Quicklime-stabilized Tuff and Clayey Soils for Highway A3 Construction in Northern Tunisia

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ABSTRACT

This study presents a comprehensive examination of the effects of quicklime (QL) addition on the stabilization of two distinct clayey soils with high (CH) and low plasticity (CL-tuff). The results showed that incorporating QL into the soils substantially improves their stabilization characteristics. Specifically, the addition of QL results in a notable decrease in the final water content of both soils, as shown by a reduction from 23.04 to 19.06% in CH and from 18.07 to 17.1% in CL-tuff at 4% QL addition. Furthermore, this study reveals a transformation in the plasticity properties of soils. Liquid Limit (LL) and Plasticity Index (PI) were reduced, with CH-tuff exhibiting a significant decrease in PI from 48 to 12 and an increase in Plastic Limit (PL) from 21.8 to 55 at 4% QL. CL-tuff also showed reduced plasticity, with PI decreasing to 8.33 at 4% QL. Additionally, the Immediate Bearing Index (IBI) was improved for both soil samples, indicating improved load-bearing capacities. For CH samples, IBI improved from 6.37 to 11.99 at 4% QL addition, while for CL-tuff, it increased dramatically from 4.5 to 23.6 for the same QL percentage. The findings underscore the effectiveness of QL in improving soil properties crucial for chemical stabilization, providing evidence that QL addition can be a key technique in soil stabilization, especially for soils with high plasticity or those requiring increased bearing strength.

Keywords-clayey soils; quicklime stabilization; soil plasticity; water content reduction; bearing capacity

I. INTRODUCTION

Clayey soils exhibit high sensitivity to variations in moisture content but are also subject to adverse impacts of environmental stressors, including climatic conditions, long-term static loading, and dynamic impacts. Therefore, stabilization of such soils, when used as road subgrade, requires remedial treatment to increase their strength properties and decrease permeability [1-10]. The use of quicklime (QL) for soil stabilization is a widely recognized technique [11]. Incorporating QL into fine-grained soils engenders a profound alteration in the soil's physicochemical properties. QL stabilization catalyzes the flocculation of cohesive soil particles, modifying the soil microstructure by inducing particle aggregation. The mechanism underlying this transformation is described in [12]. The increase of pore water-electrolyte concentration attenuates the diffused double layer upon lime addition, thus strengthening Van der Waals forces and initiating the formation of flocculent structures. This reorganization of the soil matrix fosters enhanced interparticle bonds, improving resistance to compaction efforts and leading to a higher Optimum Moisture Content (OMC).

The interaction between lime treatment and the permeability of expansive soils has been well-documented in recent studies. In [13], it was shown that lime modification initially increases the permeability of expansive soils, which stabilizes or slightly decreases with time. This behavior is due to the early effects of lime on soil structure, while the subsequent decrease is attributed to long-term pozzolanic reactions that create cementitious bonds. In [14], it was shown that treating clayey soils with lime and fly ash significantly reduces permeability, by up to 95% after a 14-day period, which is related to the reduction in the soil plasticity. In [15], a threshold for lime treatment was observed, as soil permeability decreased when lime content exceeded 4%.

In [16], Mercury Intrusion Porosimetry (MIP) was used to reveal a dual-pore structure similar to that of compacted clays, supporting previous studies [17-18]. The impact of cyclic wetting and drying was analyzed, revealing minimal initial changes in microporosity, trending towards smaller pore sizes. However, a pronounced increase in macroporosity was observed after multiple cycles of controlled suction, particularly with a QL content of 2%, implying a disruption of interparticle bonds, while microporosity remained relatively constant. This study illuminated several phenomena consequent to lime treatment: a reduction in volumetric change that illustrates the swell potential, an increase in stress sensitivity and bond formation through pozzolanic reactions, and the degradation of soil properties under severe wetting and drying cycles compared to more moderate amplitude cycles. Severe cycles were observed to induce irreversible swelling, whereas controlled cycles led to irreversible shrinkage. Despite exposure to varying wetting and drying cycles, the long-term mechanical property improvement of QL was not substantiated.

This paper investigates the stabilization effects of QL on soils with tuff content. The investigation delves into the macroscopic behavior of tuff-enriched clayey soils stabilized with QL, revealing substantial improvements in terms of moisture reduction, plasticity modification, and strength improvement. These advances are crucial for the reliable application of such soils in highway construction. By providing empirical evidence of the efficacy of QL stabilization in this context, this study opens new avenues for modeling and computational research in the field, empowering sustainable construction practices.

