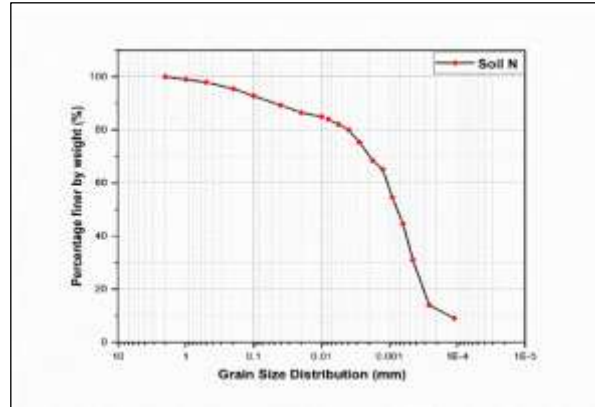


Figure 3: Grain size distributions curve for tested soil.
Source: Authors, (2026).

II.5 INITIAL SOIL BEHAVIOR ASSESSMENT

The unstable behavior of untreated soil was identified by comprehensive laboratory tests, which combined physical and mechanical properties to diagnose structural fragility. The laboratory tests listed below, as shown in the Table 1, can provide a detailed description of this diagnosis:

II.5.1 Grain Size Analysis

Based on the coefficient of uniformity ($4\% < C_u = 10.77 < 12\%$), the soil is classified as having a “transitional” structure, which allows for large interstitial voids. These formations represent the ideal environment for sudden collapse according to the criteria specified in Ayadat and Belhouari [3]. This unbalanced grain distribution explains the absence of a compact structure in the natural state.

Table 1: Geotechnical characteristics of loess Messaad (Djelfa).

Designations	Valeurs
Water content, W (%)	10.4
Specific weight G_s	2.65
Specific gravity of solid particles γ_s (kN/m ³)	27.0
Dry density γ_d (kN/m ³)	21.07
Degree of saturation, S_r (%)	13.90
Saturation content w_{sat} (%)	35.03
Sand (%)	30
Silt (%)	52
Clay (%)	18
Coefficient of uniformity C_u	10.77
Coefficient of curvature C_c	5.49
Maximum dry density γ_d (g/cm ³)	1.75
Optimum water content w_{opt} (%)	14.2
collapse potentials C_p (%)	10.01
Friction angle Φ (degree)	33.16
Cohesion, C (kPa)	11.00

Source: Authors, (2026).

II.6 MODIFIED PROCTOR TEST STRUCTURAL VULNERABILITY AND COMPACTION DYNAMICS

The results of the Modified Proctor Test Figure 4, conducted in accordance with the French standard [29], [30]. revealed a profound discrepancy between the natural dry density ($\gamma_d = 13.9$ kN/m³) and the laboratory maximum dry density ($\gamma_d \text{ max} = 17.50$ kN/m³). This significant gap serves as a definitive engineering indicator that the loessial soil possesses an “Open Structure,” which is inherently unstable in its untreated state. From a geotechnical perspective, these findings highlight the collapsible nature of loessial soils. Their natural stability relies precariously on capillary suction forces that bind the particles together; however, upon saturation or the subsequent dissipation of these forces, the structural framework undergoes a catastrophic collapse [31], [32]. This triggers a sudden and random rearrangement of particles into a more dense configuration, explaining the observed severe settlement and volumetric loss. According to the reference standards for soil classification [33], the fact that the natural density is substantially lower than the maximum Proctor density indicates that the soil lacks the necessary structural integrity to sustain engineering loads, thereby justifying the need for chemical stabilization to enhance its mechanical properties and ensure long-term stability [34], [35].



Figure 4: Proctor test apparatus.
Source: Authors, (2026).

II.7 GEOTECHNICAL CHARACTERIZATION OF LOESS SOIL SILT VIA THE CBR INDEX

The inherent structural weakness of the loessial soil (Limon Loessique) was clearly manifested in the results of the soaked California Bearing Ratio (CBR) test Figure 5, where the soil recorded a low value of 5.20%. This value classifies the soil as having a "Poor Bearing Capacity" (Portance médiocre), rendering it structurally unsuitable to serve as a subgrade for road infrastructure in its raw, untreated state. Based on the official French standard NF P 11-300 and the roadworks technical guide GTR 92, this soil falls within the category of water-sensitive fine soils, as detailed in the table 02 :

Table 2: Classification of Fine Soils According to French Standards (NF P 11-300 / GTR 92).

Soil Class	Technical Description	Passing 80 μm Sieve (%)	Plasticity Index (IP)	Methylene Blue Value (VBS)
A1	Low plasticity silt	$>35\%$	$\text{IP} \leq 12$	$0.1 < \text{VBS} \leq 0.5$
A2	Medium plasticity silt	$>35\%$	$2 < \text{IP} \leq 25$	$0.5 < \text{VBS} \leq 1.5$

Source: Authors, (2026).

