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Experimental Study of the Dynamic Behavior of Stabilised Marl with Lime

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Abstract

The variable characteristics of weathered marl cause engineering problems, particularly in geotechnics, and require in-depth studies to design structures. Where these characteristics are poor, lime is used to stabilize the soil. Experimental research is being carried out on various Tizi-Ouzou marls composed of different percentages of $CaCO_3$. The aim is to study their behavior in the presence of quicklime and its impact on the evolution of their geotechnical characteristics to provide effective and economical solutions for stabilization. These marls are mixed with increasing percentages of lime and subjected to a series of tests in which cyclic shear is essential for simulating dynamic effects. The results obtained confirm the improvement in their geotechnical characteristics. On the one hand, interstitial pressures and cyclic deformations have decreased, thus avoiding the risk of liquefaction, subsidence, or settlement. On the other hand, cyclic stresses and resistances have increased, resulting in better resistance of these stabilized marls to dynamic stresses. Finally, the number of cycles required to reach failure has increased, thus reducing the risk of pavement damage. These results depend primarily on the percentage of $CaCO_3$ in the marl.

Keywords: Marl; $CaCO_3$; Tests; Treatment; Stabilization; Behavior.

1. Introduction

Marl is a soft sedimentary rock formed by varying proportions of clay and limestone. It forms a family of soils between these two components: it is called clayey marl if it contains 5 to 35% calcium carbonate ($CaCo_3$), marl proper, where the percentage of calcium carbonate ($CaCo_3$) is between 35 and 65%, and marly limestone if it contains 65 to 95% calcium carbonate ($CaCo_3$). When extracted and in contact with water, marl can change in nature or structure and is one of the so-called 'evolving' materials [1]. These sensitive soils are the most exposed to the propagation of random waves, which lead to loss of cohesion and, therefore, loss of resistance, resulting in liquefaction, subsidence, or settlement. For several years, lime has been used as one of the most economical techniques for stabilizing this soil type, improving its characteristics and mechanical behavior. The geotechnical characteristics of these soils are often highly variable, depending on their mineralogical nature, and lime's stabilization significantly impacts their improvement [2].

Every year, the construction of roads, railways, airports, and waterworks requires the availability of several million cubic meters of aggregates, and no one is unaware of the shortage of these materials and their high cost. Lime offers the possibility of recovering different types of soil that are usually considered unsuitable. Several authors have shown that soil flexibility and mechanical performance are improved by lime treatment [3]. On the other hand, the effects of lime on soil hydraulic conductivity depend on the compaction conditions [4].

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2. Literature Review

The work of Haddad et al. (2022) [5] highlighted the direct link between calcium carbonate ($CaCO_3$) content and water content with the rate of degradation of marl and estimated its sensitivity to water variations. Materials containing sufficient well-bonded CaC03 grains (65%) hardly change. They showed that the results of the observation of accelerated weathering in the laboratory agree with those observed in situ. The marl block breaks into several pieces due to climatic factors. The repeated action of freezing and thawing by alternating night and day generated stress that led to damage or even breakage of the marl structure. Therefore, water appears to be the principal agent responsible for altering the marls. This process is accelerated when combined with humidification-drying and freeze-thaw cycles. These alterations effectively affect the material from the very first cycles. Given this, we thought it would be helpful to stabilize the material with lime and see how the cycles affected this stabilization. Seco et al. (2011) [6] investigated the stabilization of grey marl from the Pamplona region of northern Spain using a combination of additives, including lime, magnesium oxide (obtained from a commercial by-product called PC-7), rice husk fly ash (RHFA), coal fly ash (CFA) and aluminate filler (AF). In addition, the soil samples were treated with a non-standard stabilizer called Consoled System (CS), which comprised both liquid and solid phases.

Lime has long been used to enhance its strength parameters as a soil stabilizer. Certain factors affect the reactions involving additives, including the percentage of additives, curing time, curing temperature, and mineralogy. Another important aspect of this study is understanding the phenomena that govern the reactions between the soil and the additives. A review of the literature on various aspects of soil stabilization is presented. Soil stabilization with lime is a practical and economical solution. It also helps to protect the environment by minimizing the extraction of other materials (natural resources) and limiting the opening of quarries and depots, thus mitigating the project's impact on the natural environment. Lime also contributes to minimizing pollution in water treatment, destroying pathogenic germs, and absorbing and neutralizing Sulphur oxides from these gases.

Several life cycle assessment (LCA) studies have been carried out, confirming that the environmental impact of using lime as a stabilizer is much lower than that of traditional methods. For best results, we recommend using a very fine quicklime to ensure optimum reaction with the soil. This operation produces dust during spreading and mixing. If the site is far from residential areas, lime will not cause any problems, as it is widely used to improve farmland. If the site is close to homes or public places, precautions should be taken to minimize the amount of dust, which is unpleasant for humans. It is advisable to avoid spreading lime on windy days. In our case, stabilizing the marl with lime will not cause any environmental problems compared with traditional methods. When quicklime is added to soil, four types of reactions occur cation exchange, flocculation and aggregation of clays, carbonation of lime, and pozzolanic reactions between lime, silica, and alumina [7-9]. When lime is incorporated into moist soil (moist marl), three essential physicochemical processes occur: (1) hydration and ionization of the lime; (2) modification of the cation exchange capacity (CEC) [10] leading to flocculation/aggregation of the clay particles [11]; and (3) development of pozzolanic reactions: reactions between lime, silica (SiO_2), and alumina (Al_2O_3) contained in soil particles, creating cementitious products (C-S-H, C-A-H, C-A-S-H) that bind soil particles together [12, 13]. Carbonation can also occur, depending on the conditions in which the treatment is carried out.

Basma & Tuncer (1991) [14] have indicated that adding hydrated lime between 2% and 8% is the optimum quantity for soil stabilization. Lime's properties are expressed through its application by its acceleration in structural modification, which improves the soil's geotechnical properties while maintaining its nature. The study conducted by Imelhaine (2009) [15] on stabilizing lime and cement-weathered marls found that these marls respond better to lime treatment than cement. Bahadori et al. (2019) [16] have shown that the effectiveness of stabilized marls increases with increasing volcanic ash content. This increase depends on the length of the cure. In addition, the effect of silica on the stabilization of marl soil samples is significant. Seco et al. (2011) [6] investigated the stabilization of grey marl from the Pamplona region of northern Spain using a combination of additives, including lime, magnesium oxide (obtained from a commercial by-product called PC-7), rice husk fly ash (RHFA), coal fly ash (CFA), and aluminate filler (AF). In addition, the soil samples were treated with a non-standard stabilizer called Consolid System (CS), which comprised both liquid and solid phases.

James & Sivakumar (2022) [17] researched soil stabilization with lime and found that it is one of the most common methods adopted for fine-grained soils compared to coarse-grained soils. They also noted that quicklime appeared to be the most effective because of its rapid reactivity compared with other types of lime and that the purity of the lime affected its performance. The presence of sulfates in the soil in significantly high concentrations makes the soil unsuitable for lime stabilization. Driss et al. (2023) [18] studied the influence of lime addition on the geotechnical properties of Algerian expansive clay soil (fat clay) with high plasticity. The clay was mixed with a variation of lime (2, 4, and 6%); the results confirmed that adding the latter increased the pH value, which signifies the start of a chemical reaction between the clay and the lime. There was also an increase in the liquidity and plasticity limits, leading to a decrease in the IP plasticity index. Mechanical tests confirmed the reduction in the swelling rate as the lime content increased and the curing time increased.

Aqel et al. (2024) [19] studied the potential of using lime to stabilize the soil of a dam against internal erosion, known as channelling, which presents a significant risk of structural damage. The study was conducted on two clay soil types with quicklime additions ranging from 0% to 5%. The results confirm that the critical shear stress and the erosion index (IHET) increase as the percentage of lime and the curing time increase, confirming their resistance to internal erosion and the soil stabilization against the pipe. They also noted that lime is more effective with clays than clays containing sand; in their results, for 2% lime added and a curing time of 48 hours, stabilization is obtained for clays, unlike clays containing sand; stabilization is obtained at 5% and 48 hours of curing. They concluded that an increase in the percentage of lime will significantly reduce the final diameter of the water trajectory of the samples for the two types of clay soil studied.

Weng et al. (2024) [20] carried out a study on the compressibility of lime-treated dredging sludge with a high water content, using three re-molded sludges in south-east China treated with lime and high water content. Sixty odometers were carried out with a variation in initial water content of 1 to 3 times the yield strength, increasing lime content from 1% to 3%. The results showed that the yield strength of lime-treated soil increased with increasing lime content and decreased significantly with increasing water content. The optimum lime content of the soil varied significantly with water content. When lime is added to clayey soils, their plasticity changes. On the one hand, the liquidity limit (WL) decreases, whereas the plasticity limit (WP) increases, and consequently, the plasticity index (Ip) decreases [3, 21-24]. This addition also reduces swelling [25]. The effects of lime powder and nanoparticles on the properties of kaolinite clay were studied [26]. The results showed that lime stabilization improved the compaction of clay soils. Adding small lime nanoparticles increased the CBR values in the soil samples.

Kavak & Akyarlı (2007) [27] stated that the California Bearing Ratio (CBR) of brown and green clay is improved with the addition of a sufficient 5% lime, making it useful for road embankment construction. The effects of lime powder and nanoparticles on the properties of kaolinite clay were studied [26]. The results showed that lime stabilization improved the compaction of clay soils. Adding small lime nanoparticles increased the CBR values in the soil samples. Kulanthaivel et al. (2021) [28] observed that the addition of a lower percentage of lime nanoparticles compared to lime powder (1% versus 4% by weight) had a more significant impact on the compressive strength of modified clay soils. Compared with lime powder, lime nanoparticles increase the compressive strength of modified clay soils more quickly. In addition, the lime-modified soil samples reached their maximum compressive stress at lower creep levels.

Salih & Shafiqu (2024) [29] studied the impact of lime on an expansive soil composed of 60% clay and 40% bentonite. The results confirm the decrease in soil density and plasticity index, the latter being reduced from 56% to 23% for an addition of 9%. The optimum moisture content increased from 22% to 25%, while the optimum dry density decreased from 1.473 g/cm³ to 1.353 g/cm³. This study reported that the swelling rate was improved, with a decrease, and also confirmed that with this addition, the CBR value increased with the increase in the percentage of lime. The compression and swelling indices also fell. These results were also confirmed by Muhammad et al. (2024) [30], whose study was carried out on clay; he found that with lime, the optimum water content increases and the optimum dry density decreases.

Sambre et al. (2024) [31] carried out a study on the sustainable stabilization of expansive soils through the addition of lime and fly ash, using soil samples from Nashik, Maharashtra, India, to analyze their geotechnical characteristics, including their high plasticity and expansive nature. This study showed that adding these lime and fly ash mixtures impacts the soil index, technical properties, and swelling behavior. Increasing these mixtures reduces the swelling rate and plasticity index, and the CBR value also increases with an increase in the proportion of lime in the mix, indicating a gradual increase in the strength of these soils. They found that increasing the fly ash content decreased the unconfined compressive strength, whereas adding lime increased it.

Several studies have shown that shear parameters (angle of internal friction and cohesion) change with the addition of lime [32, 25, 33, 34]. Another study reported that the angle of internal friction does not depend on the curing time; it evolves through the process of flocculation/aggregation rather than the crystallization of cementitious products over time and, therefore, does not depend on the curing time [25, 33]. Most cyclical tests have been on sands and a few on clays. Very few tests have been carried out on materials between the two. In addition, virtually no work has been done on the dynamic effect of stabilized materials. Among the works on the dynamic impact, we shall mention the main ones:

Bahadori et al. (2019) [16] have shown that the efficiency of stabilized marls increases with increasing volcanic ash content. This increase depends on the length of the treatment. In addition, the effect of silica on the stabilization of marl soil samples is significant. Andersen's (2004) [35] work has shown that the cyclic strength of cohesive soil and the amplitude of cyclic shear are related. The decrease in strength and the number of cycles required to reach failure is caused by the increase in shear stress. Studies carried out on a very plastic clay (WL = 104% and Ip = 63%) treated with lime have confirmed that soil cementation modifies the stress-strain curves and the mode of failure; the ductile mode of failure for low dosages and short curing times changes to a brittle mode of failure with the increase in these two parameters and the elastic modulus Balasubramaniam (1989) [33] and Balasubramaniam et al. (2005) [34].

Jessie (2016) [36] conducted cyclic simple shear tests on two Canadian clays at constant volume. The results obtained show stress-strain curves whose stress path initially presents closed hysteresis loops and whose deformation development is slow and then gradually opens up in the form of 's'; she noted that the amplitude of the stress and the number of cycles to reach the same level of deformation have a proportional relationship.

Several cyclic constant volume Simple shear tests were carried out on a sensitive Beauharnois clay by Mustapha (2017) [37]; he noted that deformation occurs in two parts: the first is elastic with low deformation and slow development, almost linear with the number of cycles until it reaches 2% to 3%, and the second part is elastoplastic, whose increase in deformation is sudden and irreversible, whose hysteresis curves take the form of an S and open up more and more with irreversible deformation and are increasingly significant. The yield point is created by the passage from the first part to the second; it is the point where the radius of curvature is the minimum that connects them. Mustapha (2017) [37] also observed during these tests, on the one hand, a strong generation of interstitial pressure in the early stages and also that the increase in the latter is slow with the number of cycles; on the other hand, the increase in this interstitial pressure leads the effective stresses towards the failure envelope without reaching 100% of the vertical stress, in other words, without the effective vertical stress cancelling out ($\sigma'v = 0$).

The work of Boulanger et al. (2006) [38] confirmed that the mode of failure, on the one hand, for sands is caused by the phenomenon of liquefaction under cyclic stress and, on the other hand, for cohesive soils, failure occurs through cyclic softening. Boulanger et al. (2006, 2004) [38, 39] have shown that cohesive soils have a plasticity index of 7% so that the failure mode may be liquefaction, identical to the failure mode of sands. Soils with an Ip greater than 7% have a behavior similar to that of clays, and they can develop cyclic softening. Soils with an IP of less than 7% present a risk of liquefaction and are identical to sands. Andersen (1975) [40] reported that failure for undrained cyclic single shear tests is based on shear strains when $\varepsilon = \pm 3\%$. Malek et al. (1989) [41] reported that failure occurs when the effective vertical stress path reaches the static failure envelope. Other authors have verified this notion with triaxial tests [42-45].

By comparing the cyclic behavior of silty sand with the cyclic behavior of cemented sand containing cement and nano clay additives, Mollaei et al. (2023) [46] showed that the shear modulus values of cemented sand samples with a water/cement ratio of 1 are higher than the shear modulus values of silty sand samples in all shear strain ranges. The shear modulus values increased when cement was replaced by nano clay in the cemented samples, and vice versa; the damping of the samples decreased with the addition of cement. On the other hand, as the confining pressure increased, the shear modulus values of all the soils considered increased, and their damping decreased.

This work aims to study the impact of lime treatment on the dynamic behavior of marl soils in Tizi-Ouzou. In their natural and stabilized states, numerous simple cyclic shear tests were conducted on different $CaCO_3$ marls. To analyze and understand their behavior, we varied the following parameters: the cyclic stress, the number of cycles, and the nature of the different $CaCO_3$ marls.

3. Origin and Properties of the Materials Used in the Study

The marl was extracted in blocks during the earthworks for each site at different locations and depths in the Tizi-Ouzou region (Figure 1).

