Improvement of the physical and mechanical properties of a clay soil through the addition of sand and lime

Mohammed-Amin Boumehraz[1,*] , Achref Hamaidia[2] , Farida Boucetta[3] , Kamel Goudjil[4] , Mekki Mellas[5], Ines Chettibi[6], Khawla Baayou[6]

[1] *Laboratory of Research in Civil Engineering (LRGC), University of Biskra, 07000 Biskra, Algeria; and Department of Civil Engineering, University of Jijel, 18000 Jijel, Algeria; boumehraz.m.a@univ-jijel.dz*
[2] *Department of Civil Engineering, University of Souk Ahras, 41000 Souk Ahras, Algeria. hamaidia_achref@hotmail.fr*
[3] *Laboratory of Physics of Thin Films and Applications, University of Biskra, 07000 Biskra, Algeria. farida.boucetta@univ-jijel.dz*
[4] *Laboratory INFRARES, Department of Civil Engineering, University of Souk Ahras, 41000 Souk Ahras, Algeria. k.goudjil@univ-soukahras.dz*
[5] *Laboratory of Research in Civil Engineering (LRGC), University of Biskra, 07000 Biskra, Algeria. m.mellas@univ-biskra.dz*
[6] *Department of Civil Engineering, University of Jijel, 18000 Jijel, Algeria*

[*] *Corresponding Author*

Abstract:
The studied clayey soil exhibits several geotechnical issues, including low bearing capacity and high plasticity. This study aims to improve the physical and mechanical properties of this soil by adding different proportions of sand and lime, or their combination. The studied dosages are as follows: lime (L) at 2%, 6%, and 12%; sand (S) at 5%, 15%, and 30%; and combinations (2% L + 5% S), (6% L + 15% S), and (12% L + 30% S). The laboratory tests performed include Atterberg limits, Modified Proctor, direct shear test, and the California Bearing Ratio (CBR) index. The results show that the addition of sand reduces the liquid and plastic limits, increases the dry density, and decreases cohesion at high content. The incorporation of lime significantly improves the CBR index, increases the plastic limit, and reduces the optimum moisture content. The best results are obtained with the combined treatment (12% L + 30% S), which shows liquid and plastic limits of 39.97% and 19.56%, a maximum dry density of 16.82kN/m³, an optimum moisture content of 16.00%, and a high CBR index of 36.62. Therefore, the lime/sand combined treatment represents an effective solution for improving the geotechnical properties of clayey soils.

1. Introduction

Weak soils, such as loose sands, organic soils, and soft clays, are not naturally suitable for road construction projects because they lack the physical properties required to ensure the stability and durability of structures. To address these deficiencies, numerous studies have investigated the stabilisation of such soils using various additives, including lime, cement, and fly ash, with the aim of improving their geotechnical properties, increasing the bearing capacity of foundation layers, and reducing settlements [1]. In addition to these traditional stabilisers, other materials derived from environmental or societal sources, such as expanded polystyrene, brick dust, fibres, and certain organic matter, have also been studied. More recently, the use of iron ore tailings, combined with cement-based inorganic binders, has been explored as a cost-effective and sustainable solution in road engineering. This approach offers a dual benefit: valorising industrial waste while reducing its accumulation in the environment [2]. Such treatment significantly enhances the mechanical properties of soils, particularly their strength and bearing capacity, by forming cementitious bonds between particles. Moreover, it helps limit swelling and shrinkage phenomena typical of plastic soils such as clays, thereby improving their suitability for road infrastructure [3].

Lime, by increasing soil pH, promotes the dissolution of pozzolanic compounds, which subsequently react with calcium to form durable cementitious bonds. This process reduces plasticity, improves workability, and strengthens the mechanical properties of soil, such as shear strength, compressive strength, and the CBR value [4,5]. The addition of lime releases Ca^{2+} and OH^- ions: the former replaces monovalent cations and binds with clay minerals, reducing electrostatic repulsion and promoting particle aggregation, while the latter increases alkalinity [6]. The effectiveness of stabilisation depends on soil mineralogy: the optimal lime content generally ranges from 2% to 10%, depending on the clay type [4], with 4-6% for kaolinite, about 8% for illite, and 2–8% for montmorillonite. Different lime types (hydrated, quicklime, dolomitic) can be used. The combination of lime and cement kiln dust considerably enhances geotechnical properties: for example, 6% lime with 16% kiln dust reduces swelling from 19% to 2%, while 9% lime with 16% kiln dust yields a CBR value of approximately 35.95% [7,8]. According to Clementine et al. (2024) [9], the optimal addition of 8% silica sand combined with 2% lime significantly improves the stabilisation of expansive black cotton soil. This treatment increases the maximum dry density, reduces the optimum moisture content, and results in CBR and unconfined compressive strength values of 12.03% and 188.39 kPa, respectively, indicating a substantial strength gain. Younes et al.

(2023) [10] found that lime-treated sand, at lime contents ranging between 5–15% for high dry density and 7–15% for low dry density, exhibited brittle behaviour. In contrast, cement treatment provided a significant improvement in strength compared to lime-treated sand.

Salih at al. (2024) [11], reported that lime addition to expansive soils leads to a decrease in maximum dry density and an increase in optimum water content, due to the formation of a flocculated structure and the higher water demand associated with lime dissociation. Lime contents of 4–6% applied to clay soils also reduce shrinkage, swelling, and plasticity. According to Elazzabi A. (2024) [4], the optimal hydrated lime content for soil stabilisation is 8%, with a treatment time of 24 hours. The incorporation of hydrated lime considerably enhances soil mechanical characteristics. Specifically, the internal friction angle increases from 29.2° to 37.23° with a coefficient of variation of about 10.25%, while cohesion rises from 0kPa to 28kPa with a coefficient of variation of around 73.59%. Moreover, this stabilisation markedly increases the CBR value of sandy soil, improves maximum dry density, and decreases optimum moisture content as lime content increases, with an estimated coefficient of variation of 19.32%. Prasad et al. (2023) [12], investigated the effect of adding foundry sand and lime to clay soil. Tests performed at 0, 7, and 14 days showed a notable improvement in geotechnical properties. With 10% foundry sand and 5% lime, the optimum moisture content increased from 22% to 27%, while the maximum dry density initially decreased and then rose again when proportions reached 20% sand and 10% lime. The CBR index increased from 9.56 to 12.62 with 20% sand and 10% lime. Overall, the combination of 10% foundry sand and 5% lime proved most effective, particularly after 14 days of curing. Amadi et al. (2017) [13], demonstrated that lime addition reduces the liquid limit of soil, decreasing from 53% (natural soil) to 40.8% with 10% quicklime and to 46.28% with 10% hydrated lime. The plasticity index also dropped, reaching 10.55% with quicklime and 15.28% with hydrated lime. These immediate changes are attributed to cation exchange, where calcium ions released by lime replace metallic ions in the clay, thus increasing the plastic limit and reducing the plasticity index. In the longer term, pozzolanic reactions further amplify this trend, resulting in an additional decrease in soil plasticity.

