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Characterization and Structural Improvement of Chott-El-Hodna Clay: A Study on Treatments Through Hydraulic Binder

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ABSTRACT

This study examines the characterization of Chott-El-Hodna clay and the enhancement of its properties using hydraulic binders, specifically cement and lime. Soil samples from Ain El Khadra in the Chott-El-Hodna basin were treated with varying concentrations of cement and lime (2-12% by weight) to evaluate their effects on the soil's mechanical and physical properties. Employing standardized geotechnical tests, including Proctor compaction, California Bearing Ratio (CBR), unconfined compression, and ultrasonic velocity measurements, this research assesses each binder's role in reducing soil plasticity, increasing compaction, and improving load-bearing capacity. Results indicate that both cement and lime contribute to improved soil stability, with lime showing superior performance in load-bearing capacity at higher dosages, while cement provides consistent compaction and strength benefits across all dosages. X-ray diffraction and fluorescence analyses further highlight the chemical and mineral stability of the treated soils, with quartz and calcite enhancing mechanical resilience and pH buffering. These findings suggest that lime and cement treatments can significantly improve the durability of infrastructure in saline soil regions, offering targeted stabilization solutions to optimize foundational integrity in arid and semi-arid environments.

1. INTRODUCTION

In the world of civil engineering, few challenges are as widespread—and as subtly insidious—as expansive soils. Known for their unique ability to expand when moist and contract when dry [1], these soils are found in regions around the world, from the arid plains of the southwestern United States to the seasonal, semi-arid climates of North Africa. To the untrained eye, expansive soils may look like any other foundation material, but their dynamic properties can trigger foundational instability, damaging roads, buildings, and other critical infrastructure without warning [2-6]. As urbanization continues and construction ventures into new territories, understanding and managing expansive soils has become essential for building structures that stand the test of time [7].

The stabilization and properties of expansive soils have been the focus of intensive research over the past several decades. Researchers have consistently found that chemical treatments can transform expansive soils into reliable materials for use as fill and subgrade or subbase layers in road construction. This body of work underscores that when appropriately stabilized, expansive soils become not only more stable but also more versatile in various civil engineering applications [8-20].

Recent studies have brought this issue to light, demonstrating that in areas with high concentrations of expansive soil, damage can become frequent and severe. For instance, several American cities have faced costly rehabilitation projects due to unexpected soil movement, which disrupted road networks and even rendered some buildings unsafe [21, 22]. Infrastructure investment in such areas requires not only traditional engineering solutions but also targeted strategies that can stabilize these unpredictable soils. With this knowledge, the construction industry is increasingly turning to soil stabilization methods that can counteract the soil's natural tendencies, providing a stable base for roads, buildings, and even bridges in expansive soil regions.

The search for effective stabilization techniques has led engineers to innovative solutions. Chemical stabilization using additives like cement [23-25], cement and lime kiln dust [26, 27], and fly ash [28-32] has emerged as a common approach, with each additive offering unique advantages in enhancing soil strength, reducing swelling potential, and improving load-bearing capacity. However, these solutions aren't without their challenges.

In one notable study, Bouchouk et al. [33] examined the stabilization of sulfate-rich soils using various hydraulic binders, including ordinary Portland cement and binders with high ground granulated blast furnace slag (GGBS) content. They tested soil samples enriched with sulfate, analysing sulfate and heavy metal concentrations, as well as swelling and mechanical stability. Their findings showed that while Portland cement treatments stabilized sulfate content, they also led to excessive volume expansion due to ettringite formation. Conversely, GGBS-based treatments provided effective sulfate stabilization, minimized heavy metal leaching, and maintained manageable expansion levels, indicating their suitability for sulfate-rich environments in civil engineering applications.

Further investigation by Khemissa et al. [34], investigated the effects of hydraulic binders, specifically Portland cement and lime, on the physical and mechanical properties of a highly expansive clay with significant swelling potential. Through laboratory tests, they assessed the impact of different concentrations of cement and lime (ranging from 2% to 12%) on clay viscosity, swelling potential, and shear strength. Results revealed that binder treatments significantly reduced the clay's viscosity and swelling, while increasing shear strength and undrained cohesion, with optimal outcomes at higher binder contents. This research highlights the effectiveness of hydraulic binders in improving the structural properties of expansive soils and underscores their potential for practical application in areas with similar soil profiles.

This study presents new findings from an experimental analysis of highly saline, expansive clay from Ain El Khadra, in M'Sila Province, Algeria—an area where soil instability poses significant challenges to infrastructure. Unlike previous studies that focus on general stabilization methods, this research integrates mechanical, physical, and petrographic analyses, including X-ray diffraction (XRD), X-ray fluorescence (XRF), and ultrasonic velocity tests, to comprehensively evaluate the impact of locally produced cement and lime on soil stabilization. By systematically varying the binder content (2% to 12% by weight) and conducting standardized tests such as Proctor compaction, California Bearing Ratio (CBR), and unconfined compression, this study provides new insights into the efficiency of hydraulic binders in improving soil stiffness, load-bearing capacity, and compaction characteristics. The findings contribute to the growing body of knowledge on soil stabilization in semi-arid and saline environments, offering practical recommendations for infrastructure development in regions affected by expansive clays.

2. METHODOLOGY

2.1 Description of the site

Chott-El-Hodna is a vast endorheic basin spanning over 1,000 km² in M'Sila and 100 km² in Batna, located in southeastern Algeria. It lies 40 km from M'Sila and is part of an interconnected system of chotts, where waters from the Saharan Atlas and Tell Atlas converge, forming a high steppe landscape. The basin covers approximately 26,000 km^2 and is surrounded by mountain ranges with elevations reaching 1,900 m, creating a hydrologically closed system with no natural drainage outlets.

The region has an arid to semi-arid climate, characterized by low annual precipitation (~200 mm), high evaporation rates, and significant seasonal temperature variations. During winter, portions of the chott are intermittently flooded, while in summer, evaporation leads to the formation of thick salt crusts, indicative of a high-salinity environment. These cyclical moisture fluctuations contribute to the expansive nature of the soil, which undergoes swelling during wet seasons and shrinkage in dry periods, leading to soil instability.

Geologically, Chott-El-Hodna is composed of Quaternary lacustrine and alluvial deposits, with a predominance of clay-rich sediments interbedded with evaporites such as halite and gypsum. The high clay content, combined with the presence of expansive minerals like smectite and illite, exacerbates the shrink-swell behavior of the soil, making it highly problematic for infrastructure development (Figure 1).

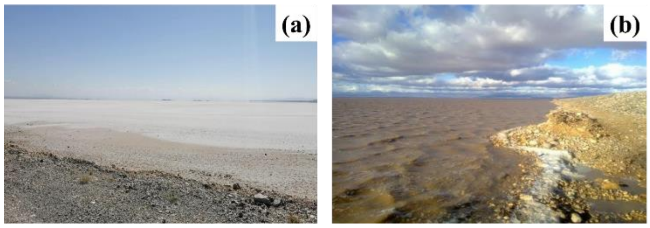

Figure 1. Chott el Hodna during the period: (a) summer, (b) winter

The study site is located in M'Sila province, where a road link project between Ain El Khadra and M'cif crosses 11 km of Chott-El-Hodna. Due to the challenging soil conditions, stabilization solutions are essential to ensure long-term infrastructure durability. Soil samples were collected at depths ranging from 1.50 to 2.20 m using a mechanical shovel to assess the impact of hydraulic binders on soil stabilization (Figure 2).