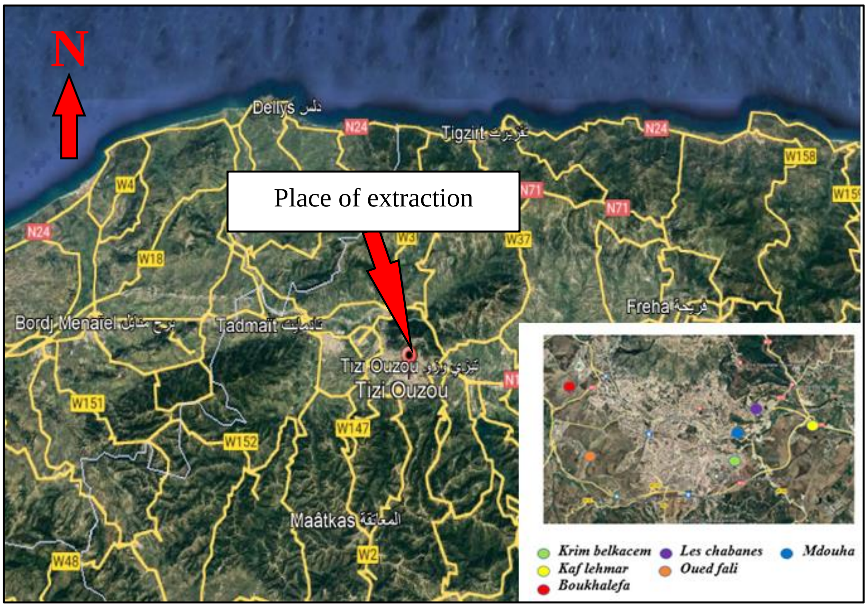


Figure 1. Extraction sites for samples of different marls from the Tizi-Ouzou region, Algeria

3.1. Chemical Characteristics

Table 1 shows these marls' chemical characteristics of VBS, $CaCO_3$, chloride, sulfate, and organic matter content.

Table 1. The chemical characteristics of the marls studied

Site	VBS	Soil Designation	CO_2 (%)	$CaCO_3$ (%)	Soil Designation	Cl^- (%)	SO_4^- (%)	MO (%)
Krim Belkacem	0.76	Loamy soil	10.29	23.39	Marl clay	0.36	0.15	trace
Les Chabanes	1.10	Loamy soil	22.00	50.00	Marl	0.33	0.141	trace
Kaf Lehmar	3.62	Clay soil	9.94	22.58	Marl clay	0.44	0.09	trace
Mdouha	1.35	Loamy soil	23.42	53.23	Marl	0.49	0.20	trace
Oued Fali	3.97	Clay soil	8.52	19.35	Marl clay	0.44	0.12	trace
Boukhalfa	3.47	Silty Clay soil	9.23	20.97	Marl clay	0.41	0.209	trace

The results obtained after conducting chemical tests on these different marls confirm that they are classified as inorganic and non-aggressive soils. According to the $CaCO_3$ levels obtained, the marls at the Krim Belkacem, Oued-Fali, Boukhalfa, and KafLehmar sites are classified as clayey marls, and those at the Les Chabanes and Mdouha sites as marly soils. According to the VBS tests, the marls at the Krim Belkacem, Les Chabanes, and Mdouha sites are classified as silty soils, the marl at the Boukhalfa site as silty clay soil, while the marls at the Oued-Fali and KafLehmar sites are classified as clay soils.

3.2. Physical Characteristics of the Marls in the Study

A program of tests to help identify marl materials, including wet, dry, and solid particle weights, water content, porosity, Atterberg limits, and Proctor characteristics. The physical characteristics of the marl at the various sites studied are shown in Table 2.

Table 2. Physical characteristics of the marls studied

Site	W (%)	e	Ƞ(%)	Sr(%)	Yh (KN/m^3)	ϒd(KN/m^3)	ϒs(KN/m^3)
Krim Belkacem	1.54	0.01	0.99	100	26.29	25.90	26.06
Les Chabanes	1.87	0.02	1.96	100	25.08	24.62	25.19
Kaf Lehmar	4.54	0.1	9.09	100	24.21	23.16	25.53
Mdouha	1.62	0.1	9.09	42.53	24.33	23.94	26.25
Oued Fali	4.61	0.15	13.04	93.41	23.94	22.88	26.34
Boukhalfa	4.76	0.14	12.28	88.67	23.92	22.84	26.08

According to the results obtained in Tables 2 and 3, these marls have low water contents due to being extracted at shallow depths and during dry periods. According to Terzaghi [47], the marls at the Boukhalfa, Les-Chabanes, Kaf-Lehmar, and Krim Belkacem sites are saturated, those at Boukhalfa and Oued-Fali are soggy, whereas the Mdouha site is damp. The dry densities of all these marls exceed 18 kN/m^3, so they are considered dense.

Table 3. Plastic and Proctor characteristics of the marls studied

Site	Wl(%)	Wp(%)	Ip (%)	Ic	ϒd opt	Wopn (%)
Krim Belkacem	23.05	19.96	3.09	6.96	21.73	9.18
Les Chabanes	21.5	18.44	3.06	6.42	21.1	9.1
Kaf Lehmar	37.39	18.69	18.7	1.76	19,78	11.10
Mdouha	24.45	21.20	3.25	7.02	20.85	9.13
Oued Fali	41.1	26.30	14.8	2.47	19.34	12.84
Boukhalfa	35.3	27.01	8.29	3.68	19.35	15

The plasticity indices of the Boukhalfa, Kaf-Lehmar, and Oued-Fali sites vary between 7 and 17. According to the Atterberg classification, these soils are characterized by average plasticity, and the marls of the Krim Belkacem, Mdouha, and Les Chabanes sites are soils with low plasticity.

According to the Proctor tests, the characteristics obtained for the different sites are optimum dry density between 19 and 22 kN/m^3 and optimum moisture content between 9 and 15%.

3.3. Characteristics of the Lime Used

The lime used comes from the Saida plant in western Algeria. The characteristics of this lime are summarized in the Table 4:

Table 4. The physical characteristics of the lime used

CaO (%)	MgO (%)	80 mm (%)	Free Water Content (W) (%)
73.25	< 4	96	0.5

According to the table's results and the specification standards (NF 196-2, NF 044 - 145), this hydrated lime from Saida suits road embankments and foundation soils.

4. Mechanical Tests

Three mechanical tests were carried out: Proctor, odometric, and conventional and cyclic shear tests.

- The Proctor test: This is a soil compaction test designed to study the variation in dry density as a function of water content. The maximum density achieved for a given compaction energy and the corresponding optimum water content can be determined by compacting the material at different water contents.
- Oedometric test**:** This test can determine the swelling of these marls under load. The sample, cut to the diameter of the ring, is placed in the odometer cell between two porous stones and filled with water. The saturated sample is subjected to a stepwise loading-unloading cycle at pressures ranging from 25 to 3200 kPa and 3200 to 25 kPa, respectively.
- The simple shear test: 25.4 mm high and 63.5 mm in diameter samples were subjected to consolidated undrained shear tests at a 1.5 mm/min speed while varying the everyday stress from 100 to 400 kPa.

The mechanical tests (odometer and simple shear) carried out on the various marls enabled us to determine their mechanical characteristics (cohesion C, angle of friction Φ, swelling index Cs, compressibility index Cc, and pre-consolidation stress σ_p). The results obtained are given in Table 5.

Table 5. The mechanical characteristics of the marls studied

Site	C (KPa)	Φ (°)	Cs (%)	Cc (%)	σ_p (KPa)
Krim Belkacem	45.5	35	0.51	14.31	28
Les Chabanes	44	36.6	0.22	14.84	90
Kaf Lehmar	80.3	31.8	1.24	16.96	47
Mdouha	8.71	39.9	0.67	15.05	115
Oued Fali	12.7	40.6	1.20	13.93	42
Boukhalfa	23.1	37.2	0.81	15.05	38

According to the cohesions obtained, the Mdouha and Oued-Fali marls are the lowest but with the highest angles. The Boukhalfa, Krim Belkacem, and Les-Chabanes marls have relatively low cohesion with fairly high friction angles varying from 35 to 37°. The Kaf-Lehmar marl has the highest cohesion of 80 kPa and the lowest angle of 32°. According to Seed et al. (1962) [48], the swelling potential of these marls is classified as low, and according to Terzaghi [47], they are moderately compressible.

- Cyclic shear, according to ASTM D6528 [49], is used for studies of landslides, earthquakes, deep foundations (soil-pile interfaces), or offshore structures and construction on embankments. The direct shear box is a modification of the Casagrande box used to test samples in lateral shear, where the cross-section is kept constant without any variation in overall volume. The device consists of a latex membrane confined laterally by a stack of thin Teflon-coated rings to keep friction to a minimum and leave the soil free to deform. The membrane holds a sample that is 70 mm in diameter and 20 mm high. The whole system is subjected to many cycles under various loading conditions (the horizontal movement of the specimen is free, and vertical movement is prevented). The research methodology and the cyclic shear apparatus are illustrated in Figure 2 (a and b).

Figure 2. a). Laboratory cyclic shear apparatus L.G.E.A (U.M.M.T.O)

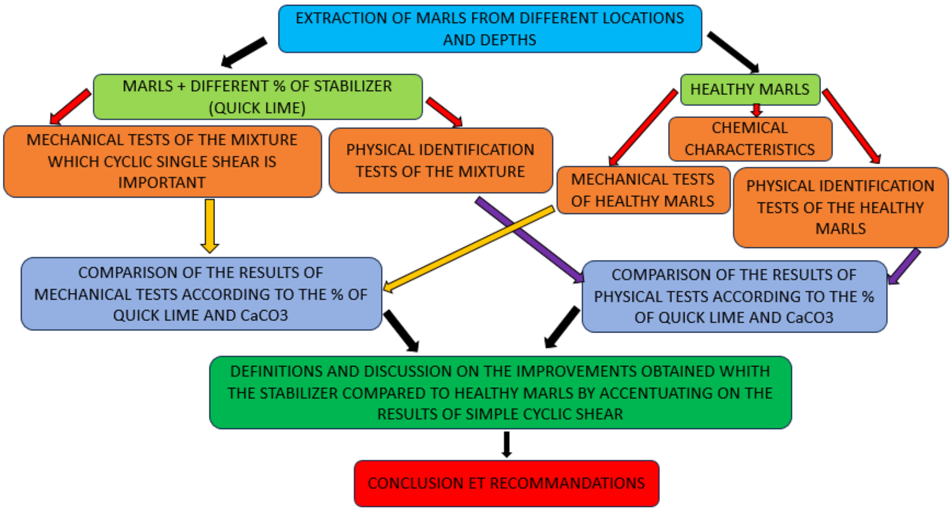


Figure 2. b). Research methodology flowchart

5. Influence of the Addition of Lime on Physical and Mechanical Tests

The influence of lime additions to marl on the odometric compressibility and stress-strain curves was studied. This lime was used in various concentrations ranging from 1 to 5%. The marl samples were compacted to the maximum. In the absence of core sampling for our study, we used reworked samples compacted to the Proctor optimum to simulate and approximate the reality of the terrain.

5.1. Effect of Lime on Void Indices and Porosity

Table 6 shows the evolution of the void and porosity indices of the different marls studied as a function of the added lime content.

Table 6. Changes in e and η in marl as a function of lime content

Lime (%)	0 %		1 %		2 %		3 %		4 %		5 %	
Site	**e**	**η**	**e**	**η**	**e**	**η**	**e**	**η**	**e**	**η**	**e**	**η**
Krim Belkacem	0.41	29.08	0.40	28.57	0.40	28.57	0.40	28.57	0.39	28.06	0.39	28.06
Les Chabanes	0.39	28.06	0.39	28.06	0.38	27.54	0.38	27.54	0.38	27.54	0.38	27.54
Kaf Lehmar	0.55	35.48	0.53	34.64	0.52	34.21	0.51	33.77	0.51	33.77	0.51	33.77
Mdouha	0.51	33.77	0.50	33.33	0.49	32.89	0.49	32.89	0.49	32.89	-	-
Oued Fali	0.55	35.48	0.53	34.64	0.52	34.21	0.51	33.77	0.51	33.77	0.51	33.77
Boukhalfa	0.55	35.48	0.55	35.48	0.54	35.06	0.54	35.06	0.54	35.06	0.54	35.06

Void indices (e) and porosities (η) decrease with increasing lime content. The lime has absorbed a certain amount of water and has clogged the particles together, resulting in a reduction in voids (e) until stabilization. Void indices decreased with percentages varying between 1.81% (Boukhalfa marl for 2% lime addition) and 7.27% (Kaf Lehmar and Oued Fali marls for 3% lime addition), and porosities decreased by 1.18% (Boukhalfa marl for 2% lime addition) and

4.82% (Kaf Lehmar and Oued Fali marls for 3% lime addition). For 1% added lime, the voids index of the Kaf Lehmar and Oued Fali marls decreased by 3.63%, and for 2% added lime, the voids index of the Les Chabanes marls decreased by 2.56%. For 1% added lime, the porosity index of the Krim Belkacem marl decreased by 1.75% and 1.96% for the Mdouha marl. For a 2% addition of lime, the porosity of the Kaf Lehmar and Oued Fali marls decreased by 3.58%. We can, therefore, deduce that void indices depend on the nature of the marl; this means the level of $CaCO_3$.

5.2. Effect of Atterberg Limits on Lime-stabilized Marls

The results obtained from the Atterberg limits of lime-treated marl are shown in Table 7.

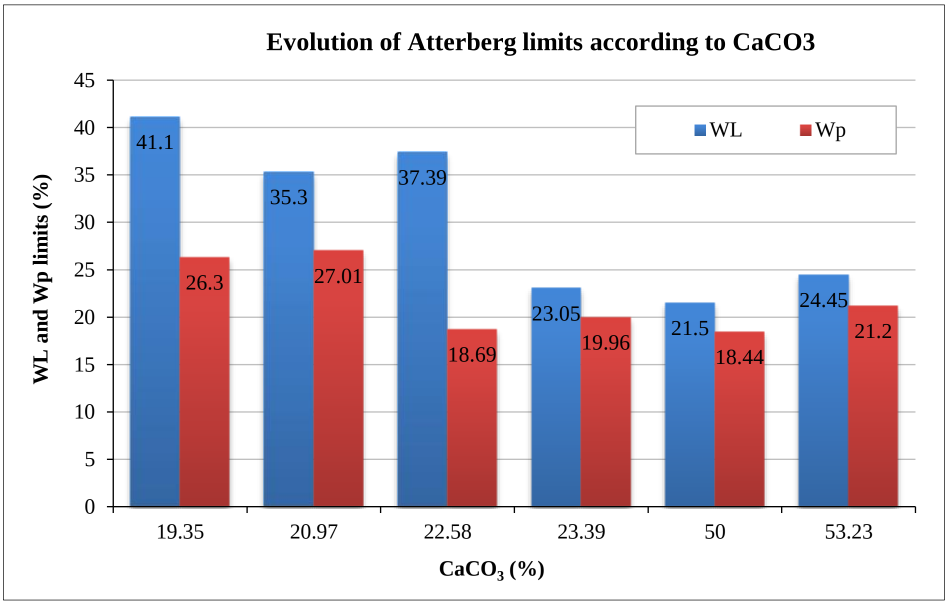
Table 7. Evolution of WL and WP in the marls studied as a function of lime content

Lime (%)	0 %		1 %		2 %		3 %		4 %	
Site	WL	WP	WL	WP	WL	WP	WL	WP	WL	WP
Krim Belkacem	23.05	19.96	23	20.26	22.95	20.77	22.80	21.31	22.71	21.99
Les Chabanes	21.50	18.44	21.30	19.28	21.19	20.38	-	-	-	-
Kaf Lehmar	37.39	18.69	36.50	32.30	35.95	33.40	35.90	34.59	35.82	35.79
Mdouha	24.45	21.20	23.12	21.49	22.85	21.75	22.78	22.35	-	-
Oued Fali	41.10	26.30	39.20	31.97	38.40	34.66	37.55	35.34	36.80	35.81
Boukhalfa	35.30	27.01	34.33	31.18	33.85	31.95	33.40	32.50	-	-

The liquidity limits of these marls treated with lime decrease slightly by a value between 1.73% (Krim Belkacem marl for 5% lime addition) and 10.46% (Oued Fali marl for 4% lime addition). For 2% added lime, the liquidity limit of the Kaf Lehmar marl decreased by 3.85%, and 6.54% for the Mdouha marl. Adding 3% lime lowered the liquidity limit of the Oued Fali marl by 8.63%. On the other hand, the plasticity limits have an inverse relationship with the lime content, the variation of which is more accentuated than that of the liquidity limits. These limits were increased by 5.42% (Mdouha marl for 3% lime addition) and 91.49% (Kaf Lehmar marl for 4% lime addition). For 1% added lime, the plasticity limit increased by 21.55% for the Oued Fali marl and 72.82% for the Kaf Lehmar marl. And at 3% lime, the plasticity limit of the Boukhalfa marl increased by 20.32%.

