Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Research Article

Effect of valorizing oil drilling waste on the strength and microstructural properties of gypseous-calcareous soil for use in Saharan road construction

Bourdache Syphax [1,2,a], Tioua Tahar [*,3,4,b], Kriker Abdelouahed [1,2,c]

[1]Laboratory of Exploitation and Valorization of Natural Resources in Arid Zones (EVNRAZ), Kasdi Merbah University, 30000 Ouargla, Algeria
[2]Dept. of Hydraulic and Civil Engineering, Kasdi Merbah University, 30000 Ouargla, Algeria
[3]Dept. of Hydraulic and Civil Engineering, Echahid Hamma Lakhdar University, 39000 El Oued, Algeria
[4]Dept. of Hydraulic and Civil Engineering, Abdel Hafid Boussouf University, 43000 Mila, Algeria

Article Info	Abstract

Article History:

Received 07 Feb 2026

Accepted 16 Apr 2026

Keywords:

Oil drilling waste;
Gypseous-calcareous soil;
Valorization;
Lime;
Compressive strength

In response to the environmental challenges posed by oil drilling waste generated from intensified oil production in Algeria, particularly in Saharan regions, this study proposes a valorization approach to mitigate their impacts. Our research aims to transform this waste into a useful resource by incorporating it into road construction mixtures. The study seeks to design an innovative and optimized formulation of gypseous-calcareous soil with oil drilling waste, specifically adapted to road infrastructure. We tested the incorporation of treated oil drilling waste into gypseous-calcareous soil formulations at rates of 5%, 10%, and 15% by weight and with the addition of 4% lime. The study evaluates the evolution of unconfined compressive strength (UCS) in these mixtures, as well as their water sensitivity, influence on California Bearing Ratio (CBR), and direct shear testing. The results reveal significant improvements in the mechanical behavior of the mixture modified with 10% oil drilling waste and 4% lime content, under laboratory curing conditions, achieving a UCS of 2.45 MPa, CBR value of 75% and shear strength parameters with an internal friction angle 35° and the cohesion 45 kPa. The Microstructural analysis further confirmed that the interaction between oil drilling waste and the gypseous-calcareous soil in the presence of lime led to the formation of a more homogeneous and compact matrix, which explains the observed improvement in mechanical properties.

1. Introduction

Oil exploitation in Algeria is particularly intensive in the Saharan regions and produces thousands of cubic meters of oil drilling waste each year [1]. These wastes, comprising drilling muds and cuttings, are often rich in hydrocarbons and heavy metals [2, 6]. In response to this environmental challenge, various valorization strategies have been developed [7, 11]. In the cement industry, Bernardo et al. [12] demonstrated that replacing limestone and clay with up to 45% Oil-Based Mud in clinker production does not compromise the mechanical properties of hydraulic binders, which is an important finding for regions such as the Saharan sedimentary basin. This approach is supported by the experimental work of Anghelescu et al. [13], who incorporated recycled coal ash and residual drilling fluids as partial substitutes for clay, revealing optimal compatibility for construction materials. Similarly, Chen et al. [14] introduced thermally treated drilling cuttings to manufacture permeable bricks that meet Taiwanese standards for compressive strength (≥15 MPa) and permeability (≥0.1 cm/s). Applied research continues with El-mahllawy and Osman [15],

---

*Corresponding author: tahar.tioua@centre-univ-mila.dz
[a]orcid.org/0009-0005-4443-4796; [b]orcid.org/0000-0001-5346-4907; [c]orcid.org/0009-0003-6297-2374;
DOI: http://dx.doi.org/10.17515/resm2026-1496me0207rs

whose clay masonry units are enriched with 10, 20 and 30% treated drilling muds and comply with Egyptian EN 771-1 standards, achieving compressive strengths above 7 MPa for load-bearing walls. However, Mostavi et al. [16] identified a technical trade-off: substituting 5% of cement with dried cuttings in concrete leads to a 10% reduction in strength, which increases to 20% at higher replacement rates 25%. Nevertheless, the use of offshore oil drilling waste in hot mix asphalt (HMA) shows promising potential: replacing 20% of conventional aggregates maintains Marshall stability (>8 kN), flow (2-4 mm), and resilient modulus (>300 MPa), paving the way for sustainable road applications [17].