II. EXPERIMENTAL INVESTIGATION

This study investigated Proctor compaction, California Bearing Ratio (CBR), and Atterberg limits. The influence of initial parameters, such as water content and lime content, on macroscopic soil characteristics was examined.

A. Materials

The samples used in this study were extracted from the construction site of Highway A3 in Beja governorate, Northern Tunisia. The first sample was extracted from a subsurface stratum located between 3 to 5 m deep (a). The second was obtained from a shallower depth ranging from 1 to 2.5 m (b).

B. Physical Properties of Natural Soils

To obtain the Particle Size Distribution (PSD) of the two soil samples, sieve analysis (according to NF P94-056) and Hydrometer (according to NF P94-057) tests were carried out.

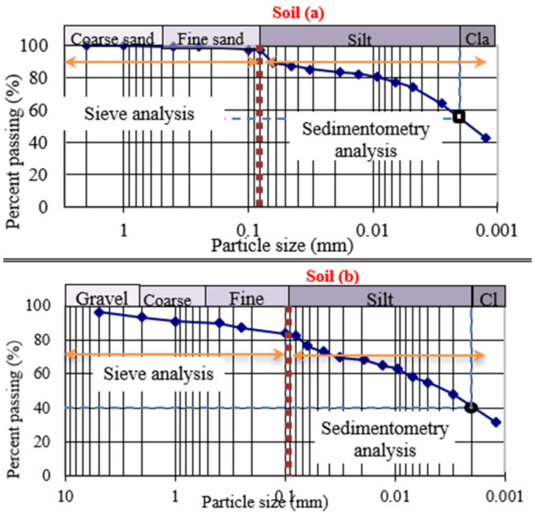

Fig. 1. PSD curves of the two soil samples.

Based on PSD results and the Unified Soil Classification System (USCS), soil 1 is identified as clay with High Plasticity (CH) with 55% of particles finer than 2 microns, and soil 2 as clay with Low Plasticity (CL) with tuff, with 40% of particles finer than 2 microns. The extension - tuff is purposefully added to remind the tuff fraction. From now on, the CH and CL-tuff notations will be used to designate the respective soils.

Methylene blue value (VBS) tests (NF P 94-068) were used to assess the swelling potential of the expansive clay. In [19], VBS tests carried out in two different clay fractions yielded a value close to 9, suggesting that both clay types exhibit expansive properties that require chemical stabilization. Similarly, in this study, chemical stabilization is required due to the high clay content and high plasticity of the two types of soils.

TABLE I. SUMMARY OF SOIL SAMPLES' PROPERTIES

Properties	**CH**	**CL-Tuff**
PSD properties		
Test sample weight (g)	398.71g	485.11g
Maximum grain size	2 mm	5 mm
Fraction passing #200	94%	80%
Atterberg limits		
Liquid limit (LL)	69.80	39.50
Plastic limit (PL)	21.80	18.50
Plasticity index (PI)	48.00	21.00
Methylene Blue Value	8.63	5.50

C. QL as Chemical Stabilizing Material

Lime, or calcium oxide (CaO), is a white, alkaline, crystalline substance produced by heating high-purity limestone (97-99% $CaCO_3$) in vertical kilns at 1100 to 1300°C. This process, which generates QL is exothermic, emitting significant heat and light while releasing carbon dioxide and water vapor. QL has a PSD ranging from 0.5 to 25 μm and is used in various industrial applications. Using locally sourced QL for soil stabilization promotes sustainability by reducing environmental impact and taking advantage of in situ soil improvement over material substitution. By improving the engineering properties of weak and problematic soils in situ, this study supports the sustainable practice of minimizing material transport and avoiding the ecological impacts associated with the extraction and import of alternative materials.

D. Experimental Method

The experimental program aimed to investigate the short-term effects of adding QL to natural silt and tuff soils. The study was conducted according to the following method:

- The humidification of 0/20 mm fraction of the samples at 3 or 4 water contents. The prepared samples were mixed with increasing QL content, varying from 1% to 4%.
- The determination of the Plasticity Index (PI) for each sample.
- Perform normal Proctor test to investigate the compaction properties and CBR test to determine the Immediate Bearing Index (IBI).