This causes the plasticity range to shift towards higher water contents (shortening of the plastic range). According to the Casagrande Abacus, the lime-stabilized marls lie below line A, so they are not very plastic silts. Results in the literature [3, 21-24] show the same behavior as those in this study. It should be noted that the plasticity limits WP of the Kaf-Lehmar and Oued-Fali marls are remarkably higher than those of the other marls, which can be explained by the low quantity of SO4 sulfates they contain, given that Sulphur compounds are disruptive to the treatment of soils with lime, so less sulfate, less disruption, which allows the lime to react better with these two marls.

Figure 3 shows the evolution of the Atterberg limits and plasticity indices as a function of $CaCO_3$ in the marls. The lower the $CaCO_3$ content (below 23%), the more sensitive the marl is to Atterberg limits. Above this limit, these characteristics tend to stabilize.



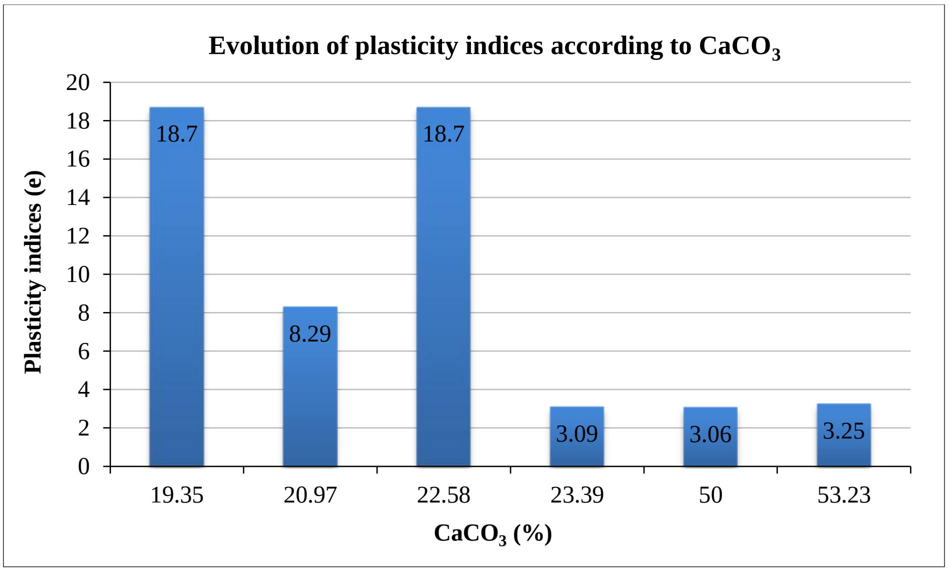


Figure 3. Evolution of WL, WP, and Ip as a function of $CaCO_3$ in marl at different sites

5.3. Effect of Lime on Marl Compressibility

Table 8 shows the changes in compressibility characteristics as a function of lime content for the marls studied.

Table 8. Evolution of Cc, Cg, and pre-consolidation stress as a function of lime content

Lime (%)	1			2			3			4			5		
Site	Cc (%)	Cg (%)	$\sigma'P$ (kPa)	Cc (%)	Cg (%)	$\sigma'P$ (kPa)	Cc (%)	Cg (%)	$\sigma'P$ (kPa)	Cc (%)	Cg (%)	$\sigma'P$ (kPa)	Cc (%)	Cg (%)	$\sigma'P$ (kPa)
Krim Belkacem	13.59	0.47	86	12.6	0.42	125	11.7	0.38	130	10.85	0.33	140	10.03	0.31	140
Les Chabanes	12.60	0.09	155	12.45	0.08	180	12.22	0.26	190	12.02	0.21	215	10.05	0.15	240
Kaf Lehmar	14.62	0.60	135	14	0.34	165	13.62	0.28	225	13.22	0.25	255	12.72	0.23	270
Mdouha	13.45	0.39	155	12.76	0.37	175	12.22	0.32	210	10.94	0.24	225	10.63	0.15	230
Oued Fali	13.73	0.55	180	13.6	0.47	190	13.43	0.45	240	13.25	0.43	245	13.11	0.38	285
Boukhalfa	14.62	0.53	150	14.12	0.32	200	13.76	0.24	225	13.56	0.21	240	13.56	0.20	240

The marls studied have swelling indices (Cg) less than 1.5%, so their swelling potential is low (Seed et al.1962) [48]. Compression indices (Cc) range from 10% to 20%. According to Terzaghi [47], these marls are characterized by average compressibility.

All these marls' compression and swelling indices decrease as the percentage of lime added increases. Similar results have been confirmed by Brandl 1981 [25]. The compression indices of these mixtures (marl-lime) were improved by a value of between 5.88% (Oued Fali marl for 5% lime) and 41.15% (Les Chabanes marl for 6% lime) compared with those of healthy marls. For 1% added lime, the compression index of the Kaf Lehmar marl decreased by 13.79%, and 17.43% for the Les Chabanes marl. For 5% added lime, the compression indices of the Les Chabanes and Mdouha marls were reduced by 34.14% and 29.36%, respectively. When Cc decreases, this results in low compressibility or improved compressibility of the mixtures (marl + lime).

The Cg swelling index of these marls was reduced from 25 to 77.42% for a lime addition of 3% (except for the Les Chabanes site). For 1% added lime, the swelling index of the Kaf Lehmar and Oued Fali marls was reduced by 51.61% and 54.16%, and for 6% added lime, these indices fell by 81.45% and 69.16%, respectively. This can be explained by cation exchange reactions, flocculation, or aggregation, which brought about an immediate improvement in the mechanical properties, modifying almost instantaneously the plasticity, workability, strength, and deformation properties of soil under load; this confirms the results of Moore, 1987 [50]. When quicklime is added, a dehydration reaction occurs, creating calcium hydroxide. This modifies the bonds between the clay particles, making them less water-sensitive. This reaction dries out the soil considerably, causing the silica and alumina in the clay particles to dissolve [51] and providing a large number of divalent calcium ions (Ca^{2+}) and (OH^-), which modify the surface charge of the clays and tend to replace the monovalent cations (Na+ and K+). The calcium ions that are not exchanged will be adsorbed, increasing ion density, which means a drop in the exchange capacity of the particles - this is the cation exchange reaction. According to Bekkouche et al.2002 [52], this results in a reduction in swelling.

In addition, lime added to fine grains of clay corresponds to a massive addition of OH^- and Ca^{2+} ions, influencing the electric charges around the clay particles and thus modifying the electric fields between them. These fields allow the development of relationships (bridges) between these particles, which reduces the apparent volume where the small grains group together to form other large grains. This is flocculation and agglomeration.

Figure 4 shows that Cc does not vary significantly as a function of $CaCO_3$. Cc varies between 14 and 17%. However, if $CaCO_3$ is less than 23% for Cg, the Cg is between 0.8 and 1.24; for $CaCO_3$ greater than 23%, the Cg varies between 0.2 and 0.67. So, the smaller the $CaCO_3$, the closer the marl material is to clay soil and the more swelling it has.

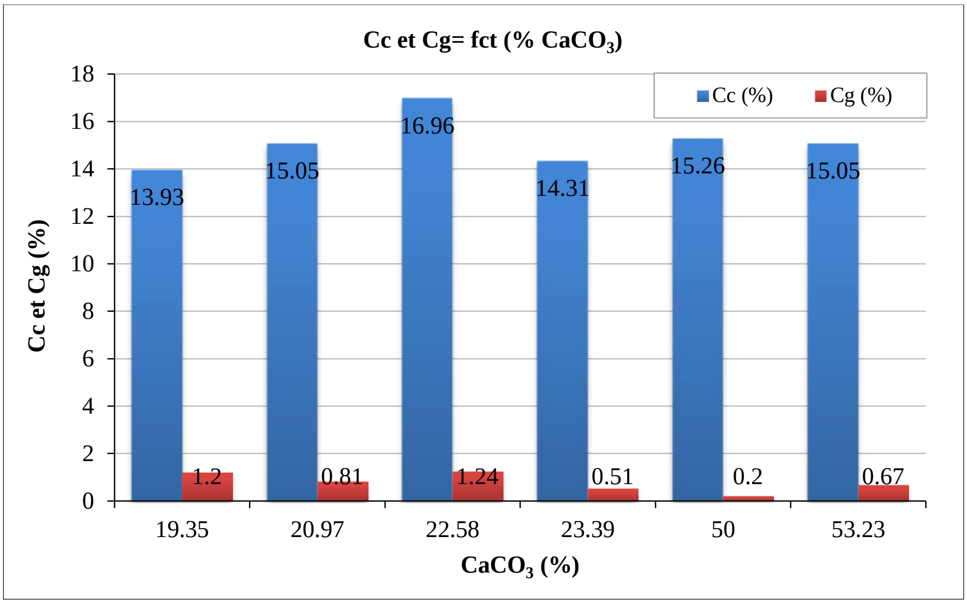


Figure 4. Evolution of Cc and Cg as a function of $CaCO_3$ in the marls studied

Figure 5 illustrates the stability of effective pre-consolidation stresses with the lime content for the different marls. These stresses consistently increase as the percentage of lime increases and notably stabilize at 4% lime addition, particularly for the Krim Belkacem, Mdouha, Boukhalfa, and Kaf-Lehmar marls. This stability provides a reliable basis for further research and engineering applications. These effective pre-consolidation stresses are significant when the $CaCO_3$ content of the marl exceeds 50% (Figure 6).

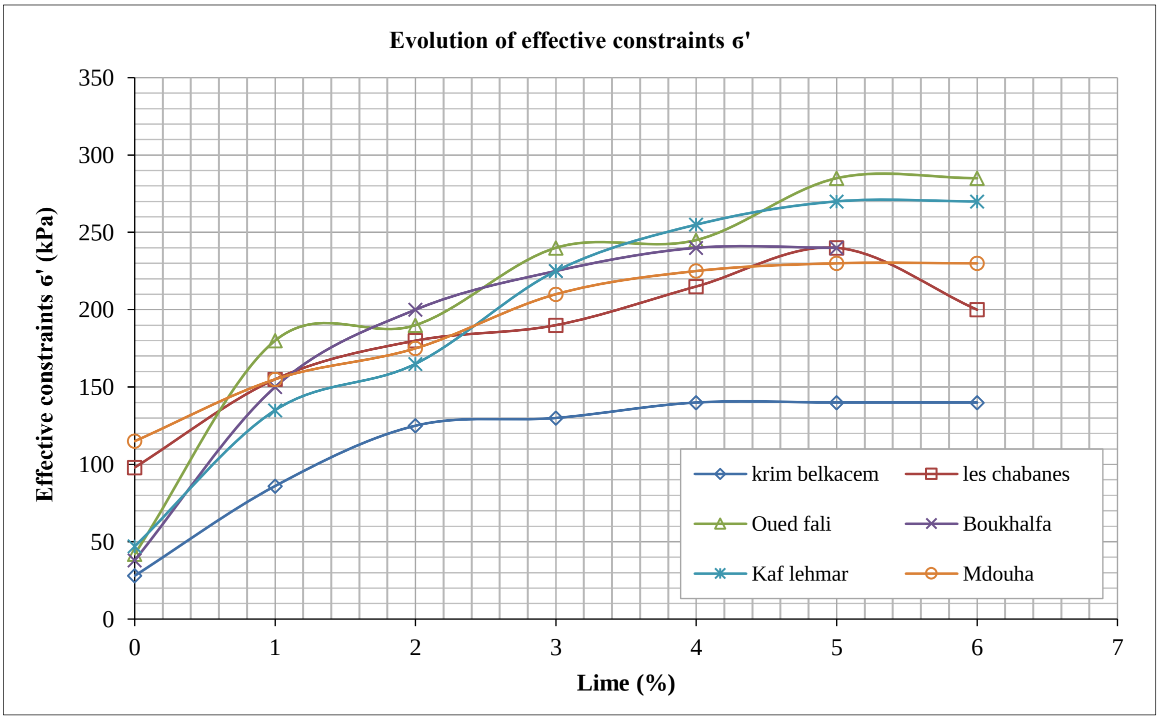


Figure 5. Evolution of the pre-consolidation stress as a function of the percentage of lime added

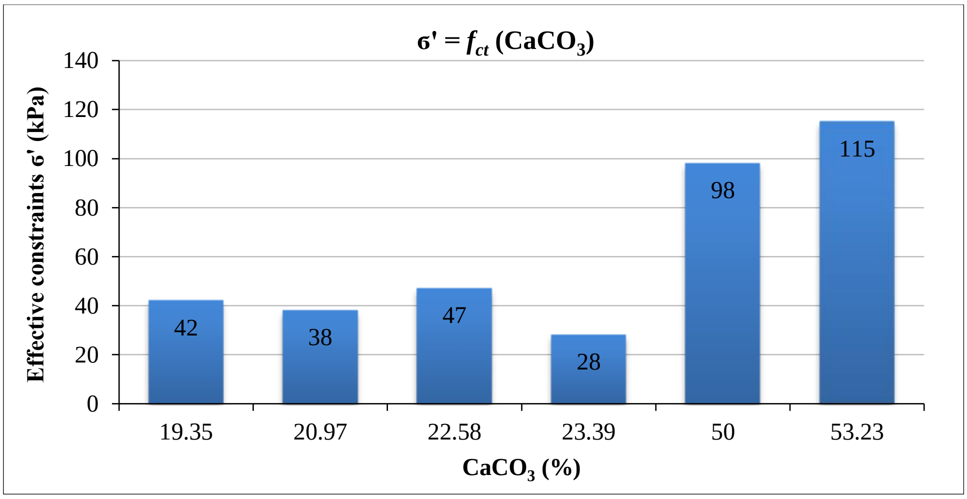


Figure 6. Evolution of the pre-consolidation stress as a function of the $CaCO_3$ content of the marls studied

5.4. Effect of Lime on the Simple Shear Strength of Marls

The marl at the various sites reacts with the lime, creating crystalline elements that cement the particles together, improving their mechanical properties. The effectiveness of this stabilization with lime is difficult to predict. The gain in shear strength depends on several variables: the mineralogy of the marl, the cation exchange capacity, the particle size, the specific surface area of the particles, the quantity of water, the lime concentration, and the ripening time [8, 9]. Figure 7 shows the shear behavior of samples of the Mdouha marl and the Chabanes treated with lime subjected to normal stresses: 100, 200, 300, and 400kPa.