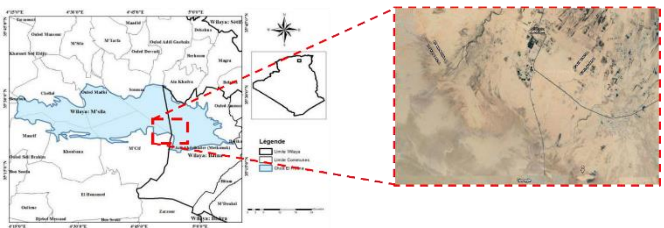

Figure 2. Geological map of Chott el Hodna, M'Sila region, scale 1/60,000

3. MATERIALS AND METHODS

3.1 Description of materials

Soil samples for this study were collected from Ain El Khadra in M'Sila Province, Algeria (Figure 1), an area where infrastructure projects, such as roads, public facilities, and light buildings, often experience significant disturbances. Initially, the samples were identified following standard geotechnical testing procedures (Figure 3). Their mineral composition was determined using X-ray diffraction (XRD) on particles smaller than 2 micrometers, a widely used technique for identifying crystalline minerals in raw materials. XRD analysis is feasible for any crystalline material due to its atoms' arrangement in defined planes, with diffraction occurring according to Bragg's law: 2d sinθ = nλ. For a specified X-ray source (π), scanning the sample at incidence angle θ reveals all lattice spacings (d) in the sample. The samples were prepared for XRD by grinding in a corundum mortar to a particle size below 80 micrometers and air-drying for one week [35]. X-ray fluorescence (XRF) analysis was also conducted using a wavelength-dispersive XRF spectrometer with a 1-kilowatt X-ray tube, and the sample pH was measured as well. Particle size distribution was assessed by wet sieving following the method in study. Sedimentation techniques were used for particles under 80 micrometers. Soil plasticity was evaluated using Atterberg limits according to the standard.

In the second phase of the experiment, mechanical performance tests were conducted on clay mixtures at specified hydraulic binder dosages. The standard Proctor test, recommended for road construction, was used in accordance with according to the standard. Additionally, an immediate CBR test was carried out following NF P 94-078, to assess soil bearing capacity. Unconfined compressive strength was measured according to NF P18-406, and ultrasonic measurements were taken to complete the analysis of the soil's mechanical properties.

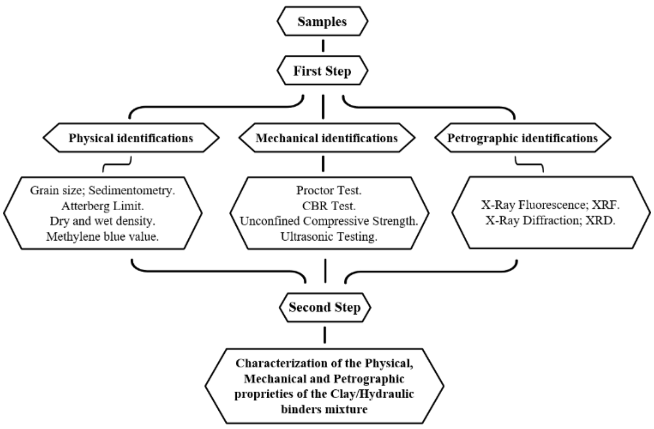

Figure 3. Flow chart of testing programme

The treatment involves mixing the soil with locally produced stabilizers (cement and slaked lime) in the specified proportions.

• The cement used, CRS Mokaouem from the Lafarge M'Sila plant, was selected for its chemical resistance and suitability for all underground works in the area.

• The lime, sourced from ERCO factories in Al-Hasasna (Saeeda Governorate), is slaked lime. Table 1 and Table 2 provide the physical and chemical properties of this stabilizer.

Cement and lime were selected based on their proven efficiency in reducing soil plasticity, enhancing compaction, and increasing strength. Cement is widely used for its pozzolanic reaction, which forms calcium silicate hydrates (C-S-H) and increases soil cohesion. Lime, on the other hand, is effective in reducing swelling potential due to the formation of calcium aluminates and pozzolanic compounds that stabilize clay minerals. Given the high salinity and alkaline nature of the Chott-El-Hodna soil, lime was also chosen for its ability to neutralize pH fluctuations and mitigate sulfate-related swelling issues. The comparative study of these two binders allows us to determine the most suitable treatment for expansive soils in saline environments.

The hydraulic binder content levels for the treatment are set at 0% for the control sample and 2%, 4%, 6%, 8%, 10%, and 12% for the treated samples.

Table 1. Physical and chemical properties of the composed cement

Designation	Commercial	Mokaouem
Physical properties	Normal consistency of cement paste (%)	25 à 28
	Fineness according to the Blaine method (cm²/g)	3200 à 3800
	Shrinkage at 28 days (µm/m)	< 1000
	Expansion (mm)	≤ 2,0
	Heat of hydration (J/g)	< 270
	Start of intake at 20° (min)	> 60
	End of setting at 20° (min)	240 à 400
	Compressive strength at 2 days (MPa)	≥ 10
	Compressive strength at 28 days (MPa)	≥ 42,5
Chemical properties	Loss on ignition (%)	0,5 à 3
	Sulfuric content SO_3 (%)	1,8 à 3
	C3S content (%)	≤ 50
	C3 A content (%)	≤ 5
	C4 AF +2C3 A (%)	≤ 22
	Magnesia content MgO (%)	1,2 à 3
	Chloride content (%)	0,01 à 0,05
	C3A aluminate content (%)	< 3.0
	Sulfuric content SO3 (%)	1,8 à 3

Table 2. Physical and chemical properties of lime

Designation	Commercial	Mokaouem
Physical properties	Density	600-900 g/l
	Absorption coefficient	< 5
	Frost sensitivity	< 30
	Extinction volume	2.73 cm3
	Refusal 630 µm	0%
	Refus 90 µm	< 10%
	Humidity	> 5
Chemical properties	CaO	> 83.3%
	MgO	< 0.5%
	Fe_2O_3	< 2%
	Al_2O_3	< 1.5%
	SiO_2	< 2.5%
	SO_3	< 2.5
	Na_2O	< 4.7 –0,5
	CO_2	< 5
	$CaCO_3$	< 10
	Insoluble in HCl	< 1

4. RESULTS AND DISCUSSION

4.1 Characterization of the study soil

Table 3 provides a detailed account of the physical and mechanical properties of a soil sample classified as "brownish to yellowish clay," each parameter offering insights into its behavior and essential characteristics for geotechnical applications. This analysis begins with depth, ranging from 1.5 to 2.5 meters, suggesting a focus on shallow subsurface conditions relevant for foundational and pavement layers. The dry and wet densities, recorded at 1.78 g/cm^3 and 2.13 g/cm^3 respectively, indicate the soil's compaction level and moisture content, with higher wet density pointing to notable moisture retention that could impact load-bearing capacity and introduce shrink-swell risks. The natural moisture content, at 16.17%, shows a moderately high-water presence that could influence soil consistency and strength under load, necessitating careful consideration in structural applications.