Recently, industrial waste materials have been added and mixed with loose soils to enhance their geotechnical properties [18, 19]. The improved characteristics of loose soils, resulting from the utilization of industrial waste additives like silica fume, ground granulated blast furnace slag, cement kiln dust, rice husk ash and fly ash, offers various advantages environmental and economic. Many studies have been conducted on the effectiveness of these industrial waste in improving soil properties. The addition of such materials improved the strength of soils [20, 22]. In addition, Sanijya et al. [23] and Al-khafaji et al. [24] studies reveal that adding industrial waste additives lead to a decrease in the plasticity index of soils. Regarding compaction, several studies Arulrajah et al. [25], Kassa et al. [26], and Pastor et al. [27] have indicated that the use of industrial waste additives significantly improved soil compaction characteristics. On the other hand, industrial waste additives interact with lime more efficiently than when used alone. Some researchers, including Alrubaye et al. [28], Zaini et al. [29] and Liu et al. [30] demonstrate that workability and strength performance of loose soils were significantly improved after applying a combined treatment.

Encrusting gypseous-calcareous soils are widely distributed across the arid regions of Algeria [31, 32], notably in Ouargla, and they are currently utilized in road construction [33]. However, their mechanical performance remains inadequate to meet modern traffic demands, so they are commonly employed in road foundation layers, exhibiting low bearing capacity, which is exacerbated by extreme climatic conditions [34, 35]. This situation often compels project owners to import higher-performance materials from distant locations, resulting in additional costs, delays in infrastructure development, increased carbon footprint, and greater logistical complexity due to long transport distances, which encourages researchers to explore the valorization of gypseous-calcareous soils in civil engineering [36, 38]. Thus, the reuse of additives derived from industrial by-products such as crushed brick waste, recycled glass powder, or treated drilling waste represents an effective strategy to reduce transport distances, lower associated costs and emissions, while promoting the improvement and sustainable use of locally available resources. Initial studies demonstrated that additives like cement enhance gypseous-calcareous soil's physical, chemical, and thermal properties [39]. Further research has revealed that adding cement with 15% ceramic powder significantly optimizes physical properties and mechanical performance, particularly compressive strength [40]. Another study investigated a hydraulic binder-treated tuff/sand mixture (65% soil, 35% dune sand, 4% binder: 2/3 lime, 1/3 cement), confirming compliance with technical criteria [41]. Additional work has highlighted that incorporating 25% dune sand into tuff increases its dry density by up to 20% [42]. Finally, mixtures with up to 30% sand achieved compliant CBR index values, while markedly improving compressive strength [43].

The objective of this research is to propose a dual ecological and economic solution, contributing to sustainable oil waste management by valorizing treated DW as an additive to gypseous-calcareous soil, to enhance its mechanical characteristics, which is a critical criterion for material selection in Saharan road projects.

2. Materials and methods

2.1. Materials

2.1.1 Gypseous-Calcareous Soil

In this study, the base material was gypseous-calcareous soil sourced from the Ouargla region of southeastern Algeria; it is utilized in road foundation layers (Fig. 1). The geotechnical and mineralogical characteristics of the soil used are summarized in Table 1.

Fig. 1. Gypseous-calcareous soil before and after compaction

Table 1. Geotechnical and mineralogical characteristics of the soil used

Property	Value	Unit
Bulk density	1.178	g/cm^3
Specific density	2.218	g/cm^3
Maximum diameter (Dmax)	50	mm
Particles < 2 mm	73	%
Particles < 0.80 mm	24	%
Maximum dry density	1.62	t/m^3
Optimal moisture content (Wm)	14.7	%
Methylene blue value (VBS)	0.45	-
Immediate Bearing Index (IBI)	28.01	-
California Bearing Ratio (CBR) after immersion	48	-
Unconfined compressive strength (28 days)	0.65	MPa
$CaSO_4 \cdot 2H_2O$	42.5	%
$CaCO_3$	28.3	%

2.1.2 Oil Drilling Waste

The drilling waste used in this study came from the Hassi Messaoud region (southeastern Algeria) after being treated using the stabilization/solidification (S/S) method (Fig. 2). Its main chemical characteristics were obtained by X-ray fluorescence (XRF) are presented in Table 2.