This classification (A1/A2) confirms that the studied loessial soil possesses high hydraulic sensitivity. The reduction of the CBR index to 5.20% serves as definitive mechanical evidence of the "Structural Instability" (Instabilité structurale) that occurs upon saturation. In this state, the particles lose their ability to maintain mechanical interlocking and resist stresses due to the collapse of weak inter-granular bonds, leading to a sudden loss of bearing capacity. Referencing the GTR 92 guidelines, any soil recording a CBR index below 8% lacks the necessary stability for engineering purposes. This necessitates a chemical intervention using the hybrid system (waste marble powder and cement) as an engineering requirement to transform this collapsible soil into a rigid and stable construction material.



Figure 5: CBR test apparatus.
Source: Authors, (2026).

II.8 ASSESSMENT OF SOIL COLLAPSIBILITY: HYDRO-MECHANICAL INSTABILITY

The double oedometer test Figure 6 serves as the definitive assessment of the soil's hydraulic sensitivity and structural stability. Analysis of the experimental results reveals a critically high collapse coefficient (C_p), reaching 10.01% at a vertical stress of 200 kPa. According to the diagnostic classification of Jennings and Knight (1975) [36], a value within the range ($10\% < C_p = 10.01\% < 20\%$) categorizes the loessial soil under the "Severe Problem" status. This catastrophic mechanical behavior is geotechnically attributed to the "metastable" nature of the raw soil structure [37], [38]. In its dry state, the structural integrity depends entirely on temporary cementing bonds and fragile matric suction forces that bridge the silt particles [13], [20]. Upon hydraulic contact (saturation), these suction forces dissipate instantaneously, causing the meniscus of water between particles to vanish and the inter-granular bonds to dissolve. This leads to a sudden

"Structural Collapse," where particles are forced to reposition into the pre-existing interstitial voids (the open structure). Such a high collapse potential (10.01%) underscores the extreme risk of utilizing this soil in its natural state; it predicts significant differential settlements and irregular subsidence, which would inevitably trigger structural cracking and functional failure in road infrastructures [38].



Figure 6: Compressibility test apparatus.

Source: Authors, (2026).

II.9 DIRECT SHEAR STRENGTH ANALYSIS

The results of the Direct Shear Test Figure 7 revealed a stark contrast in shear strength parameters, with critically low cohesion ($c = 11 \text{ kPa}$) relative to a moderate internal friction angle ($\phi = 33.16^\circ$). This mechanical discrepancy confirms that the soil's stability in its dry state is derived almost exclusively from the mechanical interlocking and friction between grains. Conversely, the soil lacks the "effective cohesion" required to maintain structural integrity under saturated conditions. Geotechnically, this deficiency in physico-chemical bonding renders the soil highly susceptible to slippage and structural collapse. Once the "apparent cohesion" provided by suction forces and soluble salts dissipates upon wetting, the dry friction forces are insufficient to prevent particle displacement. These findings are highly consistent with the geotechnical characteristics of loessial soils in the semi-arid regions of Algeria [3], [14] where the absence of robust inter-granular bonding remains a primary factor in the instability of local road infrastructures, necessitating stabilized foundations to counteract these inherent weaknesses.

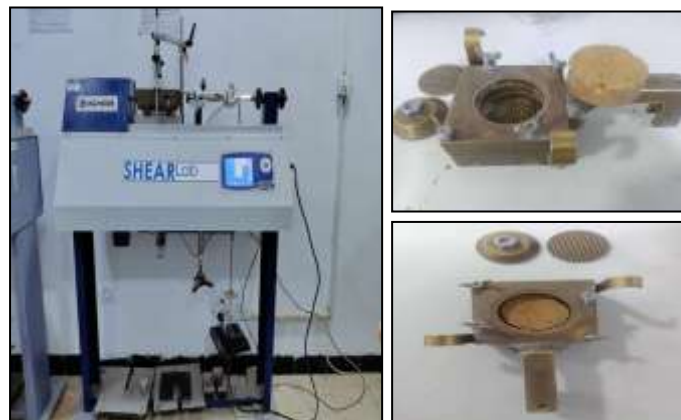


Figure 7: Direct Shear test apparatus.

Source: Authors, (2026).