With a liquidity limit of 51.75% and a plastic limit of 31.39%, the soil's plasticity index of 20.36% classifies it as plastic clay, a type prone to deformation and volume changes under moisture variation (as depicted in Figure 4).

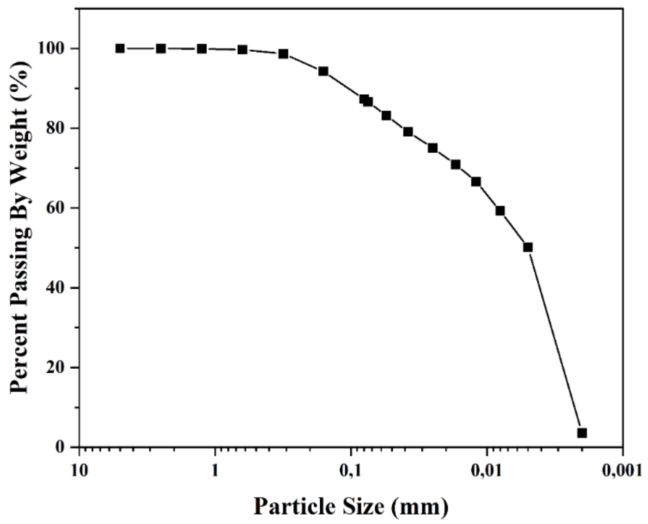

Figure 4. Grain size distribution curve of Chott el Hodna clay

Table 3. Physical and mechanical properties of the soil studied

Designation	Brownish to Yellowish Clay
Depth (m)	1.5 – 2.5
Dry density (g/cm3)	1.78
Wet density (g/cm3)	2.13
Natural moister content (%)	16.17
Liquidity limit (%)	51.75
Plastic limit (%)	31.39
Plasticity index (%)	20.36
Consistency index (%)	1.75
Methylene blue value	6.56
Clay activity	1.81
% Passing through 0,2 mm sieve	95.77
% Passing through 80-µm sieve	87.31
Proportion of clay %<2 µm	3.62
Optimum moister content (%)	20.4
Optimum dry density (g/cm3)	1.68
CBR Bearing Index	3.09
Compressive Strength (Mpa)	2.65
Ultrasonic value (Cm/µs)	0.09
pH measurement	8.2°
Salt content (g/L)	56.9

The consistency index, 1.75, denotes reasonable firmness, a quality important for structural stability, while the clay activity of 1.81 suggests moderate shrink-swell potential, which could pose challenges for structures over time. Grain size distribution, where 95.77% and 87.31% of particles pass through 0.2 mm and 80-µm sieves respectively, confirms the fine-grained nature typical of clays, affecting drainage, plasticity, and load-bearing potential. The 3.62% proportion of particles under 2 µm further reflects high cohesion and compaction potential, although it may also increase plasticity, impacting stability under load (refer to Figure 5).

The optimum moisture content of 20.4% and optimum dry density of 1.68 g/cm^3 indicate ideal conditions for achieving maximum compaction and strength, essential for stable construction (refer to Figure 6). However, with a CBR value of 3.09, the soil's natural bearing capacity is relatively low, suggesting that additional stabilization might be required for high load-bearing applications such as roads. The compressive strength of 2.65 MPa highlights moderate resistance to compression, an important factor for foundation design, and an ultrasonic velocity of 0.09 Cm/µs suggests the soil's softness and elasticity, which might necessitate structural adjustments for heavy loads. The pH value of 8.2 shows slight alkalinity, raising potential corrosion concerns for metallic structures, while a high salt content of 56.9 g/L indicates significant salinity, which could further affect corrosion rates, as well as vegetation growth, if used in environmental applications. Altogether, this brownish to yellowish clay, with its moderate plasticity, clay activity, high natural moisture, and low CBR value, points to limitations in supporting heavy loads in its natural state, and the high salinity and alkaline pH require particular considerations for embedded materials. This comprehensive analysis provides valuable information for applications where soil stability, compaction, and potential volume changes are crucial factors, informing decisions in construction, road engineering, and environmental planning where modifications or stabilizations might be required.

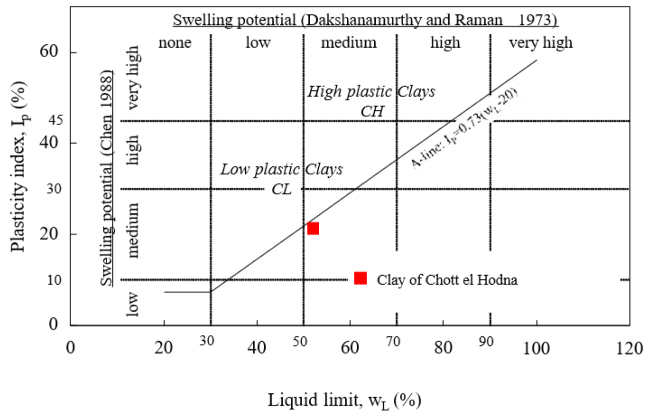

Figure 5. Grain size distribution curve of Chott el Hodna clay

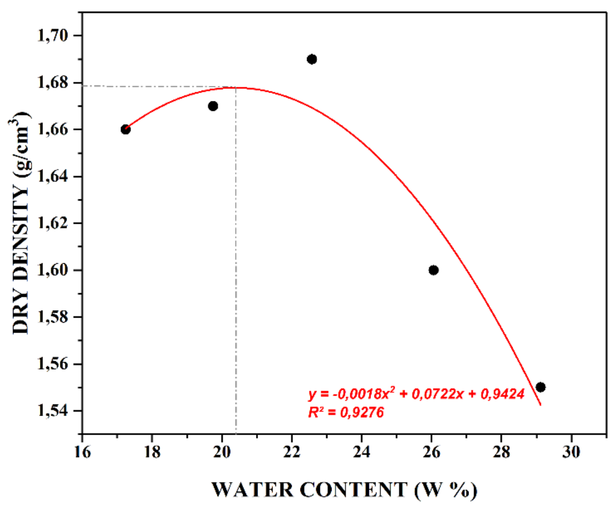

Figure 6. Compaction curve for Chott el Hodna clay

4.2 Petrographic identification of clay minerals

4.2.1 X ray diffraction

This detailed XRD analysis shown in Figure 7 provides a thorough understanding of the mineral composition within the sample, emphasizing the role each mineral plays in its physical and chemical behavior.

Primary Peak (20.27° 2θ): The 20.27° peak, with an intensity around 8,000 counts, suggests a high concentration of quartz, approximately 20.27%. This peak is not only a marker of quartz presence but also a testament to the mineral's impact on the sample's mechanical properties, such as its strength and resistance to chemical weathering.

Secondary Peaks (26.7°, 44.8°, 49.1°, and 60.3° 2θ): These additional peaks further reinforce the prevalence of quartz in the sample. The high counts associated with these peaks suggest quartz is the dominant mineral, potentially constituting 50% or more of the sample's composition. This dominance is beneficial for applications requiring high durability and mechanical stability due to quartz's well-known hardness and chemical inertness.

Calcite ($CaCO_3$): Distinct Peak (32.57° 2θ): Calcite is represented by a prominent peak at 32.57°, with an intensity of about 10,000 counts, correlating to approximately 32.57% of the sample. Calcite's buffering capacity makes it valuable in neutralizing acidic conditions, making this sample advantageous in environments with fluctuating pH levels. Calcite's chemical properties can contribute to the material's reactivity and long-term stability in applications where soil or water conditions vary.