According to the results reported by Abu-Elgasim at al. (2025) [14], the addition of 8% lime led to a significant improvement in the soil's compaction characteristics. The maximum dry density increased to 1.62 g/cm³, while the optimum moisture content decreased, indicating improved soil stability. Furthermore, a very pronounced increase in the California Bearing Ratio (CBR), which reflects the soil's load-bearing capacity, was observed: the CBR value rose from 1.7% for untreated soil to 50.7% with 8% lime, corresponding to a substantial gain in strength. Alhakim et al. (2023) [15] demonstrated that the shear behaviour of sandy soil significantly improves with the incorporation of additives, reaching maximum values at lime contents of 9% and at 12% for the lime (L)–metakaolin (MK) mixture (L–MK). Overall, lime–metakaolin (L–MK) treatment exhibits superior shear performance compared to lime-only treatment, with an optimal combination of L80MK20. The cohesion and internal friction angle of the untreated soil, initially 4.33kPa and 32.43°, increase to 57.81 kPa and 36.78°, respectively, for mixtures containing 12% L80MK20. The improvement in the shear behaviour of treated sands is mainly attributed to the densification effect and the reduction of intergranular voids. This enhancement may also be associated with short-term reactions induced by the presence of a highly active pozzolan in the L–MK mixtures. Hussein (2021) [16], studied the effect of sand columns on expansive clay soils and showed that they effectively reduce the swelling of these soils. This reduction is even more pronounced when the columns are stabilised with lime. The replacement area ratio (RAR) plays a key role in the treatment's effectiveness, with swelling decreasing as the RAR increases. Stabilising the columns with 20% lime achieves a maximum reduction of approximately 92.27% in swelling potential at an RAR of 35.84%. Hashemi et al. (2015) [17] prepared mixtures of sand (10% to 20%) and bentonite (80% to 90%) in various proportions, stabilised with 1% lime, and compacted near their optimum density. After 2 to 4 months, the bentonite reacted with the lime, causing contraction and the formation of cracks in the aggregates, thereby increasing macroporosity and decreasing microporosity. This phenomenon is attributed to the bimodal microstructure of the mixture: the granular sand skeleton stiffens the matrix, while the bentonite shrinks, leading to crack formation. This study aims to analyse the influence of chemical treatment of clay soil from the Jijel highway project by adding lime at different percentages (2%, 6%, and 12%), sand at various contents (5%, 15%, and 30%), as well as their combination. The objective is to assess the impact of these modifications on the physical and mechanical properties of the soil, which exhibits significant geotechnical problems, particularly low bearing capacity leading to settlements and subsidence.

2. Materials used

2.1. Sand

The sand used in this study is a natural marine sand, mainly composed of medium- to fine-grained sand. The physical properties of the sand are presented in Table 1.

Table 1. Physical properties of sand.

Properties	Natural water content (Wn) [%]	Bulk density [t/m³]	Sand Equivalent Test (SE) [%]
Sand	3.40	2.50	97.74

2.2. Lime

In this study, the quicklime used comes from a plant in Algeria. This product has a particle size below 0.08 mm and contains up to 90% CaO, along with low contents of SiO_2 and MgO [18].

2.3. Clay

The soil used in this study is a plastic clay collected from the Achouat area, Jijel (Algeria). The physical and mechanical properties of the clay are presented in Table 2.

The grain size distribution curve obtained by sieving and sedimentation analysis of the clay is presented in Fig. 1.

2.4. Potable water

In general, drinking water is considered free from impurities, and its physicochemical properties are deemed suitable for geotechnical testing.

Table 2. Physical and mechanical properties of clayey soil

Properties	Natural water content (Wn) [%]	Bulk density [kg/m³]	Liquid limit (LL) [%]	Plastic limit (PL) [%]	Plasticity index (PI) [%]	Maximum dry weight density (γ_{dmax}) [kN/m³]	Optimum water content [%]	CBR index [-]	Angle of internal friction (φ) [°]	Cohesion (C) [kPa]
Clay	13.57	2080	49.59	26.28	23.31	16.25	22.50	2.20	10.92	20.56
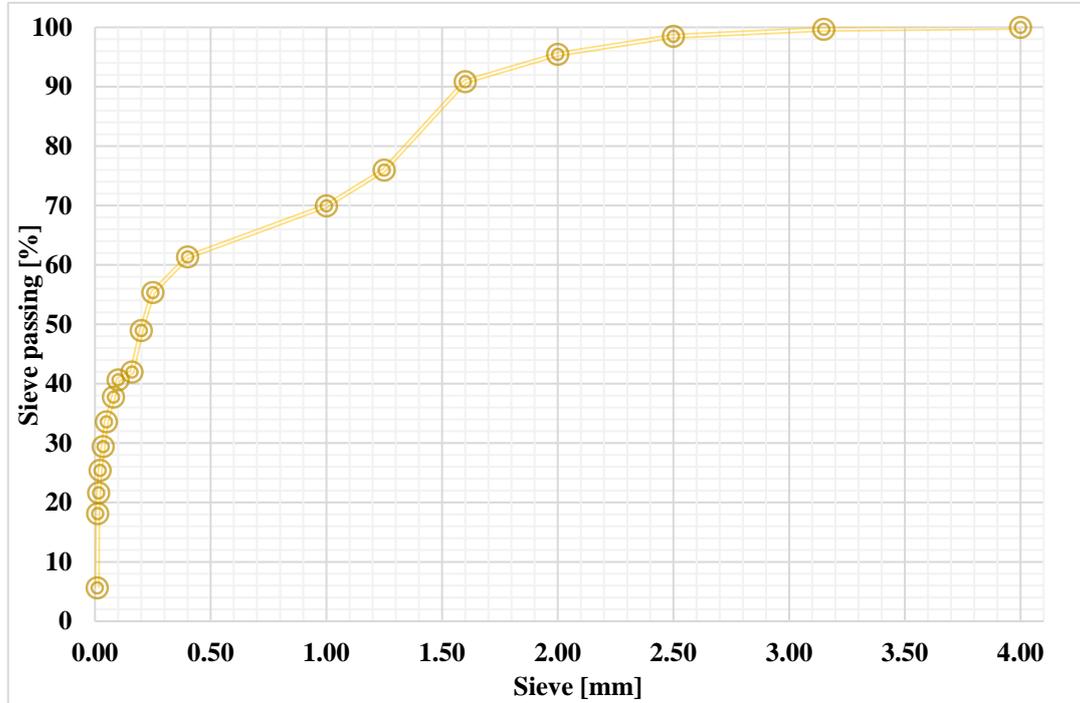
Fig. 1. Particle size distribution curve of a clayey soil