III. RESULTS AND DISCUSSION

A. Soil Initial Compaction Properties

Figure 2 shows the results of the normal Proctor test (NF P 94-093) for both soil samples before QL treatment. In road construction, compaction efforts typically aim to reach 95% of the maximum dry density ($g_{D,max}$), allowing for an optimal moisture content (ω_{OMC}) within a specific range, indicated as $\Delta\omega = [\omega_1\text{-}\omega_2]$. $\Delta\omega$ serves as a gauge measure of the soil's reaction sensitivity to increases in water content. For instance, $\Delta\omega$ values for CL-tuff and CH were 6% and 13%, respectively, indicating that clayey CH is more sensitive to changes in water content than CL-tuff. This is evident from the compaction tests, where the tuff reaches higher dry densities with increasing water content. Despite clay's tendency to be water-sensitive, these results suggest counterintuitive behavior. When considering the wide variance in water content requirements as shown by the two Proctor compaction curves, it is crucial to precisely determine the optimal lime percentages to be added based on these findings.

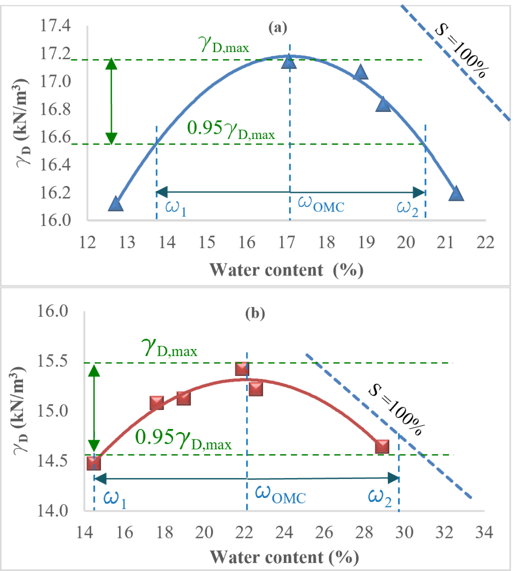

Fig. 2. Standard Proctor compaction curves for (a) CL-Tuff and (b) CH.

B. Soil Initial Swell Potential

The swelling potential is measured by recording the soaked specimen's volume change over a soaking period, with the peak increase observed after four days of immersion. For detailed design procedures for field soil-lime QL stabilization on roadbeds and railway embankments, the interested reader may refer to the relevant guidelines in [19-20]. Figure 3 shows that the swelling of the silty CH is 6%. However, as expected, the volume increase of CL-tuff is too low (0.66%, almost 1/10 of that of CH). This soil is not expansive, because the soil contains a tuff fraction and contains a lower fraction of clay than the CH, and consequently its plasticity is also lower.

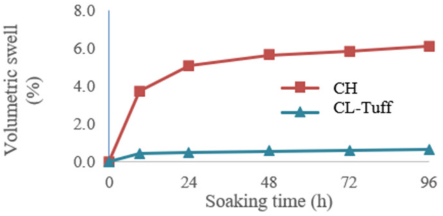

Fig. 3. Variation of volumetric swell as a function of the soaking time.

C. Soil Initial Bearing Properties

The CBR test was conducted according to NF P 94-078 and the values were obtained for the two soils on the wet side. This choice is supported by previous studies that reported that the expected compaction state in the field is performed nearly at the maximum dry density and then an increase in water content can occur by water infiltration, simulating in this manner the wetting path. However, the hydric cycle as wetting-drying was not investigated here, and some expected trends of CBR may be correlated with the uniaxial compressive strength given in [8, 16, 21]. Figure 4 provides IBI values that gradually decrease as the moisture content of soil samples increases. The results show a high sensitivity of the CBR to water content. For CH, a 6% increase in water content, from 18 to 24%, leads to a 81.7% decrease in CBR. It can also be noted that for the water content closest to the normal Proctor optimum, the CBR value is close to 5. For CL-tuff, an increase in the water content of 12% causes a decrease in CBR of 76.56%. Therefore, the CBR values of the CL-tuff soil decrease more rapidly than those of CH. This fact is explained by the potential dissolution of the tuff in the water which results from the interparticle bonds being broken.

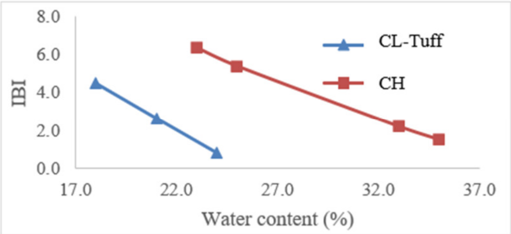

Fig. 4. Variation of CBR as a function of water content for both soils.