Fig. 2. Treated oil drilling waste before and after grinding

Table 2. Chemical XRF analysis of drilling waste

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5
Mass (%)	26.46	2.97	1.51	12.24	1.65	8.23	0.28	1.75	0.05

The chemical composition of drilling waste reported in this study is consistent with values reported in previous research, where silica, calcium, and sulfate oxides are commonly identified as the dominant components in treated drilling waste [8,9]. In order to evaluate the potential impact of grinding on the efficiency of the S/S treatment, chemical tests were conducted using Atomic Absorption Spectroscopy (AAS), before and after grinding the sample of treated drilling waste. The results revealed that, although grinding slightly influenced the treatment, the heavy metal concentrations remained below the regulatory limits, according to [44], as shown in Table 3. The grinding of the treated oil drilling waste sample was followed by a specific surface area analysis using the Blaine method, which allowed for the characterization of the material's fineness. The results showed a specific surface area of 2500 cm^2/g.

Table 3. Atomic absorption spectroscopy (AAS) results before and after grinding of treated oil drilling waste and regulatory limit values

Element	Before grinding (mg/kg)	After grinding (mg/kg)	Regulatory limit (mg/kg)
Cr	0,650	7,60	100
Ni	8,700	9,70	100
Cd	0,120	0,16	50
Hg	0,421	1,10	10
Pb	17,700	26,90	100

2.1.3 Lime

Ground lime is primarily composed of calcium oxide (CaO), with a purity exceeding 73.3% and it is generally presented in the form of a dry white powder, with a specific density of approximately 2 g/cm^3 and an apparent density ranging between 600 and 900 g/l. Impurities are maintained at low levels, notably: silicon dioxide (SiO_2) below 2.5%, iron oxide (Fe_2O_3) below 2%, and aluminum oxide (Al_2O_3) below 1.5%. The particle size distribution was controlled, with less than 10% of the particles exceeding 90 µm and none above 630 µm.

Lime stabilization was selected due to its well-known ability to activate pozzolanic reactions with siliceous and aluminous phases in soils, leading to the formation of cementitious compounds such as C–S–H and C–A–H gels. These reaction products improve the soil structure and mechanical strength. Compared with other binders such as cement or ground granulated blast furnace slag (GGBS), lime treatment is widely used in soil stabilization due to its relatively low cost and ease of field application. Previous studies have also reported satisfactory durability of lime-stabilized soils under long-term environmental conditions and cyclic wetting–drying processes [45].

2.1.4 Formulation

Different formulations were developed for the preparation of the specimens. Table 4 presents the various compositions tested, comprising gypseous-calcareous soil (S), lime (L), and oil drilling waste (DW). This allowed for a comparative analysis of the material properties based on their compositions.

Table 4. Different mixtures studied

Mixture	Soil (%)	Oil drilling waste (%)	Lime (%)
SDW0L0	100	0	0
SDW5L0	95	5	0
SDW10L0	90	10	0
SDW15L0	85	15	0
SDW0L4	96	0	4
SDW5L4	91	5	4
SDW10L4	86	10	4
SDW15L4	81	15	4

2.2. Methods

For each mixture and, three identical specimens were prepared and tested to ensure the reliability and repeatability of the results.

2.2.1 Unconfined Compressive Strength Test

Samples were prepared in cylindrical molds (Ø = 5 cm, height = 10 cm) and statically compacted using a press at the optimum moisture content defined by the modified Proctor test, achieving a compaction level of 98%. The specimens were maintained under laboratory conditions at a temperature of 25±5 °C. The curing durations were 7, 14, 28, 60, and 90 days. Once the storage time was reached, the specimens were subjected to a compressive force applied parallel to the cylinder axis, using a press at a constant speed of 1.27 mm/min until rupture in accordance with (EN ISO 17892-7) [46] (Fig. 3).