3. Sample preparation

This study investigates the effect of different lime (L) addition rates (2%, 6%, 12%), sand (S) addition rates (5%, 15%, 30%), and their combinations (2%L + 5%S, 6%L + 15%S, and 12%L + 30%S) on soil behaviour. These percentages are mass percentages, calculated from the quantities used for each test in accordance with the applicable standards. These tests were conducted in the department's Soil Mechanics Laboratory. The results obtained are presented as comparative curves, allowing them to be compared with the properties of the untreated soil and to track the changes induced by the different treatments. Four geotechnical tests were performed before and after treatment to evaluate these changes: Atterberg limits (liquid limit, plastic limit, and plasticity index), Modified Proctor test, CBR test, and direct shear box test.

4. Results and discussion

4.1. Atterberg limits

The tests concern the fine fraction of soil smaller than 0.4 mm, according to the European standard NF P 94-051 (see Fig. 2). The soil is left to rest to allow the clay particles to settle, after which the supernatant water and suspended sludge are removed before complete drying in an oven.

Fig. 2. Procedure of the Atterberg limits test on clay soil

Liquid limit (LL): The soil is mixed with water to form a paste, which is placed in the Casagrande cup (approximately 70 g of soil before or after treatment). The number of blows required to close a groove traced at the centre is recorded, and samples are taken for analysis. Each test is repeated at least four times after a 24-hour preparation period.

Plastic limit (PL): The soil is kneaded and rolled into a 3 mm diameter rod approximately 10 cm long. The plastic limit is reached when the rod cracks when lifted 1 cm at the center. This test is repeated at least four times for each treatment type [19].

Figure 3 shows the variation of the liquid limit (LL), plastic limit (PL), and plasticity index (PI) as a function of different sand contents (5%, 15%, and 30%).

According to Figure 3, it is observed that the liquid limit gradually decreases as the percentage of added sand increases, reaching 32.30% for a sand treatment rate of 30%. Moreover, it was observed that the plastic limit (PL) of the clay mixed with sand increases progressively up to a sand addition of 15%, corresponding to a PL value of 27.31%. Beyond this percentage, the PL decreases gradually, reaching a value of 23.73% at a sand content of 30%. Furthermore, the plasticity index shows a continuous decrease up to a sand content of 30%.

These results indicate that adding sand in varying proportions (5%, 15%, 30%) significantly alters the plastic properties of the soil. This addition leads to a notable reduction in the liquid limit, a slight initial increase in the plastic limit, followed by a decrease beyond 15%. The plasticity index continuously decreases with increasing sand content. This reduction reflects a narrowing of the plasticity range, corresponding to a gradual transition from a highly plastic material to a less plastic and less cohesive soil.

The curves showing the variations of the Atterberg limits with different lime contents (2%, 6%, and 12%) are presented in Fig. 4.

Figure 4 shows that the liquid limit of the treated clay increases up to a lime content of 6%, then slightly decreases at 12%, reaching 58.67%. The plastic limit reaches a maximum of 38.67% at 2% lime, before gradually decreasing to 22.14% at 12% lime. The plasticity index initially decreases to 2%, then increases continuously to 36.53% at 12% lime. These results highlight the significant influence of lime addition on the soil's plastic properties. The initial increase in the liquid and plastic limits can be attributed to surface physico-chemical reactions. However, beyond a certain threshold, deeper chemical processes, such as flocculation and pozzolanic reactions, modify the soil's internal structure, leading to a reduction in plasticity and an improvement in cohesion [4,5].

Figure 5 shows the effect of treating the soil with a combination of lime and sand on its Atterberg limits.
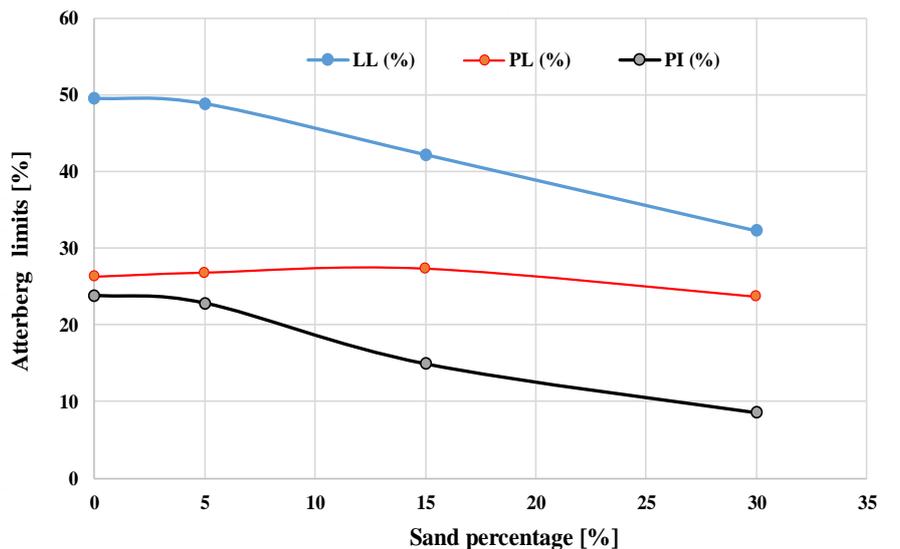