Halite (NaCl): Minor Peak (23° 2θ): Halite's presence is marked by a smaller peak with 7.5% intensity, suggesting a concentration of around 11.3%. As a soluble mineral, halite's inclusion hints at the sample's exposure to saline conditions in the past, possibly in an evaporative environment. Halite can affect the sample's response to moisture, as its dissolution in water can alter soil composition and stability in construction or geotechnical settings.

Other Quartz Peaks (44.8°, 49.1°, and 60.3° 2θ): Smaller peaks at these angles, contributing 4–10% each, provide further evidence of quartz's pervasive presence in different crystalline orientations. These minor peaks complement the primary quartz indicators, confirming that quartz is indeed the predominant mineral phase in the sample.

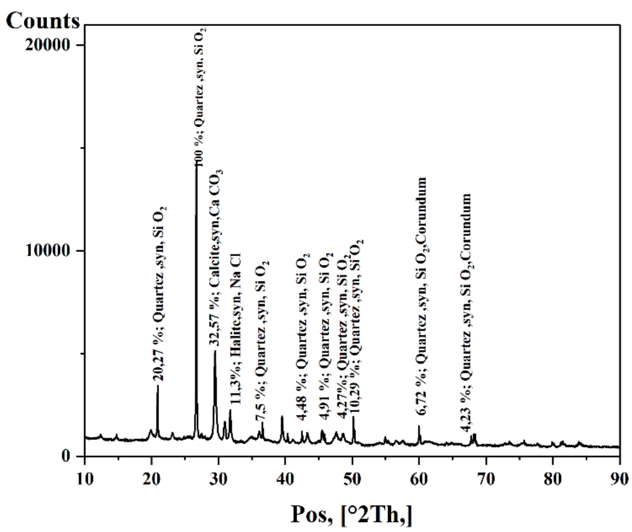

Figure 7. X-ray diffractogram of the studied clay

The XRD analysis revealed that quartz, calcite, and halite are the dominant minerals in Chott-El-Hodna clay. Quartz provides mechanical strength and durability, making it beneficial for load-bearing applications. Calcite enhances soil stability by contributing to cementitious bonding, particularly when combined with lime. Halite (NaCl) presence indicates high salinity, which can affect long-term durability due to potential salt crystallization and dissolution effects. Understanding these mineralogical characteristics is crucial for designing effective stabilization strategies, ensuring that the chosen binders complement the existing mineral phases to improve soil performance.

4.2.2 X ray fluorescence

Table 4 presents the chemical composition of Chott-El-Hodna clay, offering essential insights into its suitability for soil stabilization and geotechnical applications. The high silica (SiO_2) content of 37.555% plays a crucial role in enhancing soil strength and reducing plasticity. Silica contributes to the formation of strong soil aggregates, which help in minimizing shrink-swell behavior, making the clay more stable for construction purposes. Additionally, when combined with cement, silica reacts to form calcium silicate hydrates (C-S-H), which improve soil cohesion, durability, and overall mechanical performance.

The significant calcium oxide (CaO) content of 17.81% indicates the natural cementation potential of the soil. The presence of CaO supports pozzolanic reactions, particularly when lime or cement is introduced as a stabilizing agent. This reaction leads to the formation of calcium aluminate hydrates (C-A-H) and additional C-S-H phases, which enhance compressive strength, reduce permeability, and improve the long-term stability of the soil. The high CaO content also suggests that lime stabilization would be particularly effective in mitigating the expansive behavior of the clay.

Alumina (Al_2O_3) and iron oxide (Fe_2O_3), present at 8.69% and 3.735% respectively, contribute to mechanical strength, cohesion, and chemical reactivity in the soil matrix. Alumina is particularly reactive with lime, forming secondary cementitious compounds that improve soil bonding. Meanwhile, iron oxide enhances soil durability and resistance to external environmental factors, making the clay more suitable for load-bearing applications and construction materials. These oxides also play a key role in influencing thermal and chemical stability, which can be advantageous in road construction, ceramics, and structural engineering applications.

The presence of sulfur trioxide (SO_3) at 2.325% requires special consideration, as high sulfate levels can lead to undesirable expansive reactions in cement-stabilized soils. In humid environments, sulfates react with calcium hydroxide and aluminates to form ettringite, a mineral known for causing expansion, cracking, and long-term durability issues in soil stabilization projects. To mitigate this risk, sulfate-resistant cement or alternative stabilization methods should be considered when working with sulfate-rich soils.

The sodium oxide (Na_2O) content of 3.615%, along with a high loss on ignition (LOI) of 21.61%, indicates the presence of saline compounds and organic matter. High Na_2O levels suggest that the soil has some degree of salinity, which may affect soil-water interactions and the effectiveness of stabilization treatments.

The high silica and alumina content in Chott-El-Hodna clay supports pozzolanic reactions, making cement and lime highly effective stabilizers for improving soil strength and long-term performance. The CaO enrichment enhances cementation, particularly in lime-treated soils, helping to reduce swelling potential and improve the load-bearing capacity of the soil. However, SO_3 levels must be carefully monitored to avoid sulfate-induced expansion and cracking, especially when using cement-based stabilization. Additionally, the presence of Na_2O indicates salinity-related challenges, necessitating proper drainage and binder selection for maintaining long-term soil stability.

The XRF analysis confirms that Chott-El-Hodna clay is well-suited for stabilization using hydraulic binders, with cement providing structural reinforcement and lime improving chemical durability. These findings highlight the need for strategic binder selection based on specific geotechnical challenges, particularly in saline, expansive soils like those found in the Chott-El-Hodna basin.

Table 4. Chemical composition of Chott-El-Hodna clay

Element	Mass (%)
SiO_2	37.555
Al_2O_3	8.69
Fe_2O_3	3.735
CaO	17.81
MgO	3.195
SO_3	2.325
K_2O	1.465
Na_2O	3.615
Loss of ignition	21.61

4.2.3 Study of the physical performance of the soil/ Hydraulic binder mixture

Figure 8 presents the relationship between the liquid limit (W_l) and the plasticity index (I_p) for soil samples treated with various percentages of cement and lime.

Most samples, regardless of treatment type or percentage, fall within the low plasticity clay (CL) region, with relatively low plasticity indices (I_p) and moderate liquid limits (W_l) ranging between 25% and 50%. This classification implies that both cement and lime treatments effectively reduce the plasticity of the soil, likely making it less prone to swelling and shrinkage. None of the treated samples enter the high plasticity clay (CH) region, which would be characterized by higher liquid limits and plasticity indices. This confirms the effectiveness of both lime and cement in lowering the plasticity and stabilizing the soil.

According to the swelling potential classification, the treated samples mainly exhibit low to medium swelling potential. Lime-treated samples, especially at higher percentages, tend to position closer to the medium swelling potential boundary, while cement-treated samples tend to remain within the low swelling potential category. The difference in swelling potential between cement and lime treatments suggests that cement may slightly outperform lime in reducing swelling potential, which could be advantageous in regions where soil expansion poses a risk to infrastructure.