(a) (b) (c)

Fig. 3. (a) Manufacturing molds; (b) Demolded specimens; (c) Sample under compressive testing

2.2.2 Sensitivity to Water Test

The water immersion test is used to assess the durability of materials by measuring their compressive strength after saturation. When applied to soil, it involves immersing specimens for a specified period, to analyze their mechanical behavior under wet conditions. This procedure helps to estimate the soil material's sensitivity to water and its ability to retain its mechanical properties after saturation. The compressive strength was measured in accordance with the (EN ISO 17892-7) [46], which evaluates the stability of the soil and its suitability for use in moisture exposed environments.

2.2.3 California Bearing Ratio (CBR)

The California Bearing Ratio (CBR) test, carried out in compliance with the EN 13286-47 standard [47], is used to evaluate the relative load-bearing capacity of a soil by measuring its penetration resistance.

Fig. 4. CBR test for compacted mixtures

The protocol involves applying a force on a standardized piston (49.6 mm in diameter) that penetrates the compacted sample with size of (152.4 mm diameter and 177.8 mm height) at a constant speed of 1.27 mm/min. The CBR value is determined by calculating the ratio, expressed as a percentage, between the force required to push the piston to a given penetration depth (2.5 and 5.0 mm) in the tested sample and the force required for the same penetration in a reference material, as illustrated in Fig. 4. In our study, we focused on analyzing the CBR after 96 hours of immersion to replicate the most unfavorable moisture exposure conditions and assess the durability of the proposed mixtures against water infiltration in a Saharan environment.

2.2.4 Direct Shear Test

Direct shear tests were performed on compacted specimens, in accordance with the EN ISO 17892-10 standard [48], using an electronic normal loading system to ensure precise control of the applied stresses (ranging from 50 to 200 kPa) (Fig. 5). The testing apparatus continuously recorded the shear forces and the vertical/horizontal displacements, enabling the calculation of sample dilatancy. This approach not only allows for the assessment of granular interactions in soil-drilling waste-lime mixtures, but it also provides a direct measurement of cohesion (c) and internal friction angle (φ), which are key parameters for the geotechnical design of road construction materials, as highlighted in recent studies.

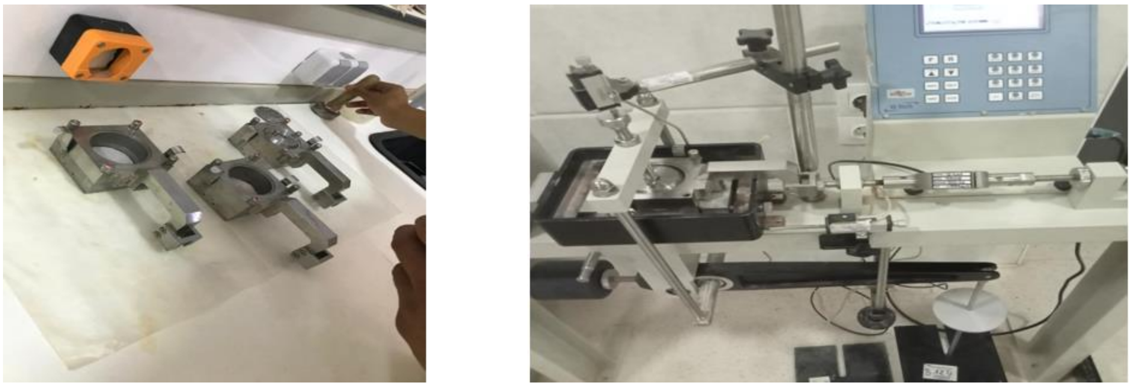


Fig. 5. Direct shear test

3. Results and discussion

3.1. Unconfined Compressive Strength

The compressive strength results for mixtures of gypseous-calcareous soil and DW, without the presence of lime, are presented in Fig. 6. The progressive incorporation of DW leads to a significant decrease in compressive strength. At 5% DW, the impact on strength remains moderate, with reduction of about 36% compared with the reference mixture (SDW0L0) at 90 days of curing. At 10% DW, a marked drop in strength is observed, with a reduction of approximately 50%, indicating more pronounced structural disruption within the soil. Finally, at 15% DW, the compressive strength of the soil continues to decrease, reaching a reduction of about 57%. This behavior can be attributed to the increase in porosity and the disruption of internal bonds within the material's matrix, due to poor chemical compatibility between soil and DW. These observations are consistent with the work of Balegha et al. [40], who demonstrated that the uncontrolled addition of industrial residues can lead to a degradation of the mechanical properties of soil.