II.10 SYNERGETIC SOIL STABILIZATION VIA HYBRID MARBLE WASTE POWDER AND CEMENT INCORPORATION

The integration of Waste Marble Powder (WMP) as a hybrid stabilizing agent, in conjunction with Portland Cement, represents an advanced technical strategy for upgrading marginal soils, effectively repurposing industrial by-products from major facilities in Sidi Bel Abbès (TamStones), Felfla, and Chlef into high-performance engineering materials. The structural efficiency of this system is derived from the synergy between the mineralogical composition of WMP—characterized by high Calcium Oxide (CaO) content (50–56%) and Calcium Carbonate (CaCO_3), and the hydraulic reactions initiated by the cement [12], [28]. Low levels of secondary oxides (SiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_3 < 3\%$), and Magnesium Oxide (MgO) ensure high chemical stability within the soil matrix. Upon hydration, the ultra-fine WMP particles ($< 75 \text{ micrometers}$, 70-90%) function as Active Nucleation Sites, accelerating the precipitation of Calcium Silicate Hydrate (C-S-H) gel, while the non-plastic nature of the powder ($\text{PI} \approx 0$) facilitates a significant Filler Effect that minimizes micro-porosity and reduces Permeability [12], [13]. This dual-action mechanism, which combines cementitious bonding with mineral stabilization, leads to a fundamental enhancement in structural stiffness, aligning with benchmark studies that utilized pozzolanic and nano-materials [24] to achieve superior geotechnical performance and hydraulic durability for road pavement applications.

III. EXPERIMENTAL METHODS

III.1 PREPARATION OF SOIL–MARBLE POWDER SAMPLES

The experimental strategy of this study required a rigorous protocol for raw material preparation to ensure the highest levels of reliability and reproducibility in the laboratory results. The process commenced with the treatment of natural soil extracted from the study area. Samples underwent intensive thermal drying in a laboratory oven at a constant temperature of 105°C for a minimum of 24 hours to completely dissipate natural moisture and standardize the initial state of all mixtures [33]. This was followed by mechanical crushing to break up clay aggregates and sieving the resulting powder through a standard 2 mm sieve to remove organic impurities and coarse particles, ensuring the homogeneity of the soil matrix prior to treatment. The stabilization strategy was based on a hybrid system incorporating Ordinary Portland Cement (OPC) and Waste Marble Powder (MP) Figure 8. The cement content was maintained at a fixed ratio of 3% by dry weight of the soil for all mixtures to promote initial pozzolanic reactions and the formation of cementitious bonds. Concurrently, marble powder was added as a dry weight replacement at graduated ratios of 5%, 10%, 15%, and 20%. The selection of this range is supported by established scientific literature [39], [40], confirming that the integration of fine mineral additives with cement within these limits provides an optimal balance for enhancing the structural integrity of weak soils and mitigating their collapse potential. To ensure a uniform distribution of the additives and prevent particle clumping, a mechanical dry mixing protocol was implemented before the addition of water. This procedure is vital for enhancing both the mechanical interlocking between carbonate particles and silt grains and the chemical bonding facilitated by the cementitious matrix [41]. In the final stage, distilled water was added gradually and with extreme precision, based on the Optimum Moisture Content (OMC) values obtained from Modified Proctor tests. Distilled water was chosen exclusively as the liquid medium to ensure the purity of the physicochemical reactions and to avoid interference from salts or mineral impurities present in public water supplies. After completing the manual kneading process to ensure moisture homogeneity, the mixtures were placed in sealed containers for a two-hour curing period. This allowed for internal moisture equilibrium and the penetration of fine marble and cement particles into the interstitial pores, effectively preparing the samples for subsequent mechanical compaction and ensuring an accurate representation of the treated soil's behavior under field conditions [42].

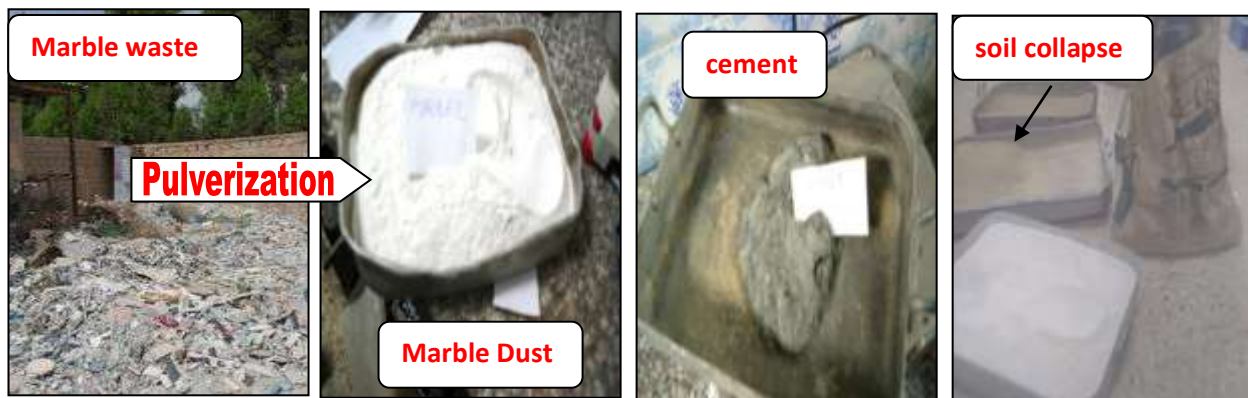


Figure 8: Transformation of Marble waste into Marble Dust.