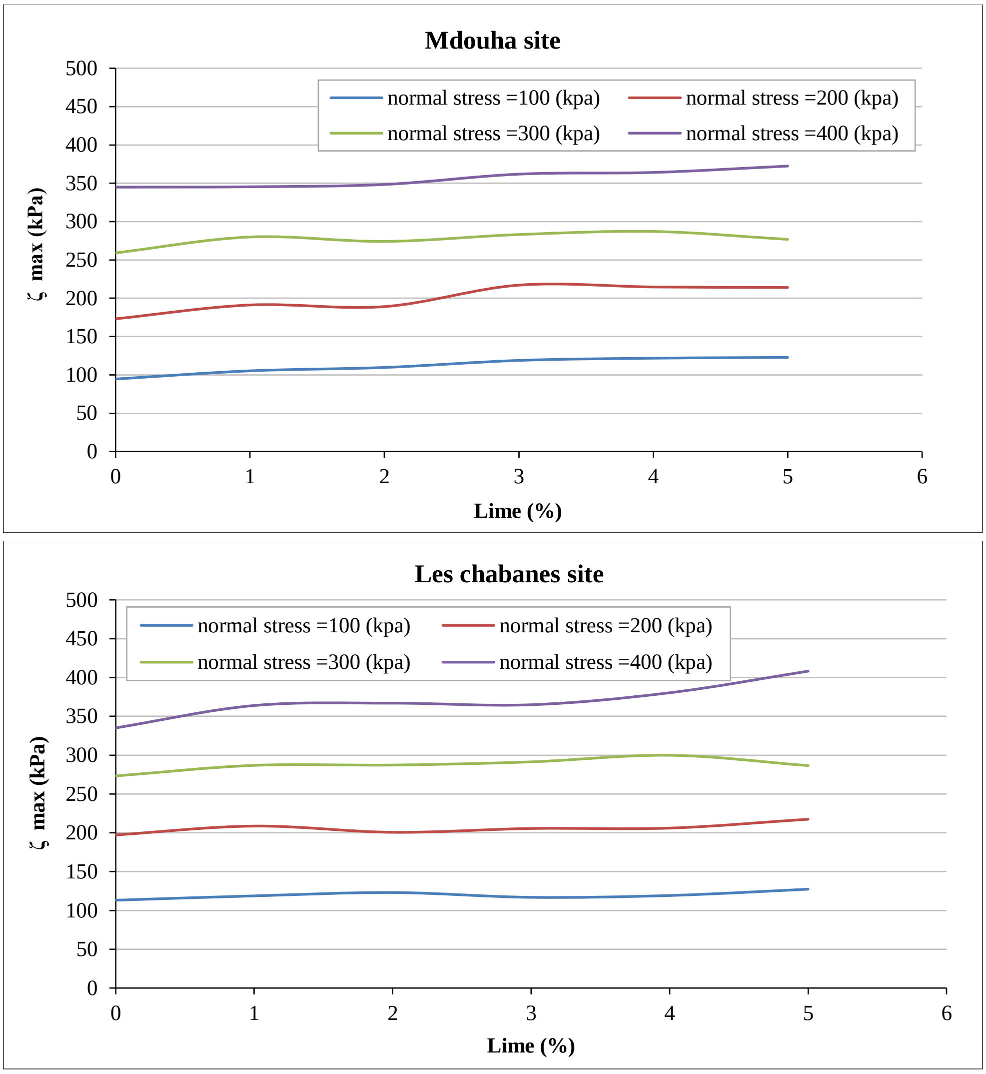


Figure 7. Evolution of maximum shear strength as a function of lime content for normal stresses at the Mdouha and Les Chabanes sites

The results show that the shear strength (ζ) increases with increasing normal stress and lime addition rate. In the natural state (0%), the maximum shear strength rose from 94.65 to 344.9 kPa for normal stresses varying from 100 to 400 kPa for the Mdouha site, i.e., an improvement of 72.56%, and for the Chabanes site, the strength increased from 113.1 to 335.1 kPa for the same stresses, i.e., an improvement of 66.24%. This development is due to the rearrangement of the grains caused by the increase in normal stress, which has increased the friction rate.

For the Mdouha site, this maximum shear strength increases with the rate of lime addition and tends to stabilize at 4% lime. Note that for the normal stress of 400kPa, we did not observe any improvement in strength up to 2% lime, and it only increases from 3% lime addition; this quantity of lime is sufficient to give rise to forces of attraction between the more resistant particles to react to a high normal stress of (400 kPa). For the Les Chabanes site, maximum shear strength generally increases with the rate of lime addition. For the normal stress of 400 kPa, we found no improvement in shear strength between 1% and 3% lime, which only increases from the 3% lime addition, which is also a sufficient quantity.

The shear characteristics obtained for the different marls as a function of lime content are shown in Table 9.

Table 9. Evolution of the cohesion (c) and angle of internal friction (ϕ) as a function of lime content in the marls studied

Lime (%)	**1 %**		**2 %**		**3 %**		**4 %**		**5 %**	
Site	**C (Kpa)**	**ϕ (°)**	**C (Kpa)**	**ϕ (°)**	**C (Kpa)**	**ϕ (°)**	**C (Kpa)**	**ϕ (°)**	**C (Kpa)**	**ϕ (°)**
Krim Belkacem	44.80	35.80	39.20	37.20	36.30	38.40	29.60	40.60	28.90	40.80
Les Chabanes	40.70	39.20	39.10	39.40	36.50	39.70	31.60	41.30	31.10	42.40
Kaf Lehmar	41.30	32.80	40.60	34.90	37.10	36.20	34.30	37.30	34	37.60
Mdouha	28	39	29.60	38.70	46.30	38.50	47	38.60	-	-
Oued Fali	-	-	20.70	37.70	27.60	36.80	31.30	35.30	41.10	35
Boukhalfa	26	36.40	30.50	36.40	38.40	36.30	40.70	36.40	-	-

The results (Table 9) show the evolution of the shear strength of the mixes (marl + lime). This resistance increases as the percentage of lime increases (case of the Mdouha site and the chabanes (Figure 7). This improvement is linked to their cohesion, which manifests at a specific humidity threshold and causes reactions between the different particles, creating forces of attraction between them. However, above this humidity threshold, the excess water separates the particles from each other, reducing the forces of attraction that bind them together. As a result, soil cohesion decreases [53].

Table 9 demonstrates that the friction angle of the treated marls (Krim Belkacem, Les-Chabanes, and Kaf-Lehmar) remains nearly constant. At the same time, cohesion decreases with the lime content, stabilizing at 4% added lime. For instance, a 1% addition of lime for Kaf-Lehmar marl results in a 48.56% decrease in cohesion, stabilizing at 3% added lime. This practical implication of the research confirms Mitchell's results and provides valuable insights for engineering applications.

For the marls at the Mdouha and Oued-Fali sites, the friction angle remains practically constant or decreases slightly; on the other hand, cohesion increases with the level of the binder. For an addition of 1% lime, the cohesion of the Mdouha marl increases from 8.71 kPa to 27.6 kPa, and for the Oued-Fali marl, the cohesion increases from 12.70 kPa to 27.6 kPa for an addition of 3% lime. For the Mdouha marl, the 1% addition of lime increased cohesion by 3.21 times the natural cohesion. For the Boukhalfa marl, this cohesion increased by 76.19% at 4% addition and is 5.39 times greater than the Mdouha marl. The increase in this cohesion is associated with the increasing formation of cementitious compounds and better crystallization of the compounds over time. These results have also been confirmed by several authors [32, 25, 33, 34], who have also shown that the addition of lime to soil influences shear parameters (angle of internal friction and cohesion). In addition, Brandl (1981) [25]; Balasubramaniam (1989) [25, 33] have reported that the angle of internal friction does not depend on the curing time and that its improvement is due to the flocculation/aggregation process rather than to the crystallization of cementitious products over time.

For the Mdouha site, the maximum resistance obtained for 3% added lime tended to remain constant; however, the curve at 4% showed a peak (Figure 8). This can be explained by a revival of the forces of attraction that occur after destruction by shearing in the presence of 3% lime, which means that this percentage of lime added is sufficient to maintain the good resistance of this mixture throughout shearing.

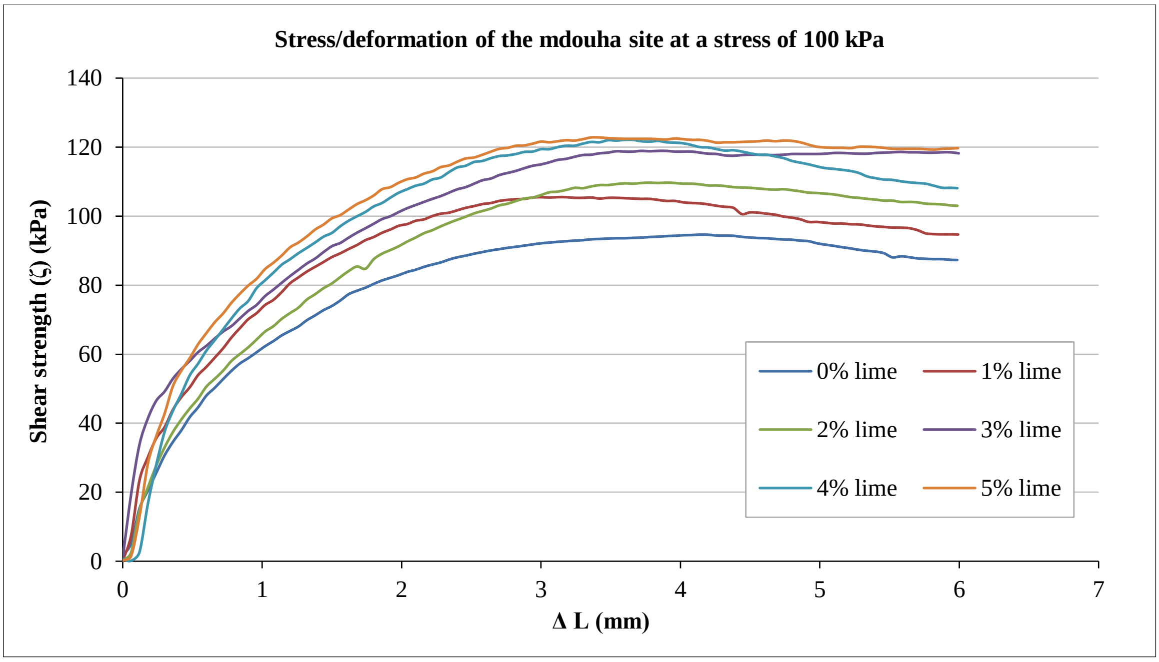


Figure 8. Evolution of shear strength as a function of lime content for a normal stress of 100 kPa at the Mdouha site

6. Influence of Adding Lime to Cyclic Shear Tests

The cyclic box shear test was chosen because it was the only one available of the dynamic laboratory tests (vibration table, resonant column, cyclic triaxial). This test reproduces appropriate and controlled cyclic stresses and enables the parameters representative of non-linear and hysteretic behavior to be identified. It was carried out under undrained conditions, so at constant volume. This choice made it possible to preserve the water in the sample throughout the test, which allowed the mixture (marl-lime) to be placed under the most unfavourable conditions, thereby increasing the risk of instability. This allows us to study the behavior of these saturated marls stabilized with lime. These undrained conditions affect cyclic strength, which shears more quickly in the presence of water, increasing pore pressure and reducing the number of cycles required to reach failure. This study aims to determine the importance of adding lime in improving the behavior of different marls in undrained conditions.

The test is carried out with a normal stress of 100 kPa. The height of the sample used is 25.4 mm, and its diameter is 63.5 mm; the shear speed used is 0.2 mm/min, where the maximum displacement is 6 mm and the maximum stress is 4400 N. The amplitude of the stress ratio varies from 0.05 to 0.4, with a variation of 0.025. The maximum number of cycles is 100, and the number of readings per cycle is 200, with a total duration of 1.33 minutes, which we consider sufficient. The parameters measured are the vertical and horizontal forces, the variation in pore pressures Δu measured at the base of the sample, and the vertical and horizontal displacements. This device is equipped with software that automatically monitors all the parameters during the process.

6.1. Effect of Lime on Cyclic Stress (Ϭcyc) and Shear Strain

Figures 9 to 14 show the evolution of cyclic stresses and strains as a function of the percentage of lime added for the different marls studied. Analysis of these stress-strain curves shows that the hysteresis curves behave elastically. Stabilized with up to 5% lime, these marls have low deformations in the first cycles and develop slowly. Deformations do not exceed 6% for the Krim-Belkacem marl, 4.25% for the marl at the Les-Chabanes site, 2.7% for the marl at the Kaf-Lehmar site, 3% for the marl at the Oued-Fali site and 2% for the marl at the Boukhalfa site (Table 8). After a certain number of cycles, the hysteresis curves open up more and more rapidly and widen with large irreversible deformations. This can be explained by cation exchange reactions, flocculation, or aggregation in which large particles give rise to fine particles by adding lime, resulting in more voids, which allows the rearrangement of these particles, resulting in more deformation. This was observed at the Krim Belkacem and Oued-Fali sites for 0 and 1% added quicklime, at the Les-Chabanes and Mdouha sites for 1 and 5% added quicklime, and at the Kaf-Lahmar site for 0, 1 and 2% added quicklime.

Depending on the nature of the marl, the number of cycles and the level of deformation vary. As this S-shape becomes more pronounced, the soil degrades further. Consequently, the evolution of the cycle's shape is due to structural changes in the marl. The marl structure undergoes a process of degradation so that the evolution of the loading cycles produces less resistance to shearing, either by accommodation of the particles or by progressive rupture of the bonds between them.

Mustapha (2017) [37] found identical results in the literature on a sensitive clay from Beauharnois. He noted that deformations occur in two parts: the first is elastic, with low deformations that develop slowly, almost linearly, with the number of cycles until they reach 2% to 3%. The second part is elastoplastic, with a sudden and irreversible increase in deformation. The hysteresis curves are S-shaped and open up more and more with irreversible deformation.

These hysteresis curves show a concentration of cycles at 2, 3, 4, and 5% lime addition for the Krim-Belkacem sites, at 3, 4, and 5% lime addition for the Kaf-Lahmar site, at 2 and 3% lime addition for the Mdouha and Oued Fali sites and at 1, 3 and 5% quicklime addition for the Boukhalfa site. These hysteresis curves do not have an "S" shape for percentages of 3, 4, and 5% for the Kaf-Lehmar marls, 2 and 3% for the Oued Fali marls, and 1, 3, and 5% for the Boukhalfa marls. This can be explained by the accommodation phenomenon, whose behavior is purely elastic and whose deformations are very low, varying from 0.4% to 1.1%, which means that at these percentages of lime addition, the normal stress imposed is not sufficient to destroy the bridges between the particles created by the lime reaction; these soils are more resistant.

The improvement in the cyclic stresses of these treated marls varies from 34.23% (Kaf Lehmar marl) and 73.91% (Boukhalfa marl) compared with healthy marls, and the deformations were reduced by 36.58% (Mdouha marl) and 92.45% (Boukhlefa marl) compared with healthy marls.

A comparison of the curves in Figures 9 to 14 show that as the cyclic shear stress increases, the number of cycles required to reach failure decreases. This behavior is typical of fine soils and has been observed by several authors. This also applies to fine-stabilised soils.

By comparing the cyclic stresses of healthy marl with those of marl stabilized with different percentages of lime (Table 10), we can see that these stresses are higher with the addition of lime, which means that the mixture requires more significant cyclic stress to reach failure and that the reduction in the rate of deformation persists as long as the behavior remains elastic. These two critical parameters are improved due to electrostatic and electromagnetic attractions and various marl-lime chemical reactions. For a 1% addition of lime, the cyclic stresses of the Boukhalfa and Oued Fali marls increased by 73.91% and 20%, respectively. For the Kaf Lehmar and Krim belkacem marls, the 3% lime content increased the cyclic stress by 34.22% and 29.41%, respectively. For the deformations of the Boukhalfa and Les Chabanes marls, the 1% lime rate reduced them by 86.79% and 37.03%, respectively. At a rate of 3%, lime reduced the cyclic stresses of the Krim belkacem, Les Chabanes, Kaf Lehmar, and Oued fali marls by 53.84%, 55.55%, 91.66%, and 91.30%, respectively. The various improvements are shown in Table 11.