With higher treatment percentages, both cement and lime show a slight reduction in plasticity index (I_p), indicating further stabilization and reduced plasticity. For instance, at 10% and 12% dosages, the samples cluster toward lower plasticity values and liquid limits. Lime treatments tend to have slightly higher liquid limits than cement treatments at equivalent dosages, meaning lime-treated soils may retain more moisture before reaching their plastic limit. This characteristic could influence soil behavior under varying moisture conditions, potentially making lime-treated soils more susceptible to changes in water content compared to cement-treated soils.

The A-line, which separates low and high plasticity clays, serves as a reference for soil behavior upon wetting. All samples lie below this line, confirming that the treated soils remain within the low plasticity category, exhibiting lower potential for excessive deformation or volume change when wet. The clustering below the A-line emphasizes the stabilization impact of both binders, reinforcing the observation that cement and lime reduce the soil's susceptibility to moisture-induced plastic deformation.

Cement-treated samples show consistent performance in reducing both plasticity and swelling potential, making cement a suitable choice for applications where low plasticity and minimal response to moisture changes are critical. Lime, while effective, appears to lead to slightly higher liquid limits and swelling potential at equivalent dosages, which may suggest a different application focus. Lime could be better suited to soils that require moderate stabilization and where slight moisture retention does not pose a significant issue. The overall reduction in plasticity and swelling for both treatments enhance soil stability, making both lime and cement practical choices for foundational and roadbed projects where soil movement needs to be minimized.

The plot illustrates that both cement and lime treatments effectively transform high-plasticity soils into low-plasticity, low-swelling soils, enhancing their suitability for construction purposes. Cement proves slightly more effective in reducing swelling potential and plasticity, while lime retains a marginally higher liquid limit, indicating potential for moisture retention. These findings support the application of both treatments based on specific project needs, with cement favored for highly stable, low-swelling requirements and lime providing a viable alternative in moderate stabilization contexts.

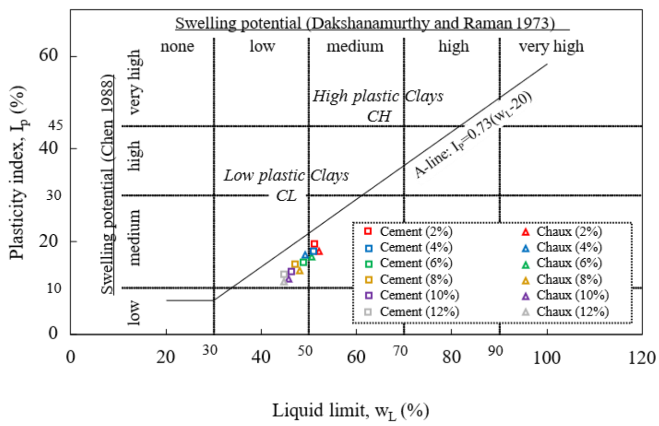

Figure 8. Treatment effect on the plasticity of the clay

Table 5 provides data on the bulk volume (Mbv in cm^3) and specific surface area (in g/cm^2) of soil samples treated with different percentages of cement and lime.

For both cement and lime treatments, the bulk volume (Mbv) decreases as the dosage percentage increases. This trend indicates a compaction effect, where higher concentrations of the stabilizer reduce the overall volume of the treated soil matrix. Cement-treated samples consistently show lower Mbv values compared to lime-treated samples at the same dosage levels, particularly at higher concentrations (8%, 10%, and 12%). For example, at 12%, the Mbv for cement is 4.33 cm^3, while for lime it is 3.56 cm^3. This difference suggests that cement is more effective at compacting the soil matrix, likely leading to increased density and stability. Specific surface area decreases with increasing dosages for both treatments, indicating a reduction in the reactive surface available in the soil. This reduction may be due to the binding agents filling voids and reducing the porosity, leading to fewer exposed surfaces. Cement-treated samples generally maintain higher specific surface areas than lime-treated samples at equivalent dosages, particularly at lower concentrations. For instance, at 2%, the specific surface area is 121.38 g/cm^2 for cement and 133.00 g/cm^2 for lime. This implies that cement might create a more consistent matrix with slightly higher surface reactivity at lower dosages, which could be beneficial in certain applications requiring moderate reactivity. As the dosage increases, the specific surface area for both treatments drops significantly, reaching 91 g/cm^2 for cement and 74.67 g/cm^2 for lime at 12%. This trend impliesthat higher dosages lead to a more compact structure, with fewer exposed surfaces, enhancing the soil's stability.

Table 5. Effect of treatments onmethylene blue value

Treatments		Mbv (Cm^3)	Specific Surface (g/cm^2)
2%	Cement	5,78	121.38
	Lime	6.33	133.00
4%	Cement	5,67	119,77
	Lime	4.89	102.67
6%	Cement	5,56	116,62
	Lime	4.56	95.67
8%	Cement	5	105
	Lime	4.33	91.00
10%	Cement	4,56	95,69
	Lime	3.67	77.00
12%	Cement	4,33	91
	Lime	3.56	74.67

At lower dosages (2%-4%), lime-treated samples show higher bulk volumes and specific surface areas than cement-treated samples. This may suggest that lime at these levels does not compact the soil as effectively as cement, allowing for more surface area and bulk volume. As the dosage reaches 8% and above, both the bulk volume and specific surface area values drop more sharply for lime than for cement. By 12%, lime-treated samples show significantly lower values for both Mbv and specific surface area, indicating that high lime concentrations lead to a compact, less porous soil structure. Cement, while also showing reduced values, maintains slightly higher bulk volume and specific surface area, indicating a balance between compaction and surface availability. The reduction in bulk volume and specific surface area with increased treatment dosage suggests improved compaction and structural coherence, which enhances soil stability. Higher dosages of both lime and cement lead to denser, less porous soil matrices, beneficial in applications requiring low permeability and high load-bearing capacity. Cement's ability to maintain slightly higher specific surface areas at lower dosages could be advantageous in applications where surface reactivity is essential for binding, whereas lime's sharper reduction in specific surface at higher dosages makes it suitable for creating highly compact, stable structures. The data reveal that both cement and lime treatments enhance soil compaction, as evidenced by reductions in bulk volume and specific surface area with increasing dosage. Cement maintains a slightly higher specific surface area at moderate dosages, indicating potential advantages in binding and reactivity. Lime, on the other hand, achieves a more compact structure at higher dosages, potentially making it more suitable for applications requiring maximum stability and minimal porosity. These distinctions guide the choice of stabilizer based on the specific structural and reactivity needs of the project, with cement providing balance at lower dosages and lime excelling in compaction at higher concentrations.

4.3 Study of the Physical performance of the soil/ hydraulic binder mixture

Table 6 presents the relationship between the dry densities (γ_d) and the optimal water content (W_{opt}) of soil samples treated with varying percentages of cement and lime. The table compares different hydraulic binders (cement and lime) at concentrations of 2%, 4%, 6%, 8%, 10%, and 12%.

For cement-treated samples, the dry density generally fluctuates slightly around values between 1.55 and 1.62 g/cm³, with the highest density (1.62 g/cm³) observed at an 8% cement concentration. This indicates that 8% cement may provide an optimal level for maximizing soil compaction. For lime-treated samples, the dry density values range from 1.53 to 1.60 g/cm³. There is a gradual increase in density as the lime concentration increases, with the highest values at 10% and 12%, both reaching 1.60 g/cm³. Lime treatments seem to require higher concentrations to achieve comparable densities to cement.