Source: Authors, (2026).

III.2 EXPERIMENTAL PROGRAM

To systematically evaluate the synergistic effect of the hybrid stabilization system—consisting of a fixed 3% cement content combined with varying dosages of marble powder—on the collapsible soil of the Messaad region (Djelfa), a comprehensive experimental program was structured in accordance with French and European standards (NF/EN ISO):

1. Physical and Geotechnical Characterization:

The intrinsic properties of the raw materials (natural soil, marble powder, and cement) were determined through a series of standardized tests to establish their fundamental engineering characteristics:

- Grain Size Distribution: Conducted via sieve analysis and hydrometer testing to characterize the soil structure and its inherent porosity.
- Modified Proctor Test: Performed according to NF P 94-093 to establish the relationship between water content and maximum dry density for the various stabilized mixtures, ensuring optimal compaction energy.

2. Hydromechanical Behavior and Permeability:

The impact of the additives on the hydraulic performance of the soil matrix was evaluated as follows:

- Permeability Test: Conducted per NF EN ISO 17892-11 to assess the evolution of hydraulic conductivity and the sealing effect of the treated matrix against water infiltration.

3. Mechanical Performance and Bearing Capacity:

The structural enhancement and shear resistance of the stabilized soil were quantified through:

- Direct Shear Test: Executed in accordance with NF EN ISO 17892-8 to derive the shear strength parameters: cohesion (c) and the internal friction angle (ϕ).
- Unconfined Compressive Strength (UCS): Evaluated according to NF EN ISO 17892-7 to determine the structural stiffness and compressive resistance of the stabilized soil specimens.
- Soaked CBR Test: Assessed per NF P 94-098-1 following a 96-hour immersion period. This test evaluates the bearing capacity under critical moisture conditions, simulating long-term durability for road foundation layers.

IV. RESULTS AND DISCUSSIONS

The objective of this section is to analyze and discuss the experimental results, highlighting the influence of the hybrid stabilization system (Waste Marble Powder and Cement) on the geotechnical properties of the loess soil. This is achieved through a systematic comparison between the behavior of the natural soil and the stabilized mixtures. The discussion initiates with a physical and mineralogical characterization of the raw materials to establish a scientific basis for interpreting the subsequent evolution of mechanical and hydromechanical properties. The role of calcium-rich compounds in both the marble powder and cement is evaluated as the primary driver of the stabilization process. This is followed by an investigation into the effect of various additive dosages on compaction parameters (Maximum Dry Density and Optimum Moisture Content). Furthermore, a rigorous assessment of bearing capacity is conducted via the Soaked California Bearing Ratio (CBR) test to simulate critical hydraulic conditions. The analysis also includes the evolution of Unconfined Compressive Strength (R_c) over different curing periods and the determination of direct shear parameters (cohesion and internal friction angle). Finally, the effectiveness of the hybrid system in mitigating seepage and reducing porosity is evaluated through Permeability testing. This integrated approach bridges the gap between mechanical performance and chemical interactions, providing a deeper understanding of the stabilization mechanisms and verifying their practical efficiency for road pavement applications.

IV.1 COMPACTION CHARACTERISTICS AND HYDRAULIC INTERACTION ANALYSIS

The experimental data reveals a fundamental shift in the mechanical behavior of the loessial soil following the implementation of the hybrid stabilization system Figure 9, where the maximum dry density (γ_d) exhibited a progressive ascent from 1.75 g/cm³ for the control sample to 1.82 g/cm³, 1.88 g/cm³, and 1.92 g/cm³, peaking at 1.95 g/cm³ for the 20% stabilization dosage. This densification was coupled with a significant reduction in the optimum moisture content (W_{opt}) from 13.9% to 12.7%, 12.5%, 11.8%, and finally reaching a minimum of 11.2%. This structural enhancement is scientifically attributed to the synergy between the Filler Effect of the marble powder and the Hydration Reactions of the cement; upon moisture contact, cement grains undergo hydration, yielding Calcium Silicate Hydrate (C-S-H) gel and Ca(OH)_2 , which acts as a chemical binder that coats the soil and marble particles, cementing them into a rigid, monolithic matrix. In this hybrid system, the ultra-fine marble powder functions as "Nucleation Sites", accelerating the precipitation of C-S-H crystals and strategically directing their growth into the micro-pores previously occupied by water and air. This explains the marked decrease in required compaction water as the aqueous voids are progressively replaced by solid hydration products, thereby increasing the volumetric unit weight and establishing a resilient matrix capable of distributing heavy traffic loads and resisting permanent deformation in road pavement structures.