Table 10. Evolution of cyclic stresses (kPa) as a function of lime percentage

Lime (%) Site	0	1	2	3	4	5
Krim Belkacem	17	17.5	17	22	18.2	28
Les Chabanes	17	22	17.8	19	19	28
Kaf Lehmar	29.8	33	34	40	28	40
Mdouha	19.5	25	18.2	22	22.5	28
Oued Fali	25	30	40	40		
Boukhalfa	23	40	40	40	40	40

Table 11. Evolution of deformation (%) as a function of the percentage of lime

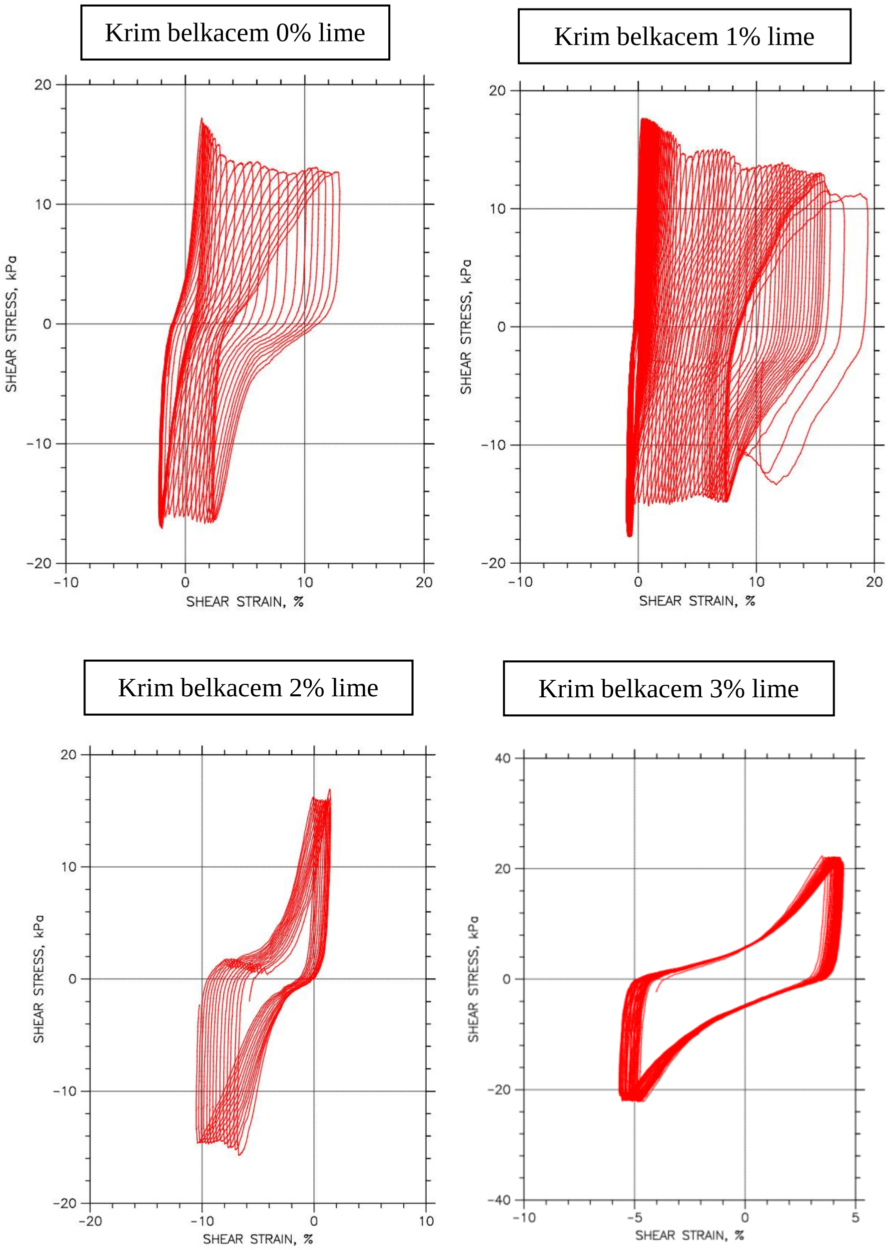
Lime (%) Site	0	1	2	3	4	5
Krim Belkacem	13	19.5	10	6	10.5	7
Les Chabanes	13.5	8.5	4	6	6	7.5
Kaf Lehmar	6	10.4	6	0.5	0.5	0.9
Mdouha	8.2	7.2	6.5	5.3	7.1	5.2
Oued Fali	6.9	7.3	1.1	0.6	-	-
Boukhalfa	5.3	0.7	6.4	0.5	4.1	0.4

These cyclic curves (Figures 9 to 14) essentially show the relationship between the fatigue effect and the cyclic loading rate. In the early stages of the test, according to its natural structure, the marl at the different sites retains its linear and elastic behavior with the relationships between the particles all intact, i.e., the capacity to store energy is very high. As cyclic loading progresses, the links between the particles resist to the maximum and begin to store energy until their resistance decreases and they lose their elasticity, so they change to elastoplastic behavior, generating irreversible deformations. In terms of energy, the marl has lost its capacity to store energy, which consequently causes the energy received to be dissipated in the form of irreversible deformations. All the curves obtained are vertical curves, generally in the shape of an "S" because, in the case of a test on coherent soil, it is not possible to observe such a curve becoming horizontal since the test never reaches ru=100% [38]. Furthermore, the hysteresis curves show that the test on coherent soil can dissipate more energy (deformations) without even reaching ru=100% than in the case of sand [54]. This development of deformations can be explained by the cohesion of the marl, which prevents the particles from separating even in the presence of lime, and by the fact that the cyclic shearing of these soils induces deformations that cause a rearrangement of the particles and can lead to a collapse of the structure. The progressive destruction of the links between the particles would influence fatigue failure.

The failure mode in the cyclic loading of soils is a fundamental factor in any dynamic study of soils. For cohesive soils, failure occurs via the cyclic softening mechanism [39, 38]. For the marls at the various sites used, the pore pressure never reached 100%, confirming that the failure mode is cyclic softening and not liquefaction.

We also note that the cyclic shear stress varies from 23 to 40 if $CaCO_3$ is less than 23% and varies from 17 to 28 kPa if $CaCO_3$ is greater than 23%. In addition, for $CaCO_3$ greater than 50%, there is no concentration of cycles before stabilization; this concentration begins to occur after stabilization and from 2% lime addition.

The Case of the Krim Belkacem Site:



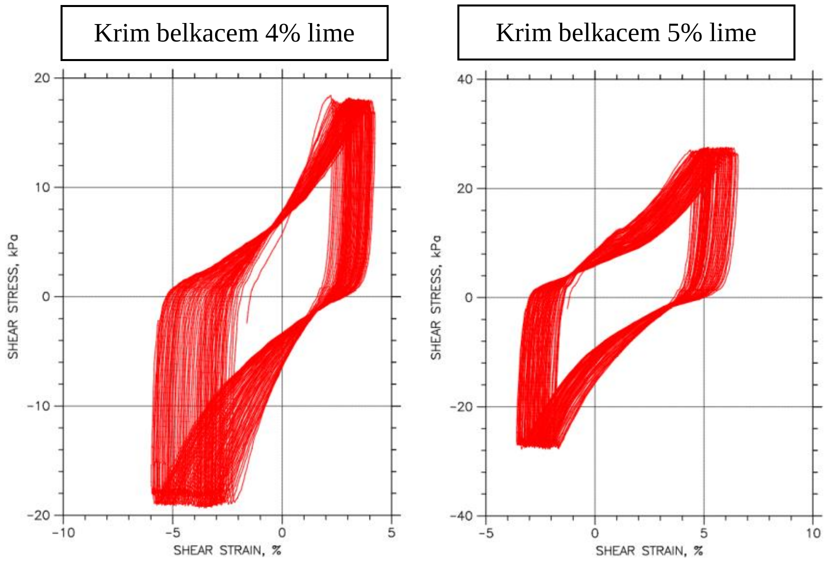
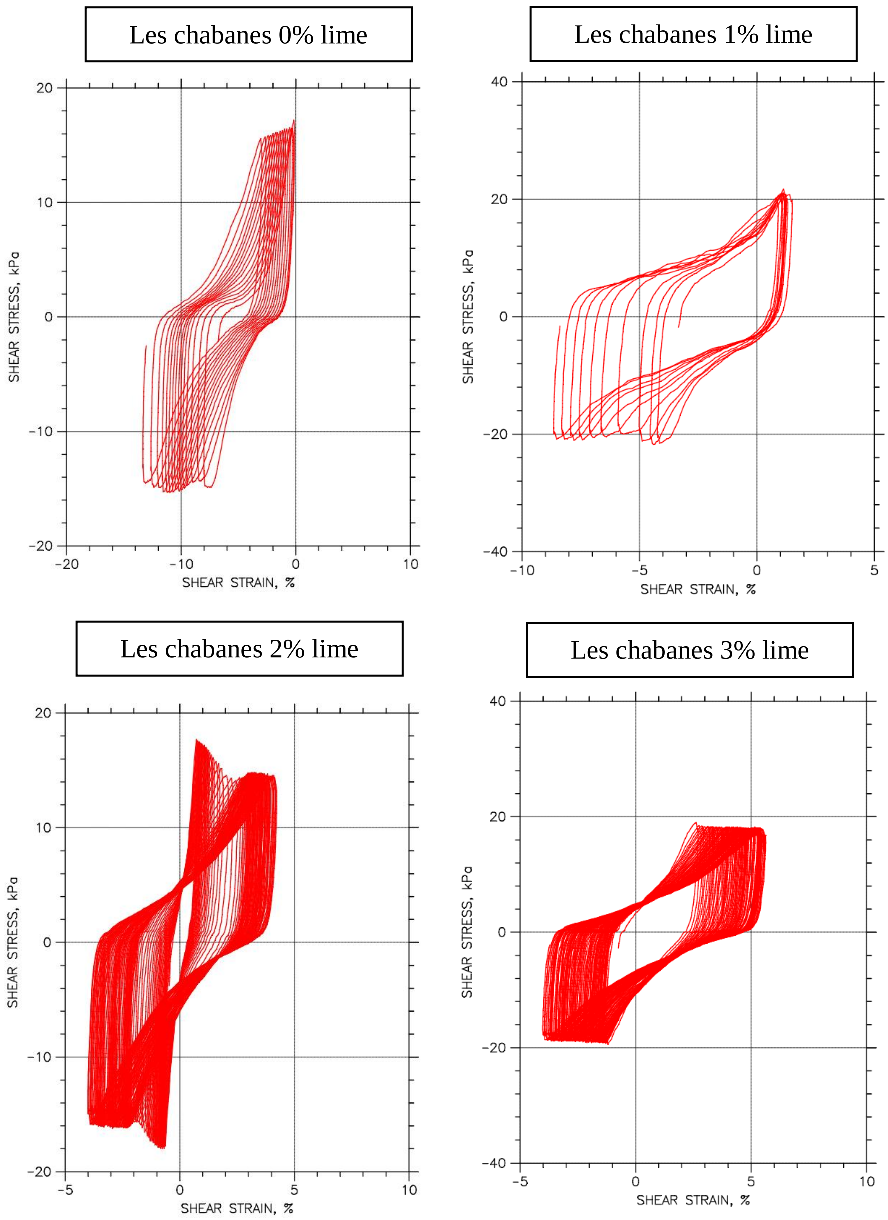


Figure 9. Evolution of cyclic stress with different percentages of lime in the marl from the Krim Belkacem site

The case of the Les-Chabanes site:



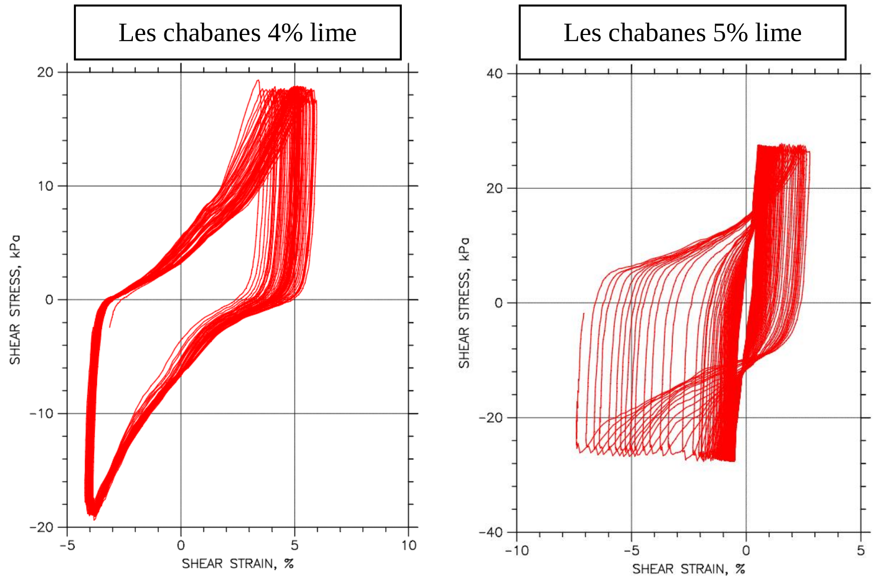
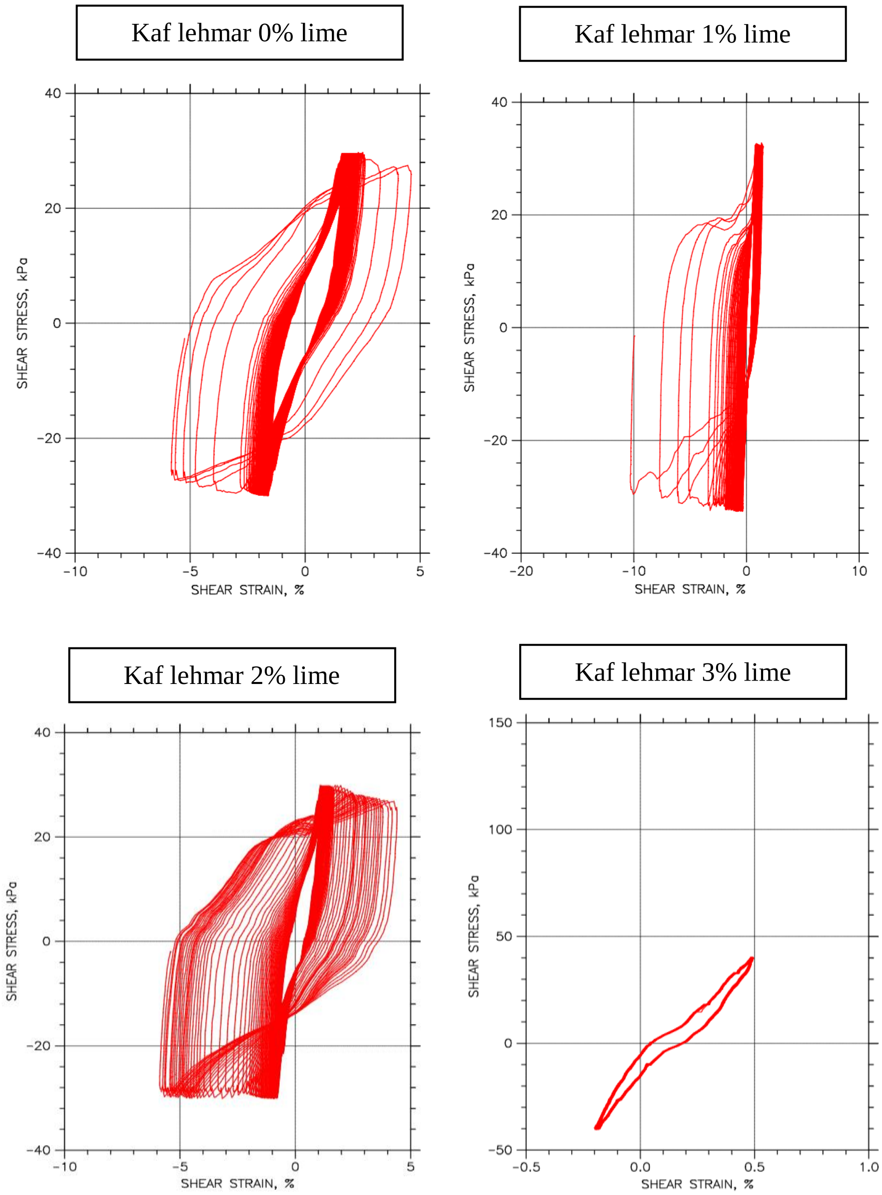


Figure 10. Evolution of cyclic stress with different percentages of lime in the marl from the Les chabanes site