D. Hydric and Plasticity Properties of Treated Soils

Soil samples exhibiting a higher water content, identified as being on the wet side, were prepared and then treated with varying amounts of QL, 1% to 4% of the soil sample's weight. Figure 5 shows that the final water content in the soil decreases with increasing lime content. This trend is observed in both soil types and is due to the addition of dry QL particles and the exothermic nature of the QL-soil hydration reaction, which together promote moisture reduction in the soil. CL-tuff samples exhibit a significant decrease in water content. This can be attributed to the reduction of the soil's affinity for water, which is a consequence of the pozzolanic reaction. The pozzolanic reaction facilitates the binding of flocculated soil particles, thereby diminishing the soil's ability to retain water [22-25]. The pozzolanic reaction is also associated with the absorption of water by solid tuff particles.

For clay soils, the reduction in water content with the addition of QL is less pronounced compared to CL-tuff, which can be primarily attributed to the pozzolanic reactions that promote increased flocculation in soils with a high clay content. This phenomenon is supported by the findings in [26], where an experimental investigation in low-plasticity fine soils revealed that a 4% QL content is optimal for stabilizing pH at a constant value, indicating a saturation point in calcium concentration. It is anticipated that the increase in pH would be more significant in CL-tuff because of a more energetic alkaline reaction (e.g. cation exchange and pozzolanic reactions). Regarding the plasticity properties, the addition of QL increases the plasticity limits of both soil types without significantly altering their liquid limits, as shown in Figure 6.

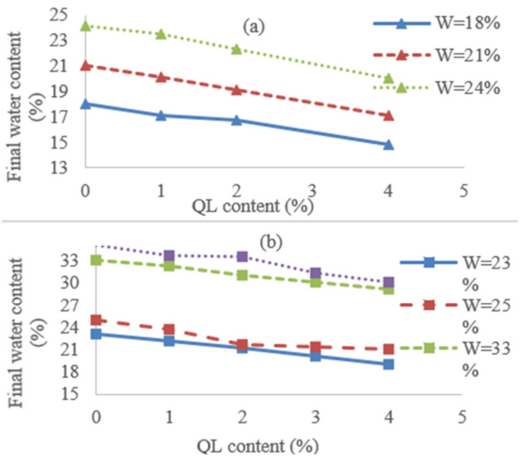

Fig. 5. (a) Tuff and (b) clayey silt hydric conditions after treatment.

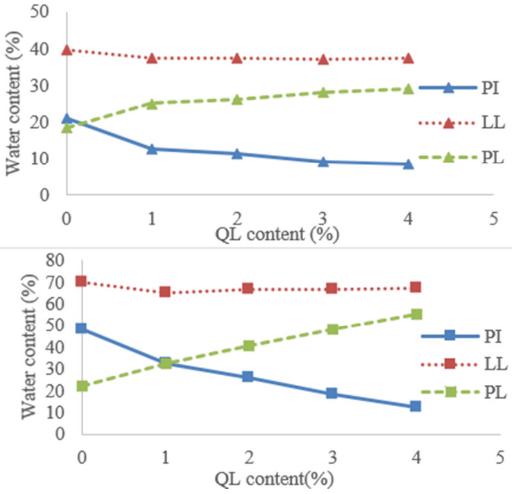

Fig. 6. Effect of QL addition on (a) tuff and (b) silt plasticity.

The increase in plasticity limit stems from QL-induced flocculation and cementation, which promote bond formation via pozzolanic reactions. With higher QL dosages, these reactions intensify over time, broadening the soil's solid range and consequently lowering the plasticity index. With a 2% QL dosage applied to CL-tuff, there is a discernible alteration in PI, with variations reaching up to 45%. In the case of CH, PI experiences a significant change of 62% at 3% QL dose. Such changes in the plasticity state significantly modify the soil's behavior, transitioning it from low to higher consistency. Figure 6 shows that both soil samples undergo a considerable decrease in their respective PI after QL treatment. This reduction reflects the transformative impact of QL on soil consistency, irrespective of the initial textural differences.

E. Effect of Lime Addition on Methylene Blue Value (VBS)

Figure 7 shows the results of a chemical analysis carried out on CH after QL addition to determine VBS. Soil VBS significantly decreased by 60% with 2% QL content and further decreased by 75% with 4% QL. This reduction in VBS underscores QL's effectiveness in mitigating the reactive clay fraction within the soil. At 2% QL content, the swelling potential of the soil was markedly reduced, leading to a decrease in volumetric changes. The optimal QL content for soil stabilization must consider the full range of parameters investigated in this study.