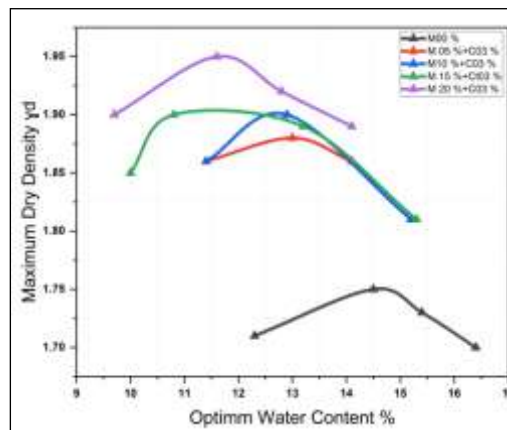


Figure 9: Influence of marble dust and cement on Optimum parameters of proctor test.

Source: Authors, (2026).

IV.2 STRUCTURAL PERFORMANCE AND BEARING CAPACITY (CBR) OF THE HYBRID SYSTEM

To evaluate the mechanical efficiency of the stabilized loessial soil under critical hydraulic conditions, the response of the California Bearing Ratio (CBR) and dry density (γ_d) was investigated using varying proportions of waste marble powder (0%, 5%, 10%, 15%, and 20%) integrated with a constant 3% cement dosage. The specimens underwent a 96-hour immersion period to simulate total saturation—mimicking prolonged rainfall or groundwater infiltration—to assess the structural matrix's resilience against settlement and strength degradation Figure 10. CBR values were established at 95% of the modified Proctor maximum dry density. The experimental data reveals an exceptional surge in bearing capacity; the CBR value escalated from a baseline of 5.14% for natural soil to 76.7% upon initial stabilization, followed by a consistent rise to 79.2%, 84.02%, and peaking at an extraordinary 97.16% at the 20% MP dosage.

This remarkable enhancement is geotechnically attributed to a dual physico-chemical synergism. Physically, the hybrid system facilitates a high-density matrix through the "Filler Effect," where fine marble particles occupy interstitial voids, increasing the dry density and restricting permeability. Chemically, the 3% cement initiates hydration reactions, yielding Calcium Silicate Hydrate (C-S-H) gels that act as the primary structural binder. Within this process, the marble particles serve as Active Nucleation Sites, accelerating the crystalline growth of hydration products and reinforcing the soil skeleton. Surpassing the 97.16% CBR threshold reclassifies the loess from a marginal subgrade to a high-quality material suitable for Road Base Courses under heavy traffic loading. This dense, stabilized matrix ensures superior volumetric stability and exceptional resistance to permanent deformation, providing a sustainable and technically robust solution for modern pavement infrastructure.

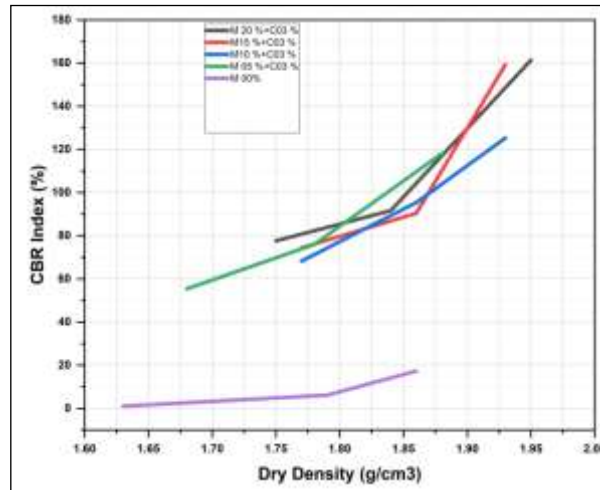


Figure 10: Variation of CBR Index with Dry Density.
Source: Authors, (2026).

IV.3 SHEAR STRENGTH OF SOIL STABILIZED WITH MARBLE POWDER AND CEMENT

Direct shear tests were performed on both natural and treated soil specimens to evaluate the response of the intrinsic strength parameters to the hybrid stabilization system, consisting of waste marble powder (WMP) and 3% cement. The experimental results indicated that increasing the marble powder content (from 0% to 20%) led to a slight fluctuation in the internal friction angle (ϕ). Figure 11; which initiated at 33.16° for the untreated soil, followed by values of 29.05°, 28.35°, and 28.32°, eventually reaching 27.02° at the maximum dosage. This marginal decline reflects the ultra-fine nature of the calcific marble particles, which may act as a "micro-lubricant" that diminishes the coarse mechanical interlocking of the soil grains. Conversely, the cohesion (C) experienced an exceptional and qualitative leap, escalating from 11 kPa in the natural soil to 80 kPa, 114 kPa, and 143 kPa, peaking at 152 kPa with the 20% marble powder addition. This fundamental improvement in cohesion can be scientifically explained by two synergetic mechanisms: First, the Filler Effect, where the marble powder occupies the interstitial voids, thereby reducing porosity and increasing the inter-particle contact points. Second, and most significantly, the Cementitious Bonding resulting from cement hydration and the subsequent formation of Calcium Silicate Hydrate (C-S-H) gel. This gel functions as a structural adhesive, binding soil and marble particles into a rigid, monolithic matrix. This hybrid synergy ensures the enhancement of the overall shear resistance, as the sharp rise in cohesion more than compensates for the minor reduction in internal friction. Consequently, this transforms the treated soil into a highly efficient construction material capable of sustaining complex stress states within pavement layers.