The case of the Kaf-Lehmar site



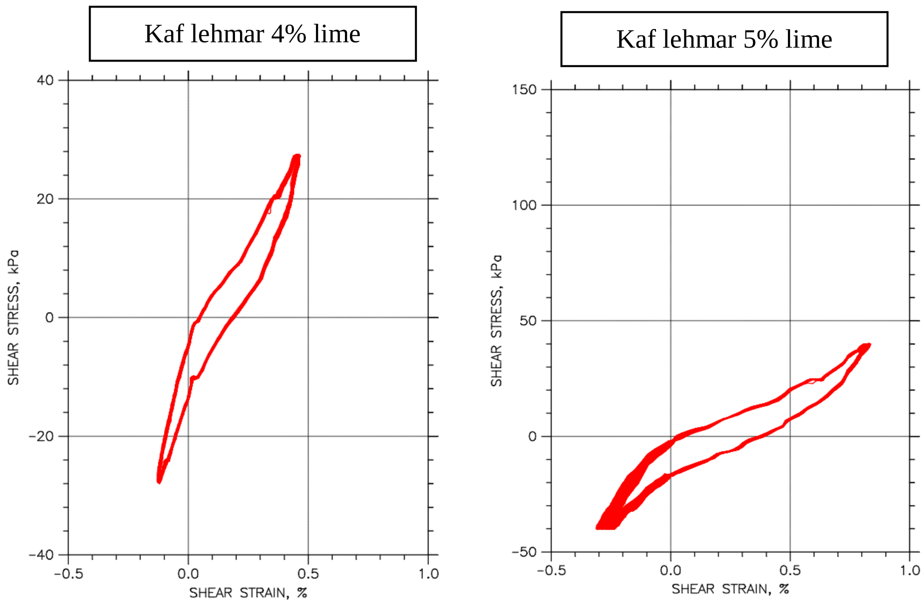
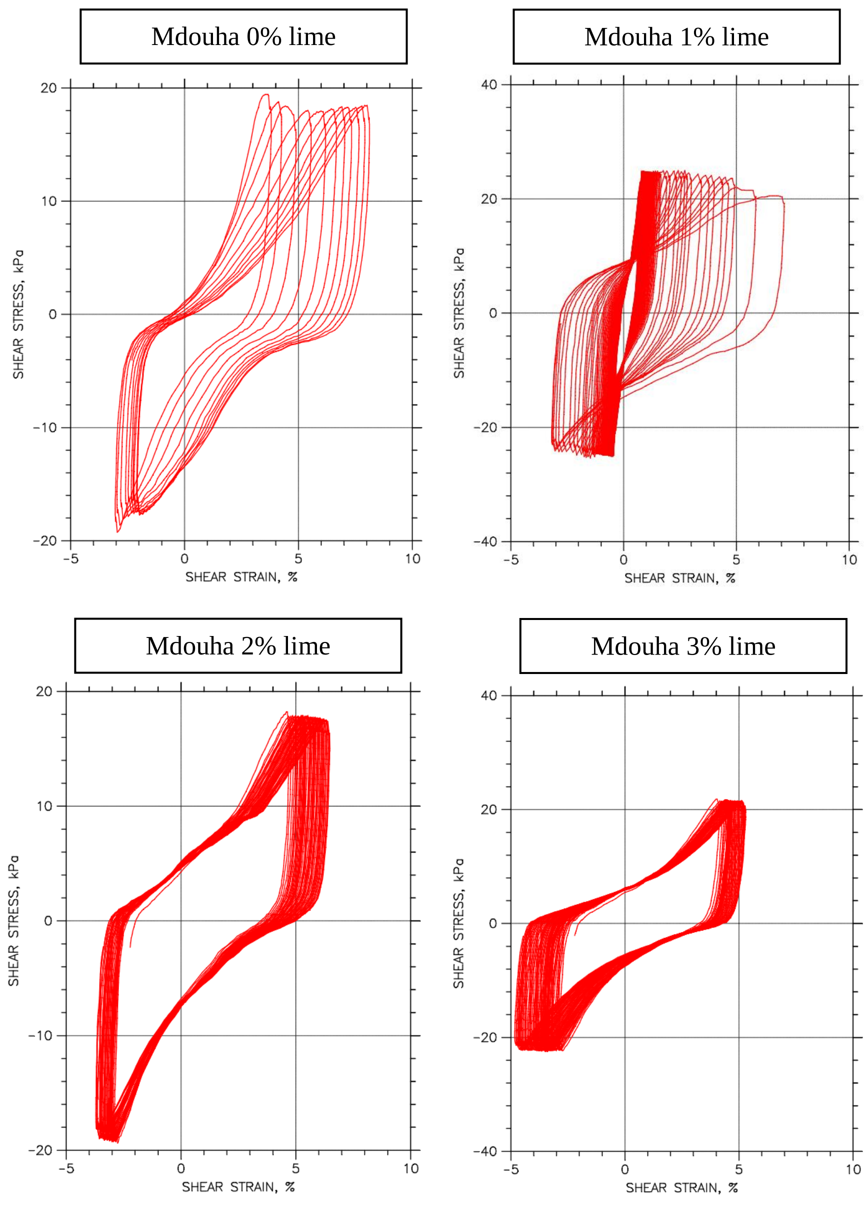


Figure 11. Evolution of cyclic stress with different percentages of lime in the marl from the Kaf- Lehmar site

The case of the Mdouha site



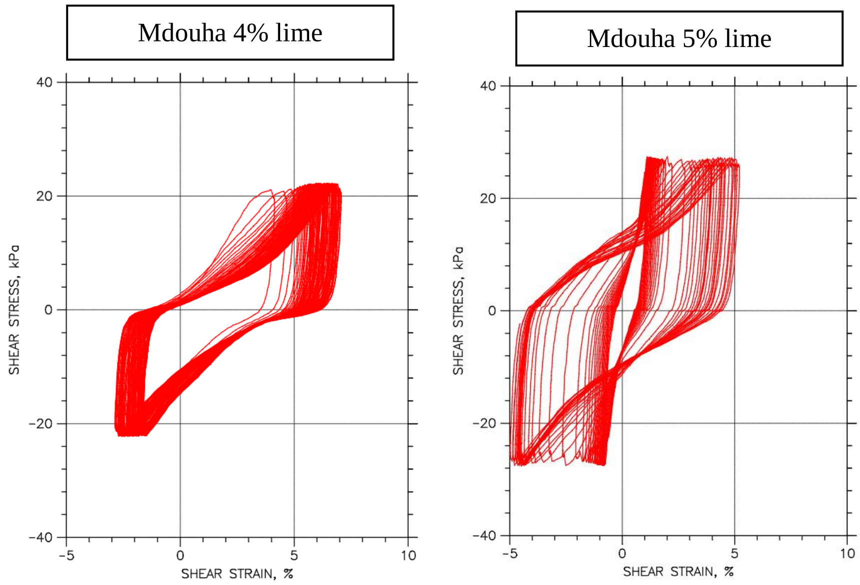


Figure 12. Evolution of cyclic stress with different percentages of lime in the marl from the Mdouha site

The case of the Oued Fali site

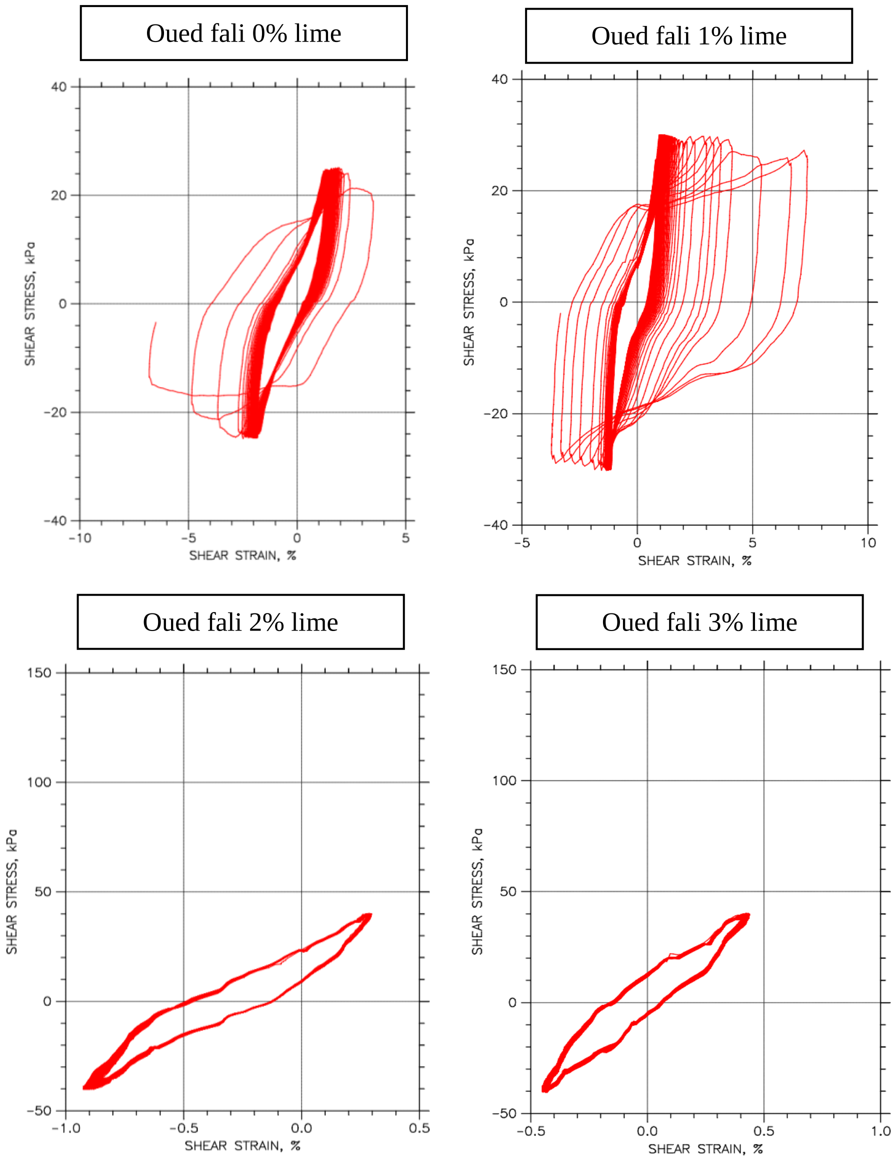


Figure 13. Evolution of cyclic stress with different percentages of lime in the marl from the Oued-Fali site

The case of the Boukhalfa site

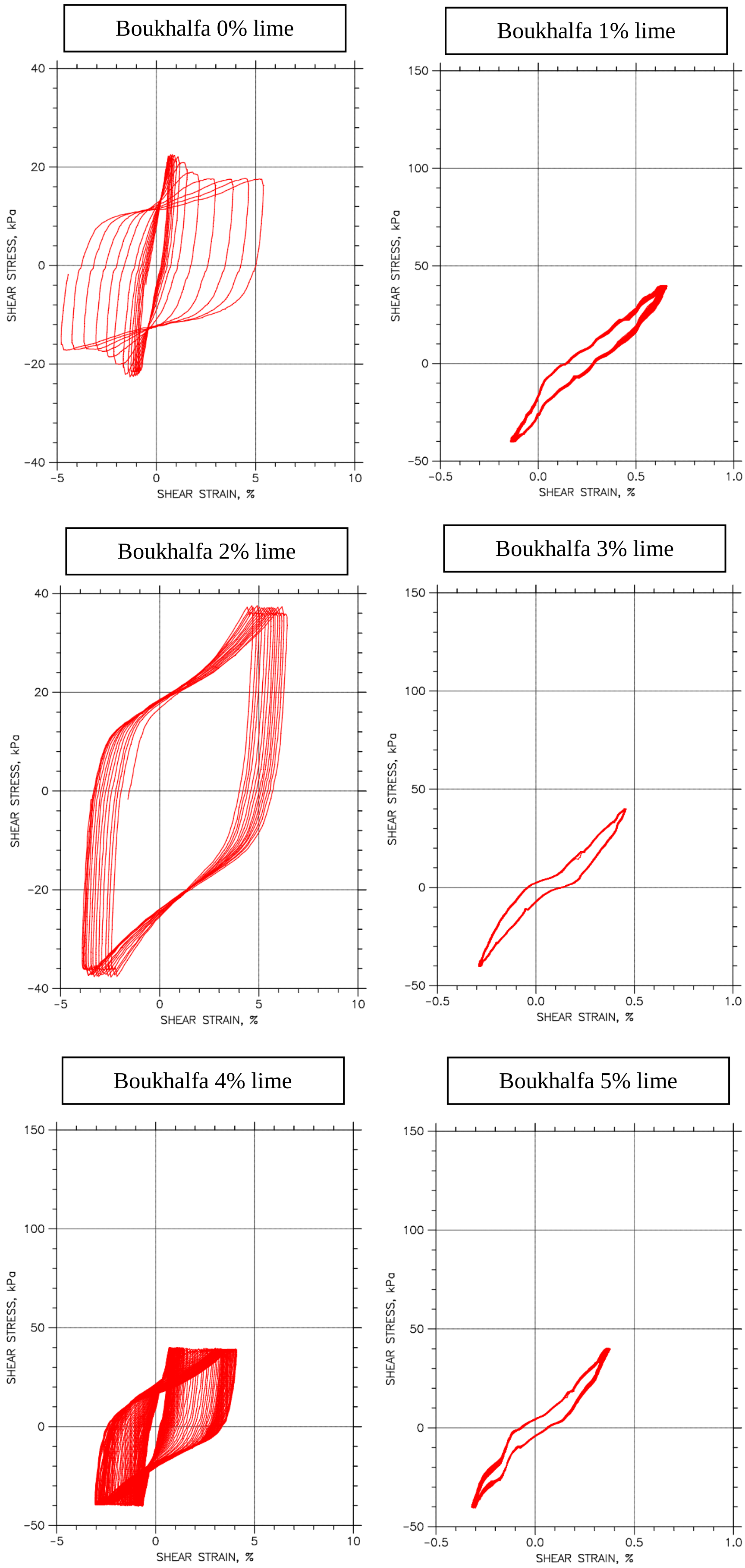


Figure 14 Evolution of cyclic stress with different percentages of lime in the marl from the Boukhalfa site

6.2. Effect of the Number of Cycles as a Function of the Lime Content

Figures 15 to 20 also show that adding lime to these marls affects the cycles required to reach failure. The number of cycles decreased for the marls at the Krim Belkacem, Les Chabanes, Kaf Lahmar, and Oued Fali sites compared with the healthy marl at the different percentages of lime addition: 1, 2, 3, and 4%. On the other hand, the number of cycles increased for the marls at the Mdouha and Boukhalfa sites for all the percentages of quicklime addition.

According to Galindo-Aires et al. (2019) [55], when new levels of deformation are reached in the soil structure, degradation can be observed in stages as a result of successive accommodations or sudden ruptures of consecutive microstructures so that each new position reached is stiffer. This effect only occurs under a certain stress level, which increases with the number of cycles, as in the case of M'douha and Boukhalfa.