The optimal water content varies inversely with dry density for most of the concentrations, suggesting a typical soil compaction behavior where higher density is achieved with lower water content. Cement-treated samples exhibit higher optimal water contents than lime-treated samples at lower concentrations (2% to 8%), but as the concentration increases, the optimal water content tends to stabilize around 7.92-8.96%. Lime-treated samples show a decreasing trend in optimal water content as the lime percentage increases. The W_{opt} decreases from 8.42% at 2% lime to 7.11% at 12% lime, indicating that higher lime content reduces the amount of water needed for optimal compaction.

Cement tends to achieve slightly higher dry densities than lime at comparable concentrations, especially at the lower treatment percentages. This difference suggests that cement is more effective at compacting the soil, which is consistent with its ability to form stronger bonds within the soil matrix.

Table 6. Influence of hydraulic binder on optimum parameters of proctor test

Hydraulic Binder		γ_d (g/cm³)	W_{opt} (%)
2%	Cement	1.57	8.96
	Lime	1.53	8.42
4%	Cement	1.57	8.67
	Lime	1.56	7.38
6%	Cement	1.56	7.61
	Lime	1.57	7.99
8%	Cement	1.62	8.38
	Lime	1.58	8.37
10%	Cement	1.55	8.51
	Lime	1.60	7.164
12%	Cement	1.58	7.92
	Lime	1.60	7.11

The lower optimal water contents for lime at higher concentrations could imply that lime-treated soils require less water to reach optimal compaction, which may be advantageous in certain field conditions where water availability is limited. Cement appears more effective at improving dry density across a range of concentrations, which may enhance load-bearing capacity and stability for construction projects. However, lime may be preferred where lower water usage is beneficial, or where moderate compaction and durability are sufficient. The table suggests that cement is more effective for achieving higher dry densities, particularly at 8%, where the peak dry density is observed. Lime, on the other hand, lowers the water demand progressively at higher concentrations, potentially making it advantageous in drier environments or applications requiring moderate strength.

Figure 9 illustrates the relationship between the strength (kN) and depression (mm) of soil samples treated with varying percentages of cement and lime. The chart includes untreated samples (0%) as well as samples treated with 2%, 4%, 6%, 8%, 10%, and 12% of either lime or cement.

Behavior of Untreated Samples: The untreated samples (0%) demonstrate the lowest strength across all levels of depression. The maximum strength of the untreated samples does not exceed approximately 1 kN, highlighting the effectiveness of both lime and cement in significantly enhancing soil strength, even at low treatment percentages. Across all treatments, strength generally increases with increased depression, suggesting that as the material compresses, it resists the applied force up to a certain limit. This trend holds for both lime and cement treatments, although the rate and magnitude of strength increase vary depending on the treatment concentration. Higher concentrations of both cement and lime generally result in greater strength. For example, at the highest levels of treatment (12%), both lime and cement-treated samples exhibit significantly higher strength compared to lower concentrations. This indicates that increased binder content enhances the soil's load-bearing capacity, which aligns with typical expectations in soil stabilization projects. At each concentration level, cement-treated samples generally exhibit higher strength than lime-treated samples for the same depression value. This is particularly evident at higher concentrations (10% and 12%), where cement-treated samples reach strengths above 3 kN, while lime-treated samples, though improved, display relatively lower strength. This difference underscores cement's superior effectiveness in improving soil strength compared to lime. Depression values vary across the treatments, with untreated and lower-concentration samples reaching higher depression values at lower strengths. In contrast, higher concentrations of lime and cement reduce the range of depression, suggesting that these treatments improve soil stiffness, thereby limiting the extent of compression under applied load. At low depression levels (0–2 mm), differences between treatments are minimal, as the soil shows only slight resistance to the applied force. However, as depression increases, the distinctions between treatment types and concentrations become more pronounced, with cement-treated samples showing steeper increases in strength.

In summary, the graph indicates that both lime and cement treatments enhance the compressive strength of the soil, with cement treatments yielding greater strength improvements than lime, especially at higher concentrations. This insight is valuable for geotechnical applications where enhanced load-bearing capacity and soil stiffness are desired. Cement's superior performance suggests it would be the preferred choice when maximum strength and minimal depression are required, while lime might be suitable for projects where moderate improvement suffices.

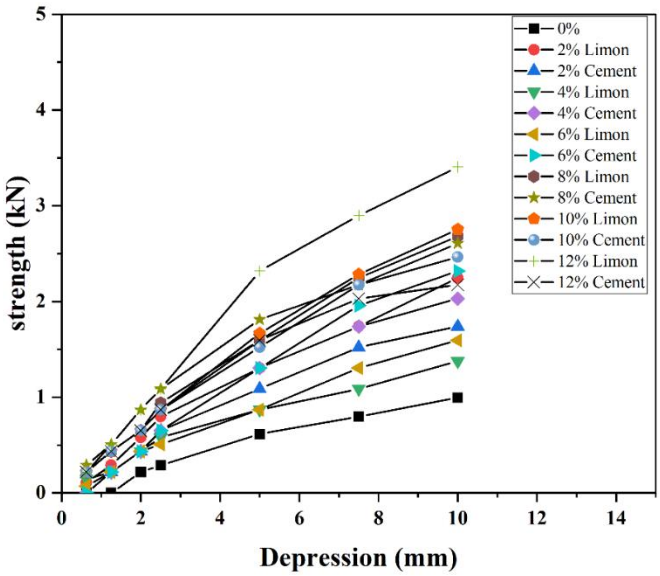

Figure 9. CBR Test results for clay and treatment mixtures

Table 7 presents California Bearing Ratio (CBR) indicators at immediate penetration depths of 2.5 mm and 5 mm, along with the maximum CBR index, for soil samples treated with varying proportions of cement and lime. The CBR test measures the strength of the soil and its load-bearing capacity, which is a fundamental property in geotechnical applications such as road construction.

For cement and lime treatments, there is a clear trend of increasing CBR values with higher dosage ratios, indicating that both additives enhance the soil's load-bearing capacity.

Lime treatment consistently shows higher CBR values compared to cement, especially at high concentrations (8% and 12%), indicating that lime may have a stronger stabilizing effect on soil strength compared to cement.

At a concentration of 2%, the lime-treated samples show a higher instantaneous CBR value at both 2.5 mm (5.965) and 5 mm (6.544) compared to cement. (4.88 and 5.453, respectively). These trends indicate that even at low concentrations, lime provides a better improvement in CBR compared to cement. For the 4% treatment, the CBR values are slightly lower for lime compared to cement, as cement maintains a constant CBR value of 4.88 in all cases, while lime decreases to 4.338. This decrease may indicate a variation in the effectiveness of lime at this specific concentration. At 8% and above, both cement and lime show significant improvement in CBR, with lime achieving notably higher values. For example, at 8%, the maximum CBR value for lime reaches 7.998 compared to 9.089 for cement, indicating that cement may start to outperform lime in specific high-load applications. At the highest concentration of 12%, the CBR value of lime reaches 11.634, while cement only achieves 7.998, reinforcing the superior performance of lime in terms of load-bearing capacity at this dosage.