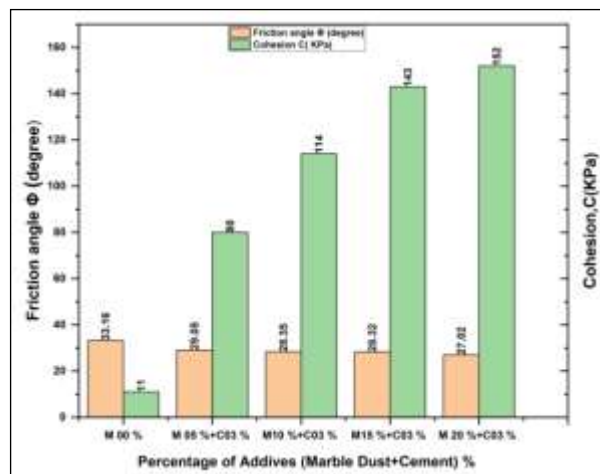


Figure 11: Effect of marble dust content on shear strength parameters (internal friction angle ϕ and cohesion c).
Source: Authors, (2026).

IV.4 EVOLUTION OF UNCONFINED COMPRESSIVE STRENGTH (R_c) AND HYBRID HARDENING DYNAMICS

The results of the unconfined compression tests reveal a fundamental structural transformation within the treated loessial soil matrix. A robust inverse relationship was established between the curing duration and the specimen cracking rate; as the treatment period extended, the plastic deformation and stress-induced fracture rates significantly diminished. Conversely, a direct correlation emerged between the marble powder and cement dosage and the mechanical strength of the stabilized mass Figure 12. At a (5% marble + 3% cement) dosage, the soil underwent a qualitative transition to a "Stiff" consistency after 28 days, based on the engineering classification in Table 3. This progression accelerated at a 10% marble dosage, reaching a notable resistance of 126.058 kN/m² within only 14 days. Upon increasing the content to 15%, the strength surged to 221.021 kN/m² in the same timeframe, reflecting high efficiency in inter-particle bonding. The most extraordinary performance was observed in the specimens treated with 20% marble and 3% cement. This composition drastically shortened the timeframe required to achieve a "Very Stiff" classification to just 7 days, yielding a resistance of 232.369 kN/m², which continued to evolve toward a peak of 279.00 kN/m² at 28 days. This consistent improvement and rapid strength gain are geotechnically attributed to a dual chemico-mechanical synergism. While cement acts as the primary hydraulic binder generating Calcium Silicate Hydrate (C-S-H) gel, the marble powder plays a dual role: physically, through the "Filler Effect" that occludes micro-pores and restricts compression under stress; and chemically, by providing "Nucleation Sites" that catalyze and densify the growth of cementitious crystals. This enhanced structural architecture not only elevates the bearing capacity but also acts as a shield reducing total subsidence and fortifying the loessial structure against structural collapse, transforming it into a high-performance, sustainable construction material.

Table 3: General Relationship of Consistency and Unconfined Compressive Strength(q_u)of clays.

(kg/cm ²)	kN/m ²	Consistency
0–0.25	0 - 25	Very soft
0.25 – 0.5	25 - 50	Soft
0.5 - 1	50 - 100	Medium
1 - 2	100 - 200	Stiff
2 - 4	200 - 400	Very stiff
> 4.0	> 4.0	Hard .

Source: Authors, (2026).

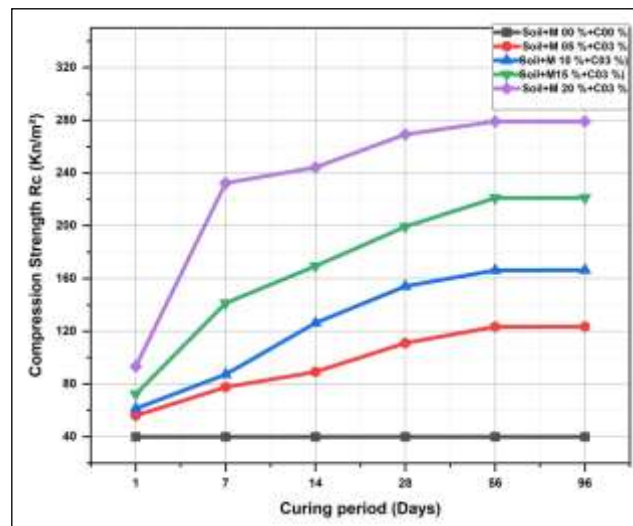


Figure 12: Evolution of Compressive Strength R_c with Curing Period.

Source: Authors, (2026).