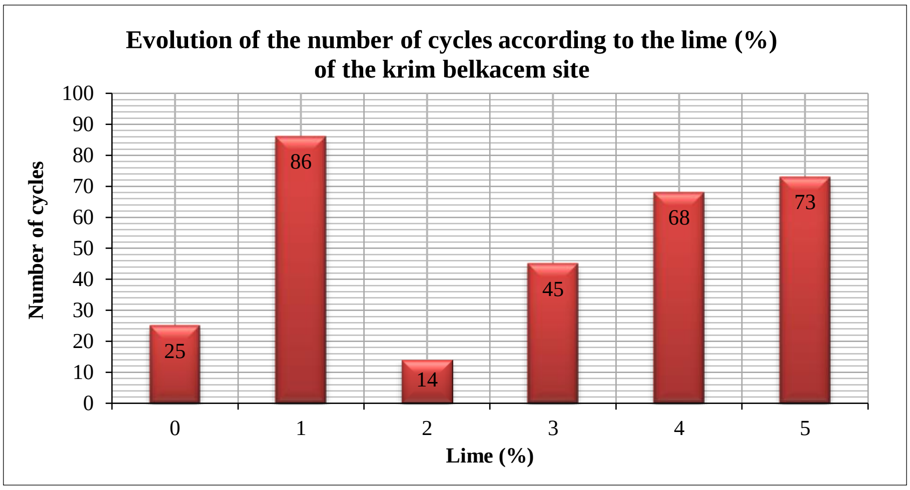


Figure 15. Evolution of the number of cycles with different percentages of lime in the marl from the Krim Belkacem site

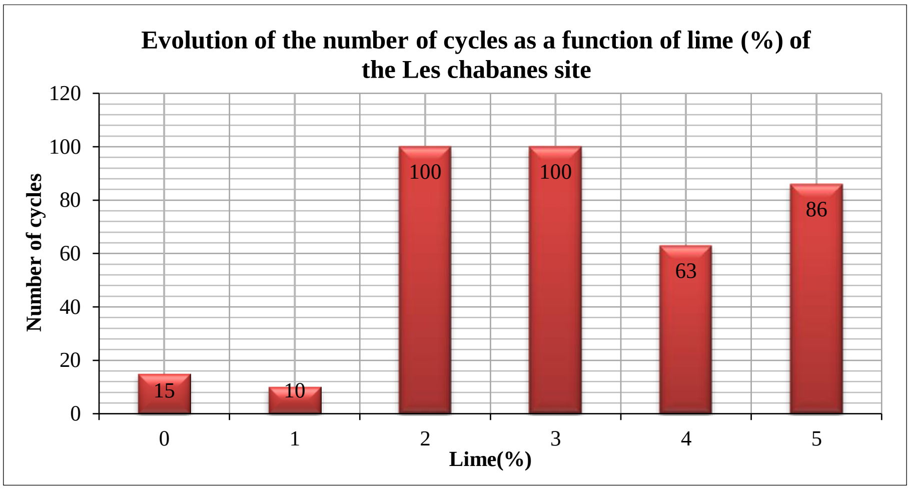


Figure 16. Evolution of the number of cycles with different percentages of lime in the marl from the Les Chabanes site

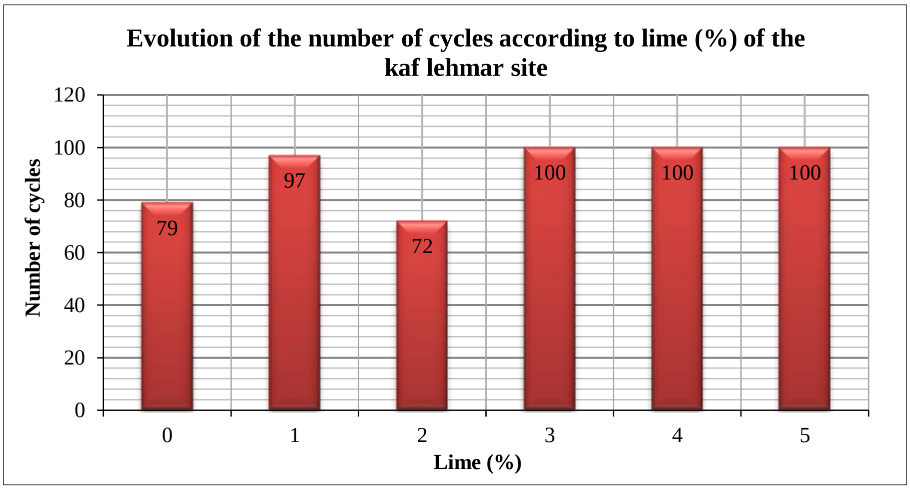


Figure 17. Evolution of the number of cycles with different percentages of lime in the marl from the Kaf Lehmar site

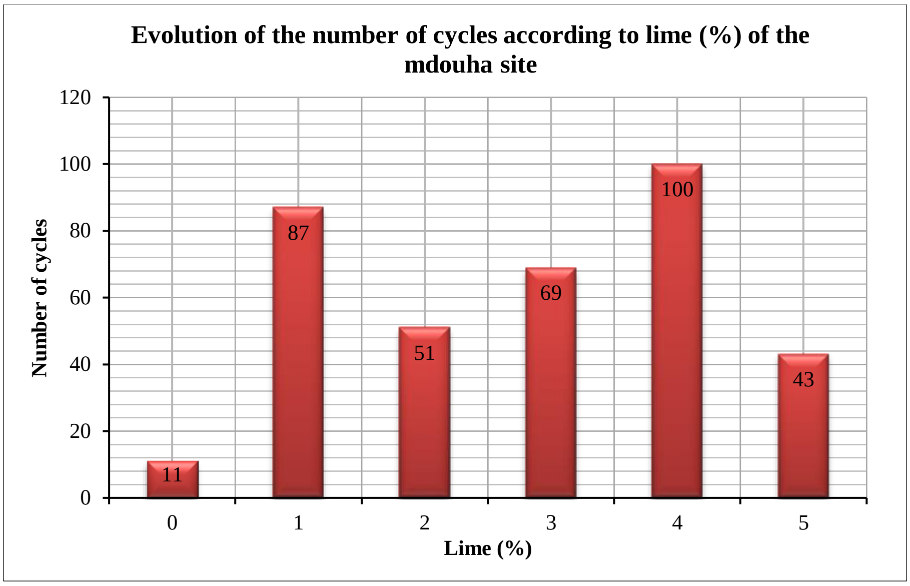


Figure 18. Evolution of the number of cycles with different percentages of lime in the marl from the Mdouha site

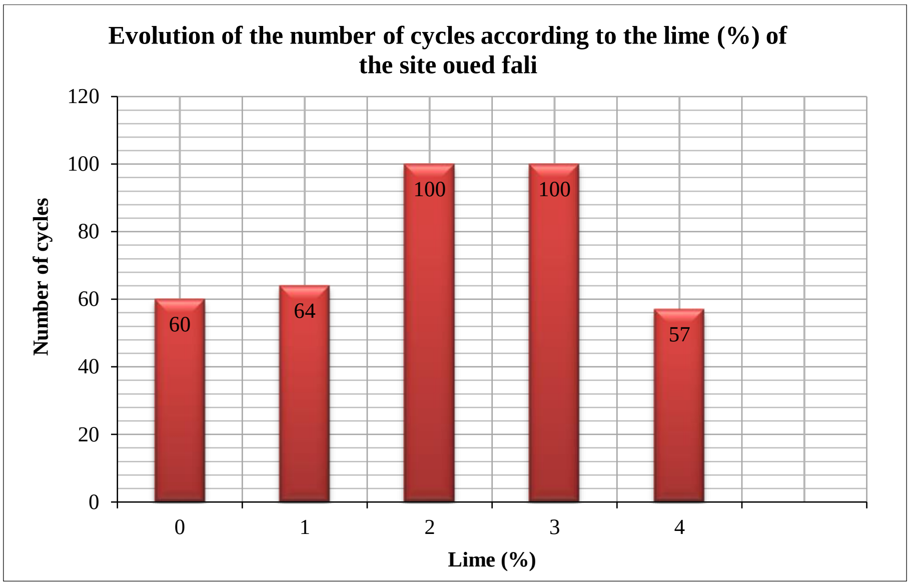


Figure 19. Evolution of the number of cycles with different percentages of lime in the marl from the Oued Fali site

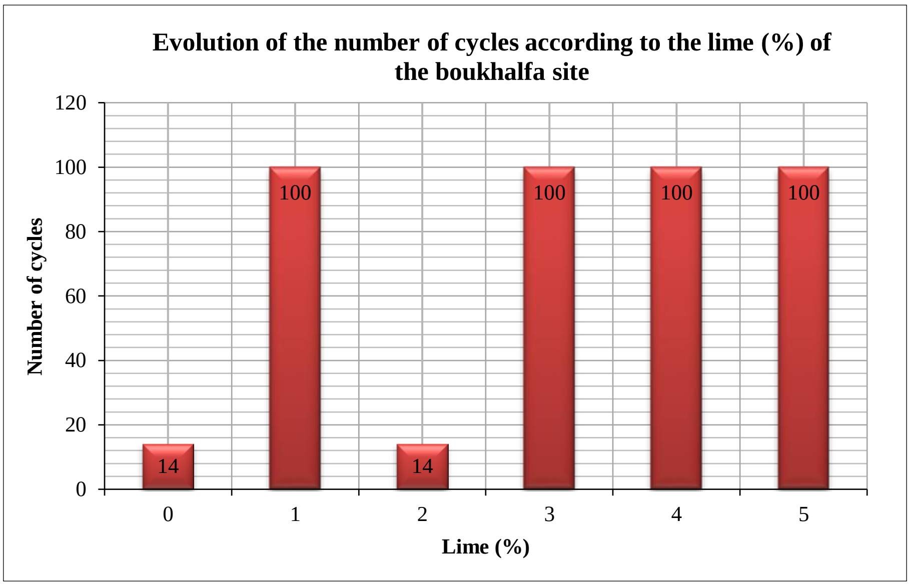


Figure 20. Evolution of the number of cycles with different percentages of lime in the marl from the Boukhalfa site

Table 12 shows the various changes in the number of cycles as a function of the Quicklime content.

Table 12. Changes in the number of cycles as a function of the percentage of quicklime added to the marl at the various sites

Lime (%) Site	0	1	2	3	4	5
Krim Belkacem	25	86	14	45	68	73
Les chabanes	15	10	100	100	63	86
Kaf Lehmar	79	97	72	100	100	100
Mdouha	11	87	51	69	100	43
Oued fali	60	64	100	100	57	
Boukhalfa	14	100	14	100	100	100

The increase in the number of cycles may be due to the accumulation (flocculation) of the particles, which have many attraction bridges and generate more resistance, requiring more cycles to break. The number of cycles can be explained oppositely by reducing the number of links between particles, with fewer attraction bridges between them. The improvement in the number of cycles is favourable to dynamic effects, as quicklime-stabilized marl will resist better and require more waves than healthy marl to reach the threshold of deformation and rupture.

For the Krim Belkacem marl, the maximum number of cycles recorded at 1% lime addition is 86; conversely, for the Kaf-Lehmar marl, the cycles stabilized at 100 cycles from 3% lime addition. There was a 26.58% increase in cycles compared with the healthy marl. For a 1% addition of lime, the number of cycles in the Krim belkacem and Kaf lehmar marls increased by 3.44 and 22.78%, respectively.

For the Les Chabanes and Oued-Fali marls, the improvement in the number of cycles is obtained at 2% and 1% added lime, respectively. The minimum number of 63 cycles is obtained for the Les Chabanes marl with 4% added lime, and this number has risen to 48 cycles, in other words, more than four times that of the healthy marl. The number of cycles stabilizes at between 2% and 3% added lime for the marls at these two sites. It is six times higher for the Les Chabanes marl and 66.6% higher for the Oued-Fali marl than the healthy marl. The marl from the Mdouha site recorded a minimum number of cycles at 5% added lime, with a value of 43, four times higher than that of healthy marl. The maximum number of cycles obtained with this marl-lime mixture is 100 cycles with 4% lime added, representing nine times the number of cycles of healthy marl.

Finally, the marl at the Boukhalfa site shows no improvement at 2% lime addition, and the number of cycles stabilizes at 3% lime addition. The maximum value recorded is 100 cycles, corresponding to seven times the number of cycles of healthy marl.

6.3. Effect of Undrained Cyclic Soil Shear Strength (Su) as a Function of Lime Content

Table 13 shows the different undrained cyclic strengths of the marls at the other sites, according to the different quicklime additions. Adding lime to the various marls increased this resistance overall, but not in proportion to the percentage of lime added. In the presence of lime, chemical reactions occur between the marl and lime particles, giving rise to attractive forces and stronger bonds more resistant to dynamic effects.

Table 13. Changes in undrained cyclic shear strength (Su) as a function of the percentage of quicklime added to the marl at different sites

Lime (%) Site	0	1	2	3	4	5
Krim Belkacem	13.2	11.4	33	51	29	42
Les chabanes	39	33.5	29	32	31	67
Kaf Lehmar	29	58	31.5	80	74	110
Mdouha	26.2	31.5	27.15	45.5	42.5	38
Oued fali	20.34	28.43	74.51	-	-	-
Boukhalfa	21.18	67.26	39.6	63.73	54.61	90.94

For the marl from the Krim Belkacem site with 0 and 1% lime added, this resistance was stable with no improvement recorded, which implies that the quantity of lime added is insufficient (1%) to improve (Su). Above this percentage, cyclic shear strength increases with the amount of lime added. Minimum strength is obtained at 4% added lime, which is 29 kPa, equivalent to twice that of healthy marl. The maximum resistance is recorded at 3% lime added, which is 51kPa, representing four times that of the healthy marl (13.2 kPa), indicating a good improvement that will allow us to conclude that these marls will be more resistant to seismic waves.

The marl from the Les Chabanes site reduces the cyclic shear strength Su for 1% lime addition from 39 to 33.5 kPa. It stabilizes between 2 and 3% and increases from 4% to reach a 71.79% increase compared to healthy marl for 5% lime addition. For a 2% lime addition, the strength decreased by 25.64%. For the marls at the Kaf-Lehmar and Oued-Fali sites, cyclic shear strength increased with the percentage of lime added. Their minimum resistance is 8.6% higher, and their maximum resistance is four times and 3.6 times, respectively, that of healthy marl. For 1% added lime, the strength of these marls increased by 100% and 39.77% respectively. For the marls at the Mdouha and Boukhalfa sites, the minimum values for cyclic shear strength are obtained at 2% added lime, and the maximum values recorded are obtained at 3% and 5%, respectively. For 1% added lime, the strength of Mdouha marl increased by 20.22% and by 3.17% for Boukhalfa marl. The increase of 3% added lime was 73.66% for Mdouha marl and 3% for Boukhalfa marl.

The increase in cyclic shear strength recorded in the marls at the various sites is due to chemical reactions between the marl minerals and quicklime, both in the short and long term. Short-term reactions include flocculation and quicklime migration, which improve physical geotechnical parameters. Long-term pozzolanic reactions (formation of aluminates and hydrated calcium silicates) lead to an accurate "setting" of the materials in contact, which improves mechanical geotechnical parameters.

The reduction in cyclic shear strength is due to the addition of sufficient lime, which causes aggregation (flocculation) of the fine particles, leading to coarse particles and a reduction in the surface area of the particle walls. This reduces friction angles and, therefore, shear strength.

6.4. Effect of Pore Pressure as a Function of Lime Content

The interstitial pressure response of the marls studied intensely depends on changes in their microstructure during lime stabilization and cyclic shear deformation. Figures 21 to 26 show changes in the pore pressure of the marl-lime mixture as a function of the amount of lime added. The results obtained are shown in Table 14.