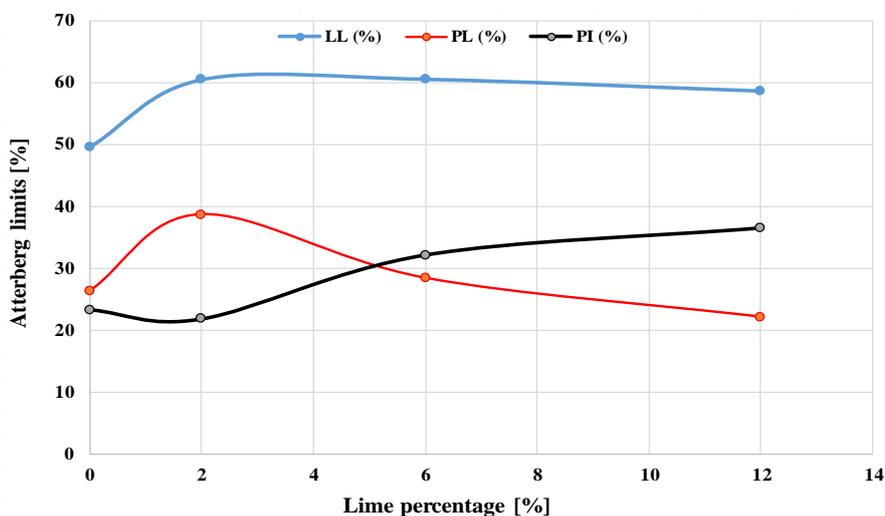**Fig. 3.** Atterberg limits curves of soil mixed with varying percentages of sand

Fig. 4. Atterberg limits curves of the soil as a function of varying lime contents
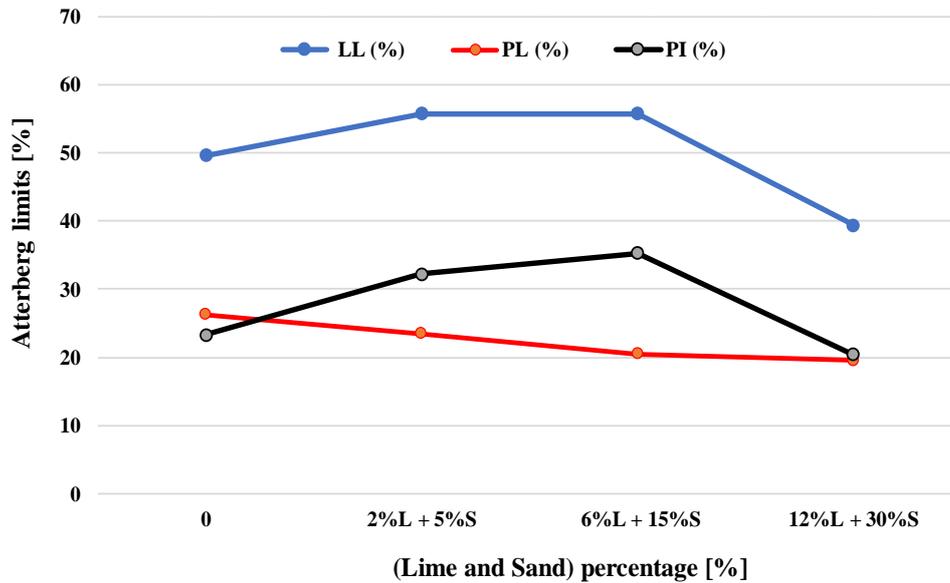
Fig. 5. Variation of the clay's Atterberg limits with different lime and sand contents

According to Figure 5, the following observations were made:

- The liquid limit of the clay-sand-lime mixture gradually increases with the addition of small percentages of binders, reaching a maximum of 55.77% for the (6%L + 15%S) combination. In contrast, a marked decrease is observed at higher dosages (12%L + 30%S). This suggests that small amounts of lime enhance the soil's water retention capacity, whereas higher dosages promote a more stable structure, reducing this capacity [4-6].
- The plastic limit gradually decreases, reaching 19.56% when the lime and sand proportions increase to (12%L + 30%S). This trend indicates that the soil requires less water to reach the plastic state, reflecting a reduction in plasticity and an improvement in compaction. These results are consistent with the literature, particularly the work of Alhakim et al. [15].
- The plasticity index initially increases, reaching a maximum of 35.30% for the (6%L + 15%S) combination, before dropping significantly to 20.41% for (12%L + 30%S). This evolution can be attributed to improved soil cohesion at intermediate dosages, while an excess of sand dilutes the clay fraction, thereby reducing overall plasticity.

The combined lime and sand treatment significantly influences the soil's plastic behaviour. Small dosages temporarily enhance its deformability without failure, whereas higher proportions, particularly of sand, reduce the Atterberg limits, reflecting an increased mechanical stability of the material.

4.2. Results of the modified Proctor test

This test was carried out in accordance with the NF P 94-093 standard. The clay used has a particle size of less than 5mm. For each test, approximately 2.5 kg of clay was mixed with water to obtain a homogeneous paste, which was then divided into five layers of the same water content. Each layer was compacted in a Proctor mould using a precise number of tamper blows. After filling and levelling, the mould was weighed, and samples were taken to determine the water content. The procedure was repeated for different water contents, and the samples were oven-dried for 24 h to perform the before-and-after drying weights [20]. The Proctor test curves before and after treatment (with sand, with lime, and mixed) are presented in Fig. 6.

Based on the results presented in Fig. 6, the following observations were made:

- According to Figure 6A, it was found that the addition of sand to clay leads to a progressive increase in maximum dry weight density, from 16.25 kN/m³ to 17.39 kN/m³. This improvement is explained by the role of sand as a granular material, which reinforces the soil structure, facilitates compaction, and reduces internal voids between fine clay particles. At the same time, the optimum water content decreases significantly, from 22.5% to 17.10%, indicating that the soil requires less water to achieve maximum compaction. Consequently, adding sand reduces the water absorption capacity of the clay and decreases the plasticity of the mixture.
- Figure 6C shows that the maximum dry weight density also increases steadily with the combined addition of lime and sand, from 16.25 kN/m³ to 16.82 kN/m³. This improvement reflects enhanced cohesion and more efficient compaction of soil particles, due to the chemical reactions of lime and the structural effect of sand as a granular stabiliser. Simultaneously, the optimum water content gradually decreases from 22.5% to 16.00%, indicating that less water is needed to reach optimal compaction. This reduction in porosity and improvement in cohesion result from the combined action of lime and sand. These findings are consistent with those reported by Elazzabi [4].
- According to Figure 6B, the addition of 2% lime initially causes a decrease in the maximum dry weight density, from 16.25 kN/m³ to 15.38 kN/m³. This low lime content is insufficient to effectively stabilise the soil, leading to a temporary dispersion of clay particles before chemical reactions begin. In contrast, for higher lime contents of 6% and 12%, the maximum dry weight density progressively increases, reaching 15.71 kN/m³ and 15.79 kN/m³, respectively. This behaviour is attributed to chemical reactions between lime and clay minerals (pozzolanic reactions), which produce cementing compounds that enhance cohesion and reduce porosity [4,5].
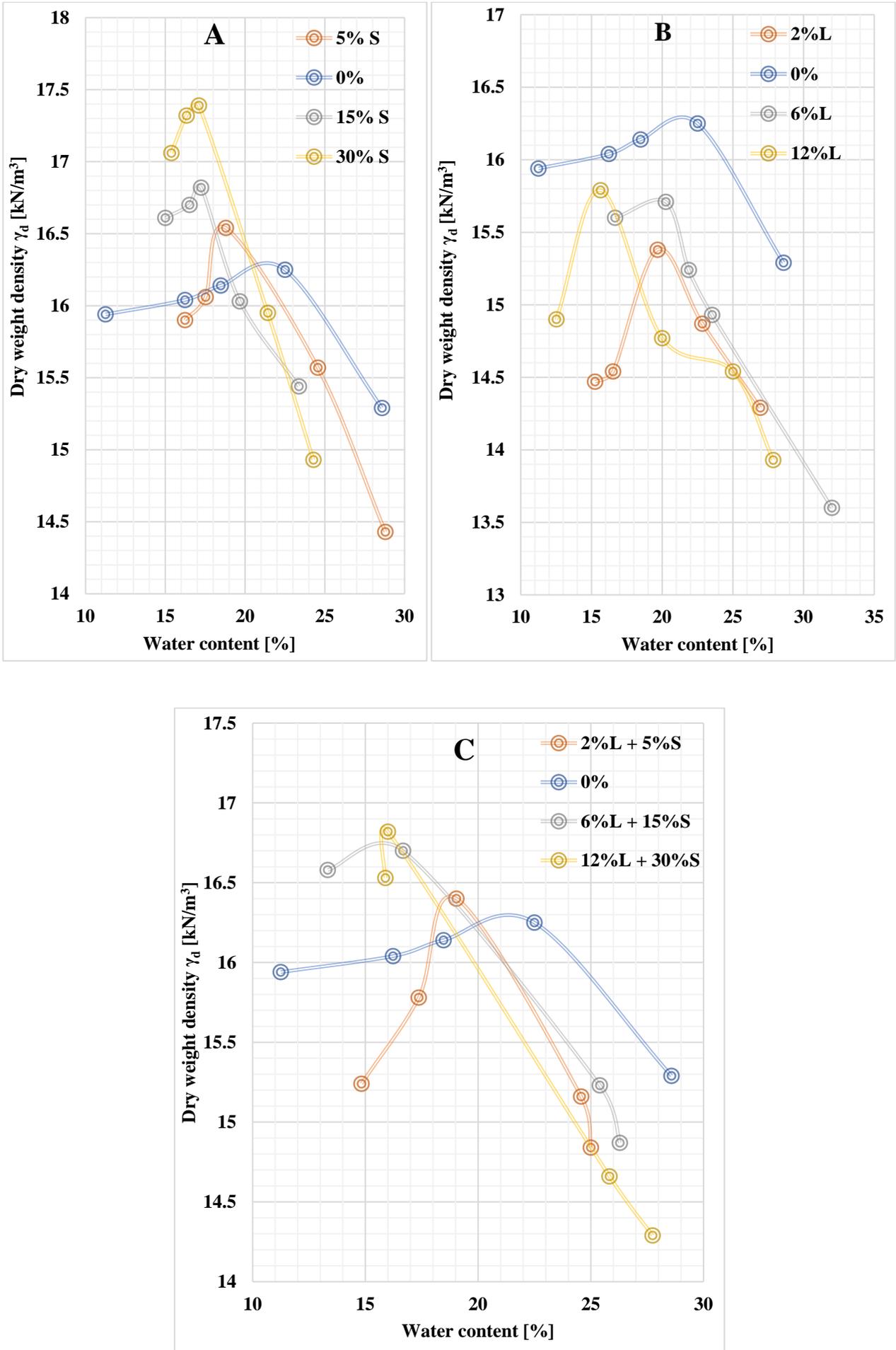
Fig. 6. Compaction curves of clay soil before and after treatment: (A) Treated with sand, (B) Treated with lime, and (C) Mixed treatment

4.3. Results of the CBR test

In this test, a clayey soil is used in accordance with the NF P 94-078 standard. The clayey soil is first dried and then sieved through a 5 mm mesh. Next, a 5.5 kg sample is taken, and the required amount of water, determined from the Proctor test, is added. The mixture is carefully kneaded until a homogeneous paste is obtained, then divided into five equal layers. Each layer is placed in the CBR mould and compacted, applying 56 blows per layer for the first series and 25 blows for the second series. The compacted samples are then soaked in water for four days. After this period, the mould containing the specimen is placed on the testing press, ensuring that the sample is centred under the piston. The piston is raised until it contacts the soil surface, and the measuring devices (dynamometer and dial gauge) are reset to zero. The penetration test is conducted at a constant rate, recording the applied forces for penetrations of 2.5 mm and 5 mm to determine the CBR index of each sample, with the CBR value retained being the maximum of the two measurements [21]. This test is performed for each type of treatment, with at least two samples tested for each treatment percentage (see Fig. 7).

Figure 8 shows the results of the CBR test carried out on a clayey soil mixed with different percentages of sand (5%, 15%, and 30%).

Figure 8 shows that the addition of 5% sand leads to a significant increase in the CBR index, reaching approximately 3.35, due to a more favourable particle size distribution and an enhancement of particle cohesion and internal friction. In contrast, at 15% sand, the CBR index drops to around 1.64, likely due to the disruption of the clay structure and loss of cohesion. At 30%, the value further decreases to about 1.10, as the soil becomes predominantly sandy and loses its plastic and flexible properties. The decrease in CBR with higher sand content is attributed to modifications in soil structure and dry density (Braja et al.) [23].