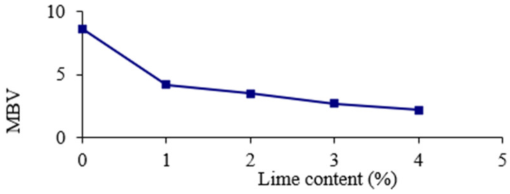

Fig. 7. Variation of VBS for lime content on the clayey silt.

F. Effect of QL on Immediate Bearing Index (IBI)

IBI testing, according to the NF P 94-078 standard, was carried out on both soils with moisture contents exceeding the optimum Proctor values of their untreated counterparts. These moisture contents were then used as a baseline for the stabilization study. As shown in Figure 8, the application of lime treatment significantly improved the IBI of the soils, demonstrating its positive effect on soil-bearing capacity. For both soils and at constant moisture content, IBI increases considerably with the addition of QL.

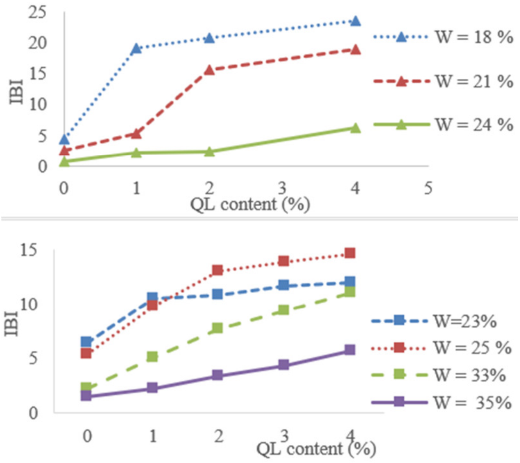

Fig. 8. Variations in IBI with lime addition for (a) tuff and (b) clay.

Without treatment, CH had a better IBI than CL-tuff soil. However, after treatment, CL-tuff achieved a higher IBI. Therefore, it seems that treating this soil can lead to better results. The presence of undesirable elements in CH impedes the kinetics of setting and hardening of the QL-soil mixture and, therefore, the performance of the treated soils. For CL-tuff and all QL content, IBI values decrease with increasing moisture content. This decrease is significant, reaching 89% for a moisture content variation between 18 and 24% (moisture content greater than OMC). For CH, the IBI does not always decrease with increasing moisture content. Starting with a QL content of 2%, there is an increase in IBI between a moisture content of 23% and 25%. Beyond 25%, IBI decreases again. This can be explained by the fact that for a moisture content of 23% and a QL content of more than 2%, the final moisture content of the mixture is lower than the OMC. Therefore, for the same compaction energy, the mixture is less compact and has a lower load-bearing capacity than a mixture with an initial moisture content of 25% that reaches the OMC after treatment.

G. *Effect of QL on Clayey Silt CBR*

Figure 9 shows that CBR was improved by adding QL. According to [19-20], the CBR for soaked samples up to 7 days should be greater than 30 for embankments 2m deep or shorter. The CBR values increase with the width of the embankment. This means that when soaking for 4 days and CBR is around 25, a greater value can be reached for this type of soil with QL immersed for more than 4 days. A minimum value for low-lime content should be more than 2%. Therefore, a very small amount of QL, such as 2% or more, improves the strength of a low plasticity CL-tuff soil.

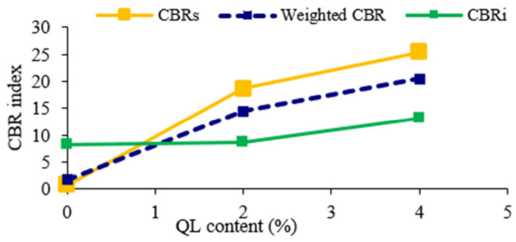

Fig. 9. CBR variation with QL content.

IV. CONCLUSION

The current study demonstrated that the addition of QL benefits soil stabilization, highlighting how it effectively reduces moisture content, modifies plasticity, and improves strength. The reduction in moisture content achieved through QL addition suggests a lower susceptibility of stabilized soil to weather-induced degradation, which is crucial to maintaining the integrity of highway foundations. The modification in soil plasticity, characterized by reduced liquid limit and plasticity index, results in a decreased potential for expansion and contraction, thus offering a more stable base for pavement layers. Finally, improved strength, as indicated by the increase in the immediate bearing index, implies a greater ability to support the heavy loads experienced by highways. These improvements directly correlate with the requirements for materials used in highway applications, thereby affirming the suitability of the treated soils for such purposes. Furthermore, they collectively indicate that QL stabilization makes the soil more resilient and reliable for highway construction, ensuring long-term performance and reduced maintenance costs.

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