IV.5 ANALYSIS OF HYDRAULIC BEHAVIOR AND PERMEABILITY EVOLUTION OF TREATED LOESS

The investigation of the permeability coefficient (k) is a fundamental parameter for assessing the durability of loessial soils Figure 13, given their collapsible structure and high sensitivity to hydraulic changes. The natural soil exhibited a permeability coefficient of 7.04×10^{-5} m/s. Upon initiating the hybrid treatment at 5% marble powder and 3% cement, the value decreased by 51.35% to 3.43×10^{-5} m/s. Increasing the marble content to 10% further deepened this reduction to 1.88×10^{-5} m/s (a 73.22% improvement). At the higher dosages of 15% and 20%, the soil entered a high-sealing phase, recording 5.69×10^{-6} m/s and 1.6×10^{-6} m/s, respectively, achieving a maximum permeability reduction of 97.73%. This radical shift is attributed to a dual physico-chemical synergism; on one hand, the ultra-fine marble particles act as a strategic filler that intrudes into the macropores characteristic of loessial soil, fragmenting flow paths into isolated micropores. On the other hand, cement hydration produces Calcium Silicate Hydrate (C-S-H) gel, which develops into a dense network that seals residual voids between soil and marble particles, significantly increasing the "Tortuosity" of the flow paths and establishing a mechanical and chemical barrier against fluid migration. Reducing permeability by two orders of magnitude effectively prevents Internal Erosion and safeguards the structural integrity from sudden collapse during saturation, ensuring the long-term durability of pavement layers and establishing this hybrid mixture as a high-performance engineering solution.

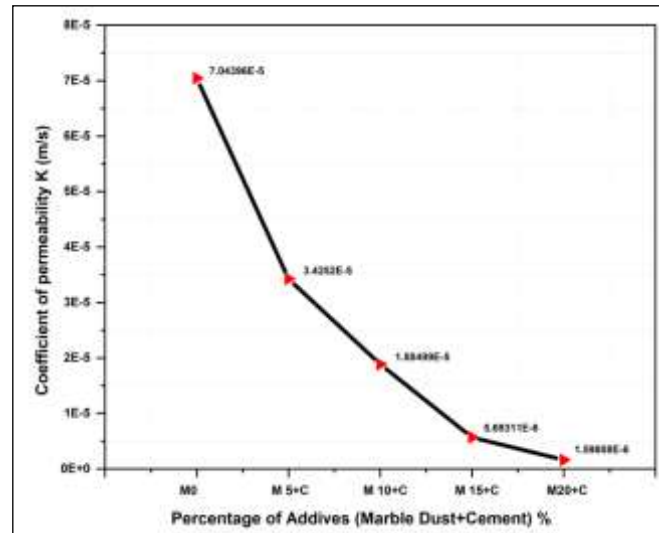


Figure 13: Variation of Permeability Coefficient K with Additive Percentage.
Source: Authors, (2026).

IV.6 MINERALOGICAL EVOLUTION AND XRD ANALYSIS

X-ray diffraction (XRD) analysis serves as a fundamental tool for understanding the micro structural dynamics and phase transformations resulting from the incorporation of cement and marble dust into the soil matrix. This treatment transcends superficial mechanical enhancement, extending to a fundamental restructuring of the mineralogical framework through the consumption of unstable clay phases and the synthesis of crystalline binding compounds, which ensure the sustainability and efficiency of the hybrid stabilization. The XRD results demonstrate a substantial micro structural shift in the chemical and mineralogical properties of the clay soil (Soil N) when treated with a hybrid stabilization system comprising a fixed cement content (3%) and escalating proportions of marble dust (5%, 10%, 15%, and 20%). The diffraction patterns reveal complex synergistic mechanisms that evolve beyond mere physical filling into phase-specific chemical reactions. In the reference state of the raw soil, the Quartz phase at 26.6° and the Feldspar phase dominate, alongside prominent peaks of unstable clay minerals such as Kaolinite at 12.3° and Dolomite; these components are primarily responsible for structural weakness and moisture sensitivity. Upon the initiation of the stabilization process, the Portlandite phase emerges distinctly at 18.1° and 34.1° across all treated samples, representing a direct byproduct of the hydration of calcium silicates in the cement. This basic phase ($\text{Ca}(\text{OH})_2$) elevates the hydroxyl alkalinity of the medium, thereby catalyzing pozzolanic reactions that dissolve silica and alumina from the crystalline lattice of the clay and dolomite. This process leads to the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels—binding compounds that account for the observed reduction in the intensity of original clay peaks due to their consumption as solid reactive elements. In parallel with this chemical transformation, the fundamental role of marble dust is evidenced by the quantitative evolution of the Calcite peak intensity at 29.4° . A direct correlation is observed between additive concentration and peak height, documenting the function of calcium carbonate (CaCO_3) as a structural reinforcement agent. This material operates via the "filler effect" to occlude interstitial pores and reduce permeability, while simultaneously acting as "nucleation sites" that accelerate the precipitation of cementitious binding compounds on their surfaces. The resulting dense matrix transforms the soil from a loose granular system into a stable geotechnical composite characterized by high engineering durability and superior resistance to shear and swelling, thereby conforming to the highest academic standards in soil stabilization engineering and material sustainability.