Fig. 7. Steps of the CBR test on clay soil before and after treatment
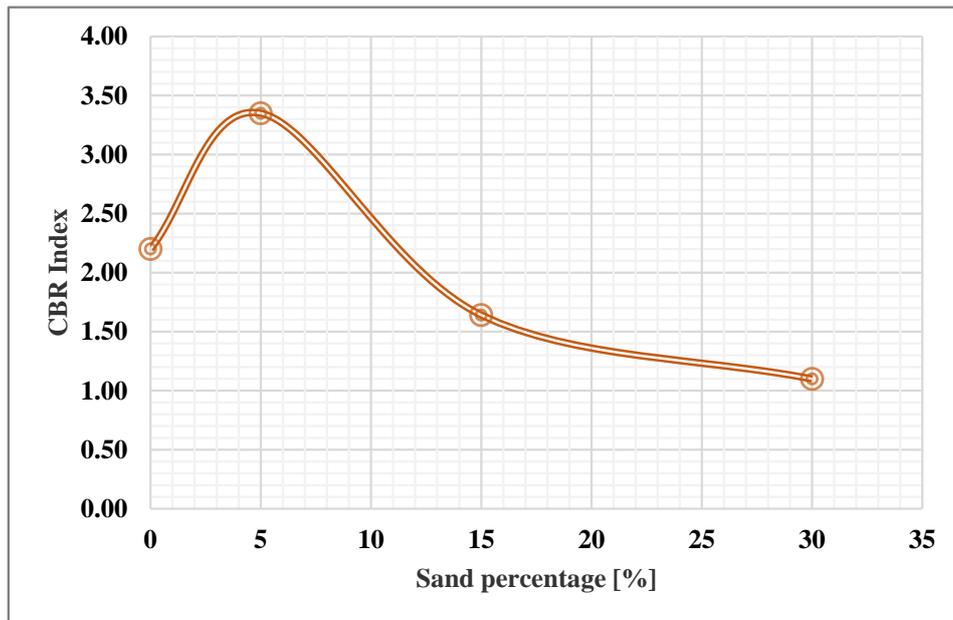

Fig. 8. Evolution of the CBR index of clay soil as a function of sand content

Figure 9 presents the results of the CBR test conducted on soil treated with different percentages of lime.

Figure 9 shows that the addition of lime leads to an increase in the CBR index. For a lime content of 12%, the CBR index reaches approximately 23.29. This improvement can be explained by a significant increase in soil cohesion and a reduction in its plasticity. Moreover, pozzolanic reactions between lime and clay minerals produce cementitious

compounds that enhance the soil's strength. These results are consistent with those obtained by Abu-Elgasim et al. [14], who found that adding 8% lime or more causes a significant increase in the CBR index and, consequently, in the bearing capacity of clayey soil.

Figure 10 shows the results of the CBR test on a clayey soil treated with lime and sand mixtures at the following dosages: (2%L + 5%S), (6%L + 15%S) and (12%L + 30%S).

Figure 10 shows that the combined addition of sand and lime leads to a significant increase in the CBR index, rising from 2.2 to 36.62 for a treatment combination of 12% lime and 30% sand (12%L + 30%S). This remarkable improvement demonstrates the effectiveness of the lime–sand treatment in enhancing soil bearing capacity and improving its load-carrying performance. These results are consistent with those reported by Prasad et al. [12], who showed that the addition of 20% sand and 10% lime increases the CBR index from 9.56 to 12.62.
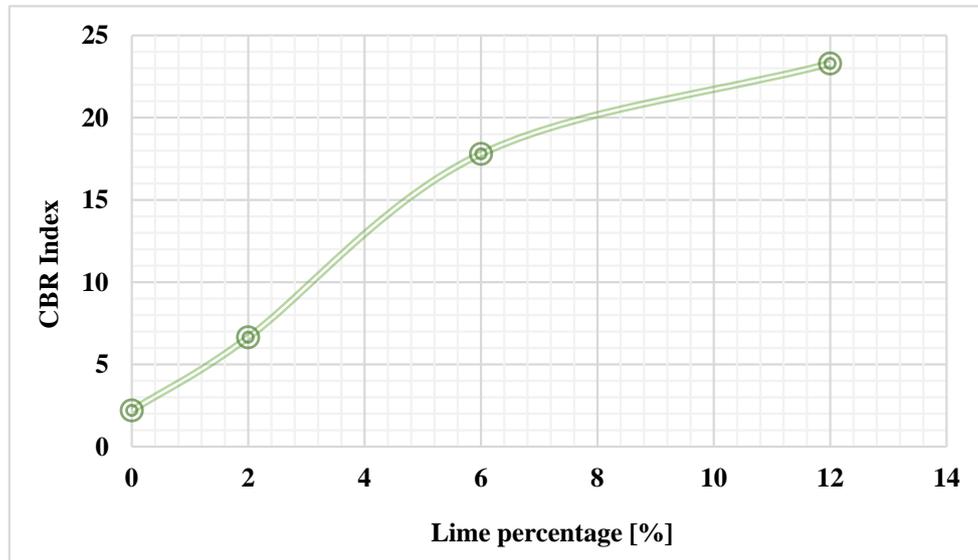

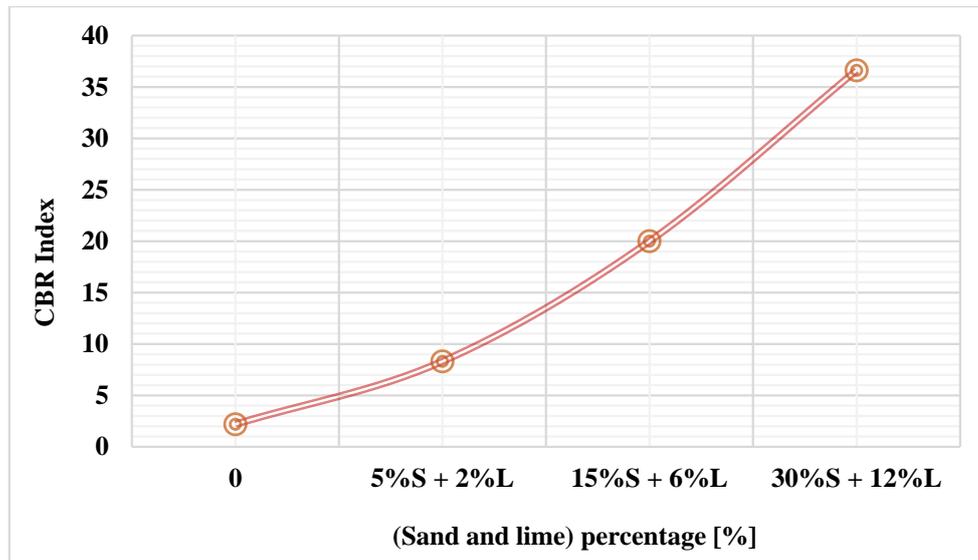**Fig. 9.** Evolution of the CBR index of clayey soil treated with lime