In contrast, the addition of 4% lime to the mixtures enhances the mechanical performance, as shown in Fig. 7. The mixtures containing DW exhibited superior compressive strength in comparison to the SDW0L4 mixture at 90 days of curing. Specifically, SDW5L4 shows an increase in compressive strength of approximately 60%, SDW10L4 exhibits a gain of about 47%, and SDW15L4 presents an improvement of around 18% compared with SDW0L4. This enhancement can be attributed to the pozzolanic reactions of lime and calcium hydroxide with the siliceous and aluminous compounds found in treated DW in the presence of water. This forms new compounds that have cementitious properties, such as calcium silicate hydrate (CSH) and calcium aluminate hydrates (CAH), strengthening the soil and reducing internal defects. These results agree with those reported by Daheur et al. [41], which highlighted that the use of hydraulic binders promotes the formation of stable silico-aluminous phases, thereby increasing the overall mechanical strength. This behavior is consistent with the study of Tayebi et al. [49] where it was observed that the use of red brick waste (RBW) as addition significantly improved the compressive strength of soil. Al-amoudi et al. [50], who also reported an increase in the compressive strength of calcareous marl soil with the addition of stabilize such cement and lime.

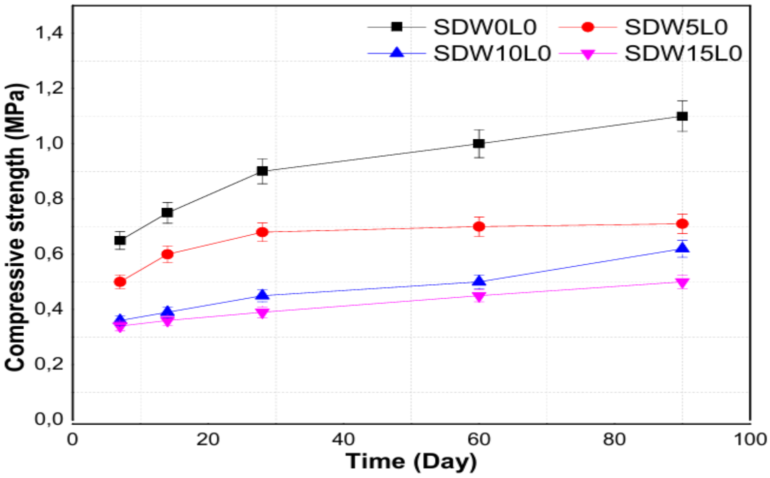


Fig. 6. Evolution of the compressive strength of soil-drilling waste mixtures without lime

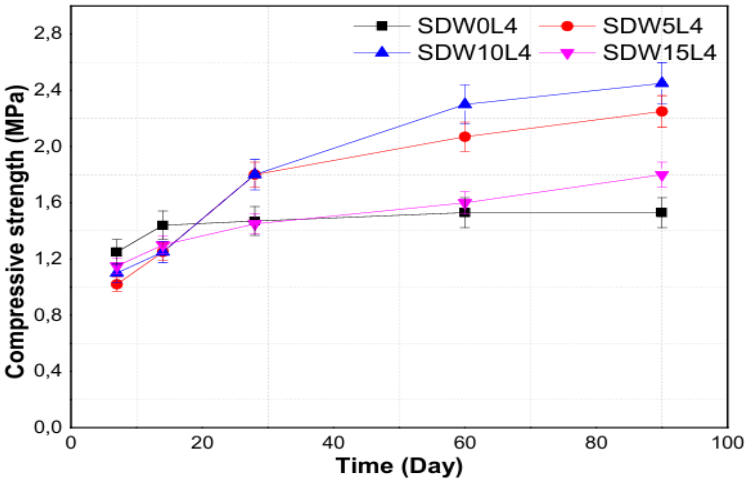


Fig. 7. Evolution of the compressive strength of soil-drilling waste mixtures with lime