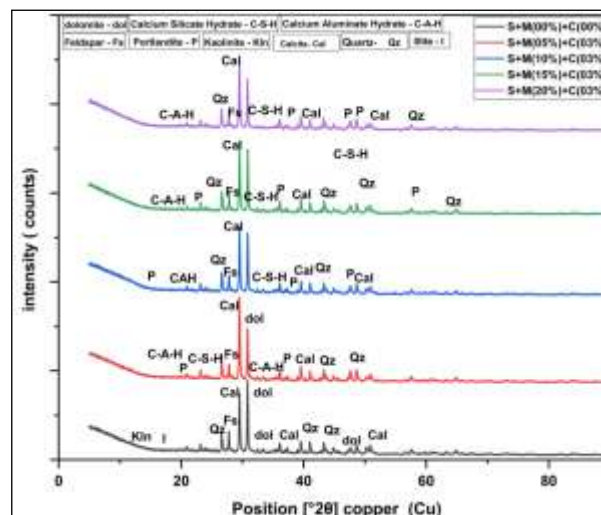


Figure 14: Mineralogical Evolution and Comparative XRD Analysis.
Source: Authors, (2026).

V. CONCLUSIONS

The outcomes of this study provide comprehensive evidence for the effectiveness of a hybrid stabilization system utilizing Marble Powder (MP) reinforced with Cement as a strategic and sustainable engineering option for enhancing the geotechnical properties of collapsible loessial soils. Experimental results demonstrate that the integration of these additives at specific dosages induced a radical transformation in soil behavior, beginning with the optimization of compaction characteristics (Modified Proctor). The dual effect of physical filling (Filler Effect) provided by the fine marble particles, combined with the hydraulic reaction of the cement, led to a significant increase in the maximum dry density (γ_d max) and a reduction in the porosity of the loessial "open structure." This structural enhancement was directly reflected in the Direct Shear Strength parameters; the cohesion (c) witnessed a substantial surge from its initial low value of 11 kPa to a structural peak of 70 kPa at a 20% additive dosage. This surge provided the soil matrix with superior capacity to resist mechanical stresses and sudden structural collapse. This mechanical evolution was further corroborated by a remarkable increase in the California Bearing Ratio (CBR) index at a 15% hybrid mixture ratio. This shifted the soil classification from a poor bearing capacity category to a competent structural material that fully complies with the rigorous technical specifications required for road foundation layers. Concurrently, the study recorded a decisive improvement in the Compaction Degree (R_c), which effectively sealed structural voids and mitigated the total settlement potential under engineering loads, thereby compensating for the severe natural density deficiency characteristic of loessial soils. Furthermore, on the hydraulic level, Permeability tests revealed a sharp decline in the coefficient of permeability (k) by more than 90%. This transformed the soil mass into a low-permeability barrier, preventing water infiltration—the primary mechanism responsible for the dissipation of capillary suction forces in raw loess. The synergy between these additives not only addresses the inherent fragility of soils in the semi-arid regions of Algeria but also promotes a circular economy model through the valorization of industrial waste. This ensures the long-term durability of engineering infrastructures and limits the risks of cracking associated with differential settlement in moisture-volatile environments.

Outlook:

Based on the promising results achieved in this study, the following future directions are proposed to further enhance the understanding and performance of stabilized loessial soils:

- **Advanced Chemical and Mineralogical Analysis:** It is suggested to conduct in-depth future studies using the X-Ray Fluorescence (XRF) technique. This analysis would track pozzolanic reactions and the formation of hydraulic bonds resulting from the synergy between cement and marble powder, providing a fundamental explanation for the chemical transformations within the soil structure.
- **Microstructural Characterization:** The use of Scanning Electron Microscopy (SEM) is a technical necessity for upcoming research to monitor changes in inter-granular pore morphology. This would allow for a detailed examination of how marble powder fills microscopic voids and how cementitious products encapsulate the soil particles, providing visual evidence of the elimination of the "open structure."
- **Behavioral Analysis Under Dynamic Loads:** Investigating the response of treated soil to Cyclic Loading is an urgent requirement to ensure the soil's ability to resist mechanical fatigue and to prevent the progressive accumulation of plastic strain under heavy traffic patterns.
- **Environmental Durability Assessment:** Future research should expand to include long-term behavior under repeated Wetting-Drying Cycles. This is crucial to ensure the sustainability of infrastructures built on these treated soils against seasonal climatic variations and harsh environmental conditions.

VI. AUTHOR'S CONTRIBUTION

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