Fig. 10. Variation of the CBR index of a clayey soil treated with combined additions of lime and sand

4.4. Results of the shear test

The direct shear test is carried out in accordance with the European standard NF P 94-071-1, on a clayey soil previously dried and sieved to 5 mm. A 90 g specimen is weighed, then moistened with a predetermined amount of water and thoroughly mixed until a homogeneous paste is obtained. The specimen is then placed in the shear box between two grooved plates, oriented perpendicular to the direction of shearing, together with two porous stones, and subjected to a loading piston. The box is mounted on the shear apparatus; the dial gauges and the proving ring are set to zero, and a normal stress of 1, 2, or 3 bar is applied. After removing the pins connecting the two halves of the shear

box, shearing is performed at a constant rate, and the shear forces are recorded until failure of the specimen. The amount of water used corresponds to the soil's optimum moisture content before and after treatment, as determined by the Modified Proctor test. From the shear curves, the shear strength parameters (cohesion and angle of internal friction) are determined for each specimen, whether treated or untreated [22].

Figure 11 shows the variation of cohesion (C) and the angle of internal friction (φ) of the clayey soil as a function of sand content.

Figure 11 illustrates that the addition of sand at different percentages leads to a continuous decrease in cohesion, from

20.56 kPa for untreated clay to 4.63 kPa for a mixture containing 30% sand. This reduction is explained by the progressive loss of the natural cohesion of the clay due to changes in its structure. Indeed, the material evolves from a fine and cohesive texture to a more granular and coarser structure, characterised by a significant decrease in interparticle adhesion, which is a key property governing soil cohesion. Moreover, the maximum value of the internal friction angle is observed at 5% sand content, reaching 19.13°, indicating an improvement in shear strength due to enhanced intergranular friction. In contrast, for sand contents of 15% and 30%, only slight variations in the internal friction angle are observed compared with the initial state, indicating a growing influence of the intrinsic mechanical properties of sand on the behaviour of the mixture. These results are consistent with those found by Al Rawas et al [24], who showed that the shear strength parameters of sand-clay mixtures increase with increasing clay content.

Figure 12 illustrates the variation of the shear parameters of clay according to different lime contents (2%, 6%, and 12%).
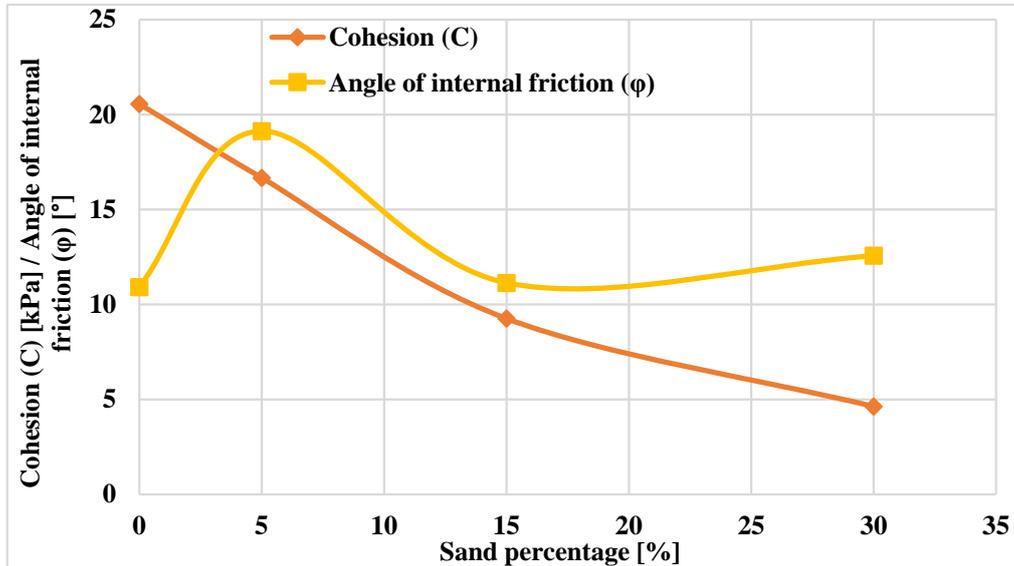

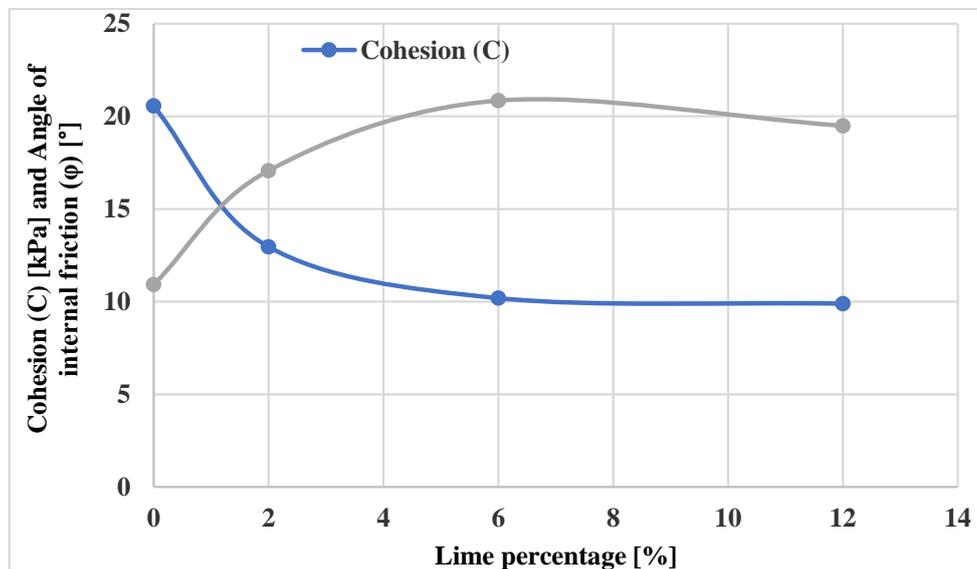**Fig. 11.** Evolution of the shear test parameters of a clayey soil as a function of sand addition

Fig. 12. Evolution of the shear test parameters of a lime treated clayey soil

Figure 12 shows that soil cohesion decreases continuously, from 20.56 kPa for untreated soil to 9.89 kPa at a lime content of 12%, corresponding to the maximum percentage added. This indicates that an excess of lime reduces the natural cohesion of clay as chemical reactions progressively alter its structure. Moreover, the internal friction angle increases steadily up to a lime content of 6%, reaching 20.85°. Beyond this threshold, a slight decrease is observed, with the angle reaching 19.49° at 12% lime. This behaviour can be explained by chemical reactions between lime and clay minerals, known as pozzolanic reactions, which produce cementing compounds that enhance the mechanical behaviour of the soil. The obtained results do not fully match those of Elazzabi [4] regarding cohesion, but they are similar in terms of the internal friction angle. According to Elazzabi, adding 8% lime increases the internal friction angle from 29.2° to 37.23° and cohesion from 0 kPa to 28 kPa.