The immediate CBR values at 2.5 mm and 5 mm for each treatment dose are very close to each other, indicating that both lime and cement contribute to consistently improving strength across penetration depths. The maximum CBR index closely aligns with the penetration index at 5 mm in most cases, indicating that the full potential of the treated soil strength is often realized within the depths of the initial loading.

Lime treatment appears to be particularly effective in enhancing soil strength at high doses, achieving the highest CBR values at 12%. This indicates that lime is highly suitable for applications requiring maximum load-bearing capacity, such as heavy pavements or base layers in road construction. Cement, despite its effectiveness, shows relatively lower CBR values compared to lime, which may make it less useful in cases where maximum load-bearing capacity is a priority. However, its consistent performance in CBR at low doses suggests that it may be useful in cases that require moderate strength without the need for high concentrations of materials.

CBR values indicate that both lime and cement effectively increase the load-bearing capacity of treated soils, but lime generally performs better at higher doses, reaching higher maximum CBR indices. The superior performance of lime at high concentrations makes it ideal for high-load applications, while cement provides stable strength improvements at lower doses. This comparison is valuable for selecting the appropriate stabilizing agent based on specific geotechnical needs, where lime is preferred for achieving maximum strength, while cement is preferred for achieving moderate and consistent improvements in soil stability.

Table 7. Index CBR of clay and treatment mixtures

Treatment		Immediate C.B.R Index at 2.5mm	Immediate C.B.R Index at 5mm	Max C.B.R Index
2%	Cement	4.88	5.453	5.453
	Lime	5.965	6.544	6.544
4%	Cement	4.88	6.544	6.544
	Lime	4.338	4.362	4.362
6%	Cement	4.88	6.544	6.544
	Lime	3.796	4.362	4.362
8%	Cement	8.135	9.089	9.089
	Lime	7.05	7.998	7.998
10%	Cement	6.508	7.635	7.635
	Lime	6.508	8.362	8.362
12%	Cement	6.508	7.998	7.998
	Lime	8.135	11.634	11.634

Figure 10 illustrates the relationship between the resistance (MPa) of soil samples and the dosage percentage of lime and cement used as stabilizing agents. Both lime and cement demonstrate a positive correlation between dosage and resistance, indicating that as the percentage of either stabilizer increases, the soil's compressive strength improves. However, the trends reveal some differences between lime and cement treatments at varying concentrations.

For both lime and cement, resistance increases progressively with higher dosages, highlighting the effectiveness of both binders in enhancing soil strength. This increase is particularly notable in the lower range (0% to 8%), where the resistance improves more steeply as dosage rises. Up to 6%, cement and lime show very similar resistance values, reflecting comparable performance in this range. However, at 8% and above, lime-treated samples begin to show slightly higher resistance than cement-treated samples, with lime reaching its peak at around 12% dosage. Beyond 8%, the resistance for lime continues to increase, peaking at a resistance level slightly above that achieved by cement at the same dosage. Cement resistance, while still improving with higher dosages, appears to increase at a slightly slower rate than lime in the higher dosage range.

For lime, resistance reaches its peak value just above 12 MPa at the 12% dosage, indicating a strong enhancement in strength. This peak suggests that lime performs exceptionally well at higher dosages, providing notable strength improvements. Cement, on the other hand, shows a smoother and slightly more linear increase across the dosages, achieving a resistance close to 12 MPa at 12% but not exceeding lime's peak value. Cement may therefore be beneficial where consistent, incremental improvement in strength is required rather than a high peak. The slightly higher resistance achieved by lime at 12% suggests that lime could be advantageous in applications where maximum compressive strength is required. The performance of lime at higher dosages may make it suitable for projects involving heavy loads or where long-term stability is paramount. Cement, while slightly lower in peak resistance compared to lime at 12%, offers consistent strength improvements, making it versatile for general soil stabilization needs. Its smoother resistance curve suggests it can provide reliable enhancements without sudden peaks, which may be beneficial in applications where uniform strength is desired.

Both lime and cement effectively enhance soil resistance with increased dosage, although lime appears to achieve a slightly higher peak resistance at the upper dosage levels. Lime's superior performance at 12% suggests its potential as a preferred stabilizer in projects requiring maximum strength, while cement offers a balanced and consistent improvement across dosages. The choice between lime and cement would therefore depend on the specific strength requirements and the project context, with lime being favorable for maximum strength and cement providing steady, reliable resistance improvements.

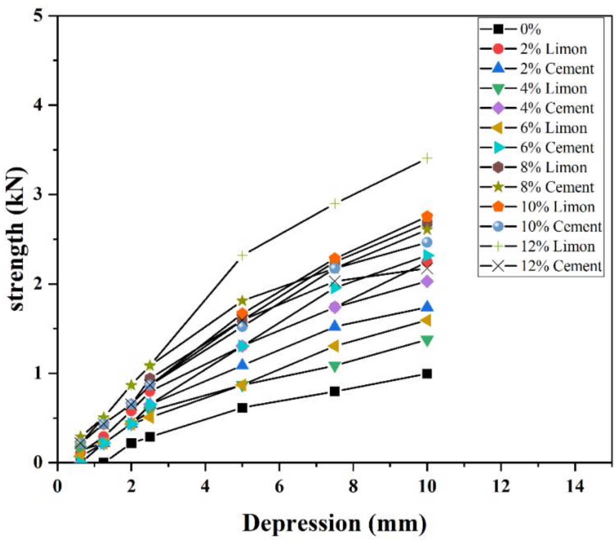

Figure 10. Effect of treatment on compressive strength

Figure 11 depicts the relationship between the speed (cm/µs) of ultrasonic waves through soil samples treated with various dosages of lime and cement. The ultrasonic wave speed provides insight into the material's density and elastic properties, often used as an indirect measure of stiffness or compaction quality in treated soils.

For both lime and cement treatments, there is a clear trend of increasing wave speed as the dosage percentage rises, suggesting that higher concentrations of these binders improve the density and stiffness of the soil. This increase in ultrasonic wave speed reflects a more compacted and structurally coherent soil matrix, as the binders facilitate stronger particle bonds within the soil. At lower dosages (0% to 4%), cement-treated samples exhibit a slightly higher ultrasonic speed than lime-treated samples, with cement reaching approximately 0.14 cm/µs at 4% compared to around 0.12 cm/µs for lime. This difference suggests that cement initially enhances the soil's density more effectively than lime at these lower dosages. As the dosage increases beyond 4%, lime-treated samples begin to match and eventually slightly exceed the ultrasonic speed of cement-treated samples. By the 12% dosage level, lime reaches a maximum speed close to 0.18 cm/µs, slightly outperforming cement, which levels off at around 0.16 cm/µs.

The results indicate that both lime and cement are effective at increasing soil stiffness, as demonstrated by the rising ultrasonic speeds. However, lime shows a slightly higher maximum value at higher dosages, suggesting that it may have a marginally superior ability to enhance the soil's structural coherence when used in greater quantities.