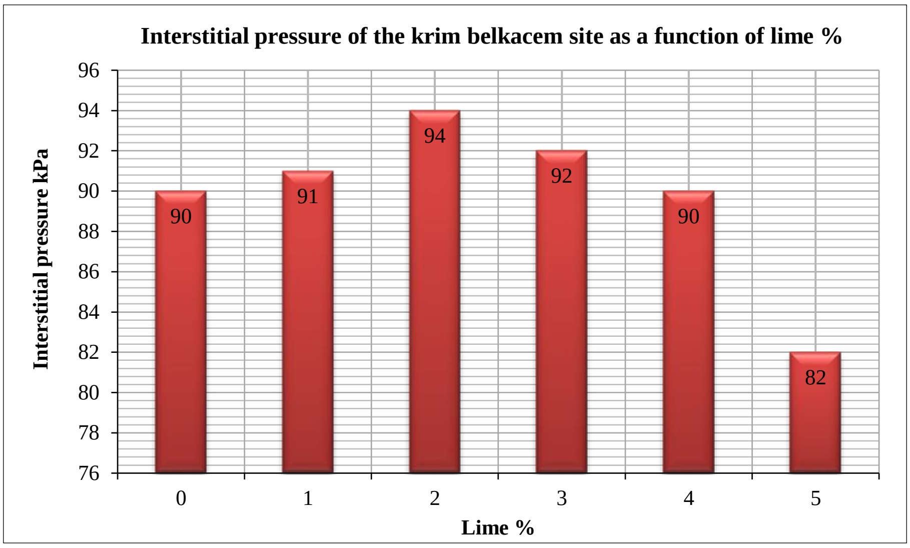


Figure 21. Evolution in interstitial pressure with different percentages of lime in the marl at the Krim Belkacem site

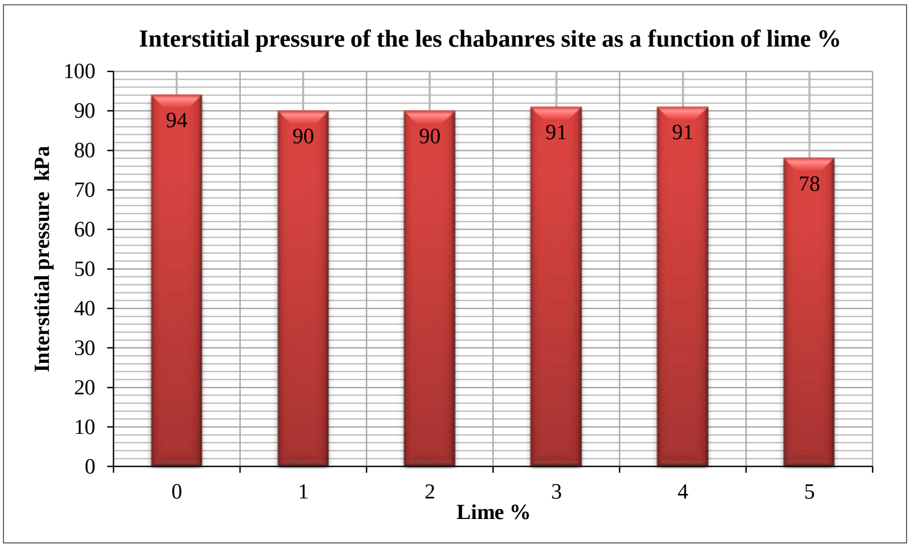


Figure 22. Evolution in interstitial pressure with different percentages of lime in the marl at the Les Chabanes site

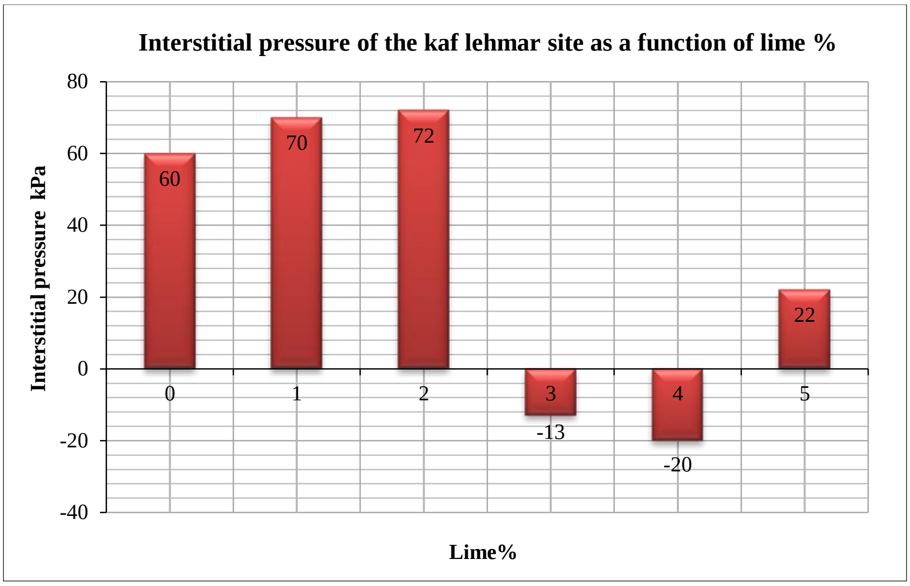


Figure 23. Evolution in interstitial pressure with different percentages of lime in the marl at the Kaf Lehmar site

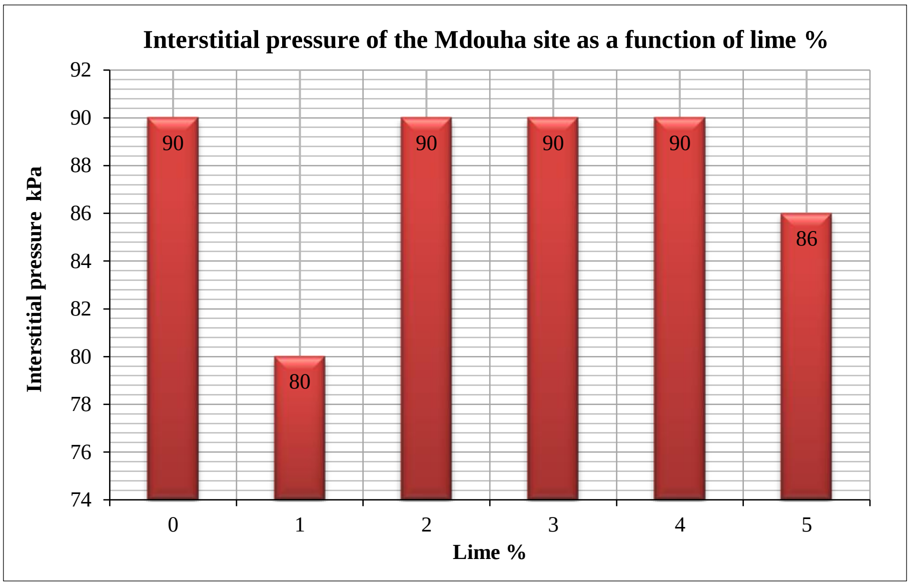


Figure 24. Evolution in interstitial pressure with different percentages of lime in the marl at the Mdouha site

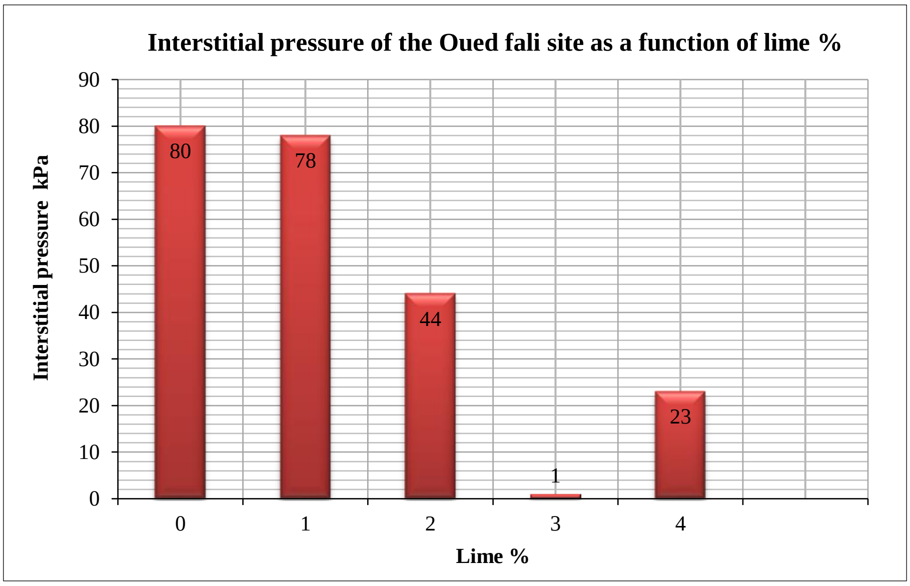


Figure 25. Evolution in interstitial pressure with different percentages of lime in the marl at the Oued Fali site

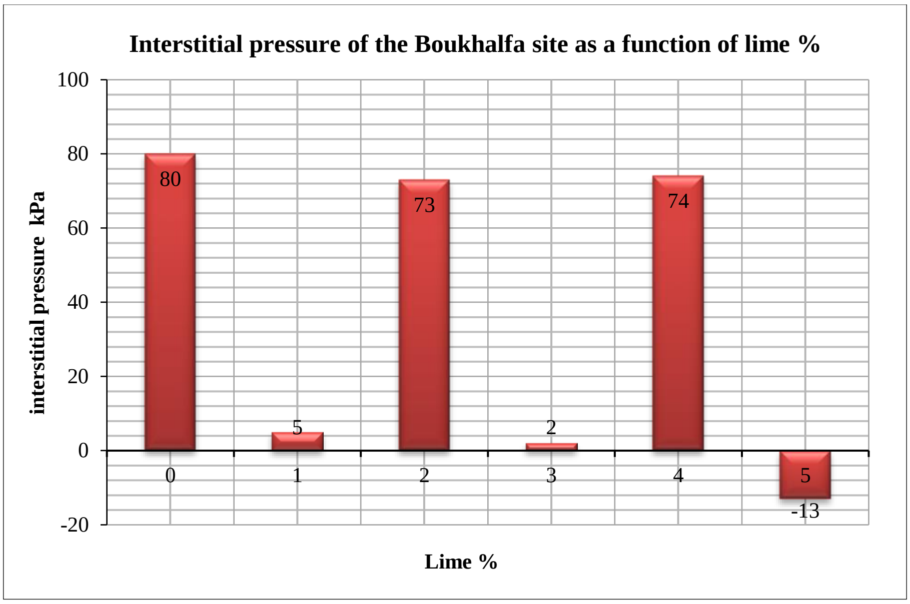


Figure 26. Evolution in interstitial pressure with different percentages of lime in the marl at the Boukhalfa site

Table 14. Evolution in interstitial pressure as a function of the percentage of quicklime added to marl at different sites

Lime (%) Site	0	1	2	3	4	5
Krim Belkacem	90	91	94	92	90	82
Les chabanes	94	90	90	91	91	78
Kaf Lehmar	60	70	72	-13	-20	22
Mdouha	90	80	90	90	90	86
Oued fali	80	78	44	1	23	-
Boukhalfa	80	5	73	2	74	-13

For the marls at the Krim Belkacem and Kaf-Lehmar sites with 1% and 2% added lime, the interstitial pressures increase and reach their maximum value at 2%, representing an increase of 4.45% and 20%, respectively, compared with the healthy marl. From 3% added lime, they decrease with increasing lime content, where their minimum value is recorded at 5%, representing decreases of 8.9% and 63.34%, respectively, of the healthy marl. For the marls at the Les Chabanes, Boukhalfa, Mdouha, and Oued-Fali sites, interstitial pressures decrease with the percentage of lime added. For 1% added lime, the interstitial pressure of these marls decreased by 4.25%, 93.75%, 11.11%, and 2.5%, respectively. For 2% lime, the interstitial pressure of the Oued Fali marl decreased by 45%.

For the marls at the Kaf-Lehmar and Boukhalfa sites stabilized with 3%, 4%, or 5% lime, the interstitial pressures become negative, confirming the existence of suction, which has a favorable influence on the shear strength of the marls. The cyclic shear strengths obtained at these percentages are high. For 3% added lime, the interstitial pressure of the Boukhalfa marl decreased by 97.5%, and for the Kaf Lehmar marl by 63.33% at 5% lime. The interstitial pressure values obtained for all the marls did not reach the vertical stress (100 kPa), which explains why the failure was due to cyclic softening [39].

The increase in interstitial pressure can be explained by the fact that the pressure in the marl-lime mixture encourages the pozzolanic reaction through the mobility of ions [8]. The transfer of ions released by the marl is made possible by the presence of this interstitial water, which encourages the formation of cement within a more or less extensive zone around the grains of lime. The rearrangement of particles and the consumption of interstitial water during this reaction encourage the contraction of marl aggregates, reducing pores and increasing water pressure. When lime is added, the decrease in interstitial pressure can be explained either by the evaporation of water caused by the lime (exothermic reaction) or by the presence of excess water in the lime, which separates the marl particles from each other, reducing the forces of attraction and creating more voids, thus reducing interstitial pressures.

The disorder affecting the properties of the marl is not random. It is linked to its structure, to fatigue, and to the history of its formation, which has its exact laws (tectonics, erosion, transport, and sedimentation, etc.) and to the very nature of the marl material, then to the extraction of samples (quality) and measurement errors, including those caused by the equipment and operating procedures, all of which makes it challenging to reproduce tests and results accurately.

7. Conclusions

This study enabled us to analyze the behavior of marl at various sites in Tizi-Ouzou by stabilizing it with quicklime. Laboratory tests were carried out to study the evolution of the physical and mechanical characteristics, using the simple cyclic shear test to analyze the dynamic behavior of the mixtures (marl + lime).

From this analysis, the addition of quicklime to these marls results in a significant improvement in their geotechnical (physical and mechanical) characteristics, with a reduction in void indices, plasticity indices, compression, and swelling coefficients, making marl soils less porous, less plastic, less compressible, and less swelling. Compared with the healthy marls' characteristics, the void indices decreased, with percentages varying from 1.81% to 7.27% for the different marls and from 73.52% to 99.84% for the plasticity indices. The compression coefficients and swelling indices have decreased from 5.88% to 41.15% and from 43.13% to 81.45%, respectively, resulting in a good improvement in the characteristics of these marls.

Overall, this quicklime stabilization showed a good improvement in stress, with increases ranging from 1.34 to 1.74, and in cyclic strength, with increases ranging from 1.45 to 4.29, giving good dynamic resistance before failure. The results showed that the marls from the different sites behaved differently with each percentage of lime added. On the other hand, adding quicklime to the various marls reduced the deformation rate, which varied from 36.58% to 92.45% compared with healthy marls, resulting in greater strength for these mixtures.

The interstitial pressure of most of these marls decreased with quicklime, with the reduction varying from 4.44% to 98.75% compared with healthy marls, depending on the percentage of lime added. On the other hand, the number of cycles obtained for all the marls increased with the addition of lime, with increases ranging from 1.26 to 9.09. This reduces the risk of slippage or collapse of the marl massifs. The cyclic softening mechanism obtains their failure mode.

The results obtained from these simple cyclic shear tests on the different marls confirm that these parameters are generally improved with the addition of quicklime, and their evolution is independent of the rate of addition. This makes it tricky to set a rate of lime for better efficiency in stabilizing these marls. The lime content of the marls studied is 3% and 4%, respectively. However, it should be noted that this rate can vary with the percentage of $CaCO_3$.

After analyzing and comparing the results obtained with the $CaCO_3$ that differentiates the marls, we found that the maximum improvements are obtained for marls with a $CaCO_3$ content of over 23%; this is seen in the compression and swelling results, which are reduced to a maximum compared to other marls with a $CaCO_3$ content of less than 23%. Deformations and pore pressures were at their highest values, while stresses and cyclic resistances were at their lowest. In our case, $CaCO_3$ at 23% is the rate that divides the marls, which allows us to say that there is a critical threshold for $CaCO_3$ content that significantly influences the effectiveness of stabilization. Further experiments are required on several marls with different $CaCO_3$ to confirm this threshold.

It should be stressed that the disorder affecting the properties of the marl is not random. It is linked to the history of their formation, which has its exact laws (tectonics, erosion, transport, sedimentation, etc.), and to the very nature of the marl material. Then, it is linked to the extraction of the samples (quality) and measurement errors, including those caused by the equipment and operating procedures, which do not make it easy to reproduce tests and results accurately.

Interesting avenues for further research and development are opening up in the context of this work and, thus, are prospects for extending it. We can mention three main perspectives:

- Perspective 1: Given the importance of structural effects on the behavior of marl soils, continuing research into the microscopic observation of this lime-stabilized material using SEM would be necessary. An analysis is needed to study these lime-treated marl soils' cracking and failure patterns and how they change with the addition rate, comparing them with breast soils. It would also be essential to carry out a more in-depth study of the microstructural mechanisms during cyclic shear deformation, as this structural change seems to influence the cyclic behavior of the various marls significantly.
- Perspective 2: These improvements will likely change when the treated marl is subjected to drying-wetting water stresses. The major challenge is to monitor this evolution and determine the durability of the treatment's effects.
- Perspective 3: Numerical work must be carried out to study the applicability of stabilized marl in the ground to facilitate its use in pavements.

In addition, as part of a future project, the authors intend to examine other characteristics, such as the altered rheology and environmental impacts of processed marl in the road sector.

8. Declarations

8.1. Author Contributions

Conceptualization, M.L. and B.M.; methodology, M.L. and B.M; software, M.L.; validation, M.L. and B.M.; formal analysis, M.L.; investigation, M.L.; resources, M.L.; data curation, M.L.; writing—original draft preparation, M.L.; writing—review and editing, M.L. and B.M; visualization, M.L.; supervision, M.L.; project administration, B.M.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

Data sharing is not applicable to this article.

8.3. Funding

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

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