Figure 13 shows the shear strength parameters of a clayey soil treated with combined lime and sand.

From Figure 13, it can be seen that cohesion decreases continuously, from 20.56 kPa for the untreated soil to 7.41 kPa

for the maximum combination (12%L + 30%S). This reduction is due to the effect of sand, which causes a loss of the soil's plastic and cohesive properties, making it similar to sandy soil, which is naturally low in cohesion. The highest internal friction angle, 24.32°, was observed for low treatment proportions (2%L + 5%S), due to the improvement of particle surfaces and the increase in interparticle friction. For higher proportions (12%L + 30%S), the angle decreases to 22.14°, due to the formation of less

effective fine materials by the lime [15] and the disruption of particle contacts caused by the excess sand. However, the friction angle for the combination (12%L + 30%S) remains higher than that obtained with 12% lime alone. Moreover, the best shear parameters are achieved with moderate proportions of the mixed treatment, highlighting the effectiveness of a balanced combination of lime and sand.
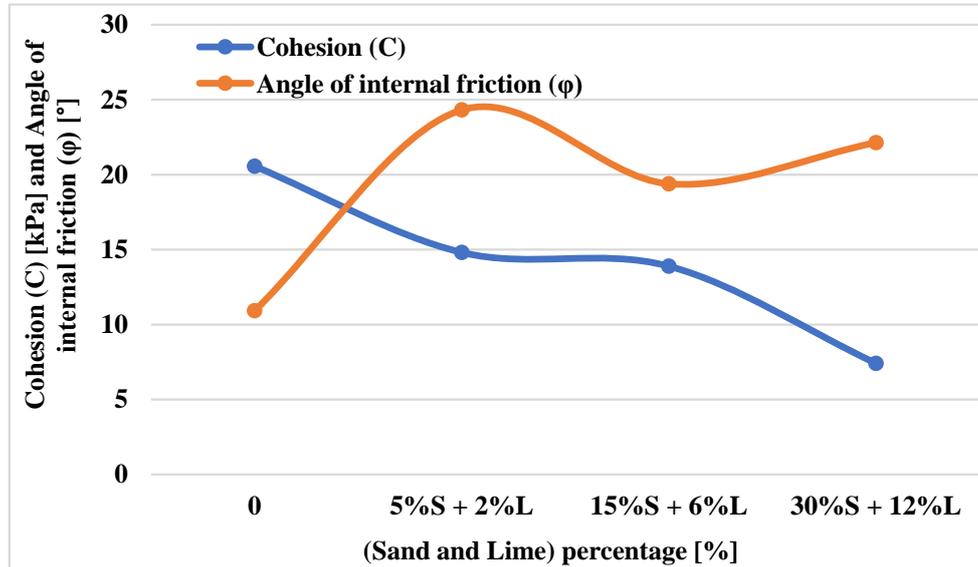

Fig. 13. Evolution of the shear strength parameters of a clayey soil treated with combined lime and sand additions

5. Conclusion

The obtained results lead to the following conclusions:

- The incorporation of sand resulted in a decrease in both the liquid and plastic limits. The minimum liquid limit, equal to 32.30%, was obtained at a sand content of 30%. In addition, an increase in dry weight density was observed, reaching 17.39 kN/m³ at 30% sand, which represents the maximum value among all the studied mixtures. A slight improvement in the internal friction angle was also noted, with a value of 12.57°. However, high sand contents led to a significant reduction in soil cohesion.

- The use of lime led to an improvement in the internal friction angle, which reached a value of 19.49°, accompanied by a decrease in cohesion compared to the untreated soil. An increase in the plastic limit was also observed, with the maximum value of 38.67% recorded at a lime content of 2%, which represents the highest value among the different treatment percentages. Furthermore, an improvement in the CBR index, and thus in the bearing capacity of the soil, was observed. The maximum CBR value, equal to 23.29, was obtained at a lime content of 12%, corresponding to the highest treatment level. In addition, a lime content of 12% results in a reduction in the optimum moisture content to 15.64%, which is the lowest value compared to the other dosages, along with a slight increase in the maximum dry density. These changes are attributed to chemical reactions between lime and clay minerals.

- The best results were obtained with the combined sand–lime treatment at a content of 12% lime and 30% sand (12%L + 30%S). At this formulation, the liquid and plastic limits exhibit acceptable values of 39.97% and

19.56%, respectively. This treatment percentage also provides very good compaction characteristics, with a maximum dry weight density of 16.82 kN/m³ and an optimum moisture content of 16.00%. Moreover, the highest CBR index value was obtained for this mixture, reaching 36.62, which is the greatest among all the formulations studied. A significant improvement in the internal friction angle was also observed, reaching 22.14°, the highest value recorded, obvious a relatively low cohesion.

- In conclusion, the combined treatment with lime and sand represents an effective and complementary solution to improve the geotechnical properties of clay soils and make them compliant with road engineering requirements.

Clay soil treated with 12% lime and 30% sand (12%L + 30%S) exhibits satisfactory mechanical and compaction characteristics. Indeed, the CBR index increased from 2.2 for the untreated clay to 36.62 after treatment. Moreover, the maximum dry weight density rose from 16.25 kN/m³ for the natural soil to 16.82 kN/m³ after treatment. In addition, the optimum moisture content decreased from 22% before treatment to 16% after treatment. Regarding shear strength parameters, a decrease in cohesion was observed, from 20.56 kPa for the untreated soil to 7.41 kPa after treatment, while the angle of internal friction significantly increased from 10.92° to 22.14°. Finally, all these results confirm the feasibility of using the treated clay (12%L + 30%S) in the construction and compaction of the subgrade layer for a highway project in the Jijel region (Algeria).

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