Table 8. Chemical composition of Chott-El-Hodna clay/ Hydraulic binder mixture

Element / Hydraulic Binder			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	L.O.I
Mass %	2%	Cement	38.69	8.96	3.93	17.31	3.33	2.12	1.51	3.65	20.5
		Lime	36.42	8.42	3.54	18.31	3.06	2.53	1.42	3.58	22.72
	4%	Cement	38.92	8.67	3.75	18.28	3.25	2.1	1.44	3.72	19.87
		Lime	37.78	7.38	3.45	20.43	2.91	2.37	1.32	3.41	20.95
	6%	Cement	38.17	7.61	3.73	19.52	2.97	1.89	1.36	3.41	21.34
		Lime	35	7.99	3.24	22.4	2.91	2.65	1.37	3.11	21.33
	8%	Cement	36.75	8.38	3.64	19.46	2.99	2.03	1.42	3.6	21.73
		Lime	37.63	8.37	3.59	19.61	3.09	1.88	1.24	3.46	21.13
	10%	Cement	37.94	8.51	3.84	19.41	3.06	2.06	1.48	3.29	20.41
		Lime	37.17	7.16	3.3	22.33	2.78	2.13	1.31	3.07	20.75
	12%	Cement	37.46	7.92	3.63	20.84	3.09	2.48	1.37	3.47	19.74
		Lime	33.83	7.11	3.06	24.19	2.59	2.21	1.33	2.86	22.82

Cement provides a more immediate improvement at lower dosages, making it potentially more suitable for applications requiring quick enhancements in density and stiffness without the need for high dosages. The higher ultrasonic speeds achieved by lime at higher concentrations (10% and 12%) imply that lime may be preferable in projects where maximum compaction and stiffness are desired, particularly when budget or material limitations are less of a concern. For applications requiring effective soil stabilization with moderate dosages, cement could be advantageous due to its higher performance at lower concentrations, allowing for quicker compaction improvements with less material.

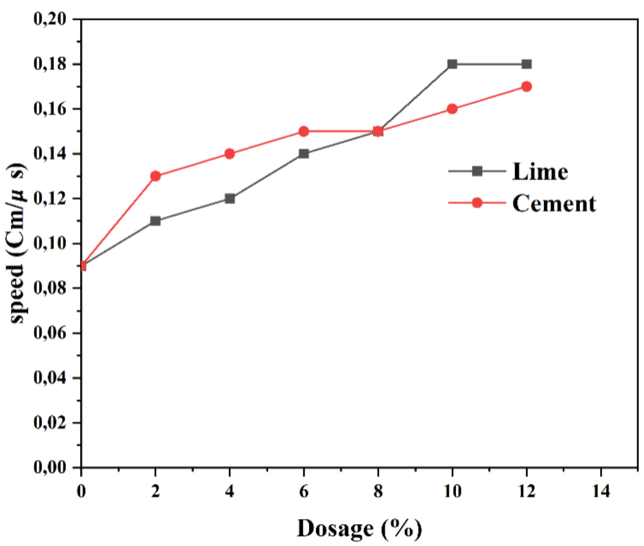

Figure 11. Speed of ultrasonic waves through soil samples treated with various dosages of lime and cement

The graph indicates that ultrasonic wave speed increases with dosage for both lime and cement, demonstrating the positive impact of these binders on soil stiffness and compaction quality. Lime ultimately achieves a slightly higher maximum wave speed at the highest dosage level, suggesting its suitability for high-strength applications. Cement, while not reaching the same peak, provides effective improvements at lower dosages, making it a practical choice for projects requiring moderate enhancements in soil density and stiffness without high material costs. These findings highlight the strengths of each binder, guiding the selection based on specific project requirements.

4.4 Study of the petrographic performance of the soil/ hydraulic binder mixture

4.4.1 X ray fluorescence

Table 8 showcases the mass percentages of various oxides in soil samples treated with different concentrations of cement and lime, highlighting the distinct impact each stabilizer has on soil composition. Observing the silica content (SiO_2), we see that it remains relatively stable across all treatment levels, with cement-treated samples showing marginally higher SiO_2 than those treated with lime. This stability suggests that cement binds slightly less silica than lime does, which may be due to the differing chemical interactions each stabilizer introduces to the soil matrix. Alumina (Al_2O_3) percentages decrease subtly as the treatment concentration increases, with cement-treated samples generally retaining slightly higher alumina values. This may indicate that cement has a minor tendency to preserve alumina compounds compared to lime, which could influence the soil's reactivity and cohesion properties. The iron oxide (Fe_2O_3) content remains consistent across treatment levels but tends to be slightly lower in lime-treated samples. Cement appears to retain more iron oxide, possibly due to the chemical binding mechanisms activated in the presence of cement. Calcium oxide (CaO) levels rise notably with higher lime concentrations, as expected due to lime's calcium-based composition. While cement also increases CaO levels in the soil, the effect is not as pronounced as with lime, underscoring lime's effectiveness in enriching soil with calcium, which can enhance durability and strength.

Magnesium oxide (MgO) shows minimal variation across both cement and lime treatments, indicating that MgO remains relatively unaffected by either stabilizer. This stability suggests magnesium oxide plays a limited role in the chemical reactions taking place within the treated soil. Sulfur trioxide (SO_3) content shows a slight reduction with increasing treatment concentrations, and lime-treated samples typically contain more SO_3, potentially due to sulfate impurities in lime. This fluctuation could affect the soil's long-term performance, particularly in sulfate-rich environments. Both potassium oxide (K_2O) and sodium oxide (Na_2O) exhibit slight decreases as treatment levels increase, with Na_2O showing a consistent reduction, especially in lime-treated soils. This decrease could indicate limited chemical interaction or potential leaching of these elements within the stabilized soil. Lastly, the loss on ignition (L.O.I) values generally increase as treatment concentrations rise, more prominently in lime-treated samples. This trend suggests that lime treatment encourages greater organic material decomposition, likely due to increased alkalinity.

In summary, cement and lime each impart unique changes to the soil composition. Cement treatment seems to bind silica and iron more effectively, providing structural reinforcement, while lime treatment notably enriches the soil with calcium and promotes decomposition of organic matter, enhancing its chemical durability.

5. CONCLUSIONS

Based on the comprehensive analysis of the experimental results the study's findings indicate significant potential for the use of hydraulic binders, particularly lime and cement, in enhancing soil properties. These stabilizers effectively reduce soil plasticity, increase compressive strength, and improve bearing capacity, essential for infrastructure stability in areas with challenging soil conditions.

In particular, the results highlight that lime, at higher concentrations, is especially effective in maximizing load-bearing capacity, making it suitable for applications requiring high structural strength, such as roadbed stabilization. Conversely, cement demonstrates consistent performance across various concentrations, offering a reliable option for applications needing moderate improvements in soil stability with controlled material costs. Additionally, the differential impacts on soil compaction, as observed in ultrasonic wave speed and density measurements, underscore the specific adaptability of each binder: lime for high-compaction requirements and cement for stable, incremental strength enhancements.

The petrographic analyses further corroborate the stabilizing effects of these binders on soil chemistry, with lime significantly enriching calcium content, essential for durability in saline environments. The X-ray diffraction results reflect a stable mineral composition, where quartz's predominant role aids in the mechanical strength, and the presence of calcite adds beneficial buffering properties against pH changes. These characteristics enhance the suitability of treated soils for use in high-demand engineering applications where stability and resistance to environmental variations are paramount.

This study provides valuable insights for optimizing soil stabilization in saline, expansive soils, guiding engineering practices to ensure lasting durability and resilience of structures. Future research could focus on long-term field tests to assess the performance of these stabilizers under variable climatic conditions, further solidifying their role in sustainable geotechnical engineering solutions.

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