3.2. Sensitivity to Water

Immersion tests revealed that samples without lime rapidly disintegrate in a humid environment, indicating weak internal cohesion and heightened water sensitivity (Fig. 8(a)). In contrast, samples with 4% lime maintain their structural integrity after immersion and show a progressive increase in strength after immersion, reaching a maximum at 10% DW content, as shown in Fig. 8(b) and Fig. 9. Compared with the reference mixture SDW0L4, the compressive strength after immersion increased by about 24%, 41% and 25% for SDW5L4, SDW10L4 and SDW15L4, respectively. This improvement could be attributed to the effect of lime, which reduces water sensitivity through the formation of insoluble cementitious products, such as calcium silicate hydrates (C-S-H), that reinforce the material's structure. The results of the current study are consistent with the research carried out by Moayyeri et al. [51], Goual et al. [52] and Abdulrasool et al. [53], which focused on different types of hydraulic binder and lime. Their findings indicate that the use of cement, fly ash, micro silica and lime considerably reduced the adverse effects of moisture in soils. This phenomenon has also been noted in previous research regarding soil stabilization using different types of agricultural residues ash, such as carried out by Alavéz-ramírez et al. [54], Sharifi et al. [55].


(a)

(b)

Fig. 8. Immersion test results: (a) specimens without lime that disintegrated after immersion and (b) specimens with lime that retained structural integrity after immersion

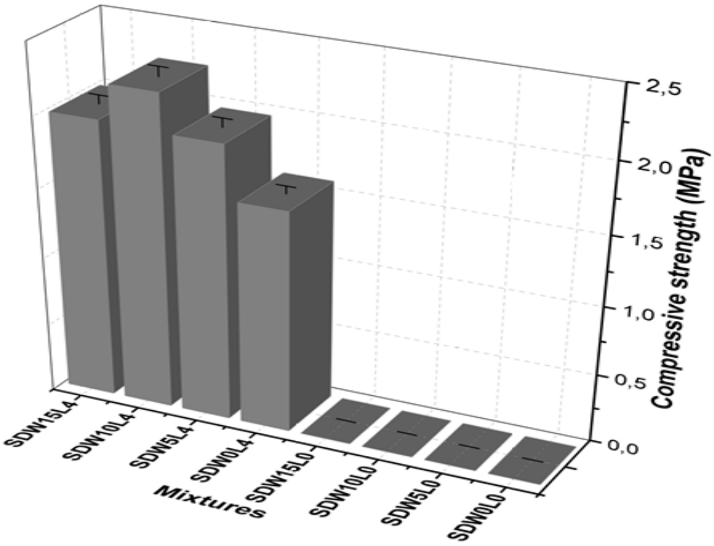


Fig. 9. Evolution of the compressive strength of soil-drilling waste mixtures after immersion tests

3.3. California Bearing Ratio (CBR)

The variety of CBR values of mixtures with and without lime is shown in Fig. 10. The addition of DW without lime significantly reduces the CBR index. When the amount of DW is increased, the CBR index of mixtures is decreased. Therefore, mixture SDW15L0 gave the lowest CBR index of all, with value of 35%. This decrease in bearing capacity can be justified by the increased porosity and degradation of the granular bonds of mixtures with DW. In contrast, incorporating DW with 4% lime significantly improves the bearing capacity of soil. The SDW10L4 mixture gave the best CBR index, achieving a value of 75%. These results confirm the chemical reactions between the lime and the reactive compounds present in the mixtures with DW, which produce cementitious products that improve the bearing capacity of the soil. These results agree with those reported by Sadeghi et al. [38], who observed a similar improvement in mechanical properties during the stabilization of gypsum soils using sustainable additives for road construction.

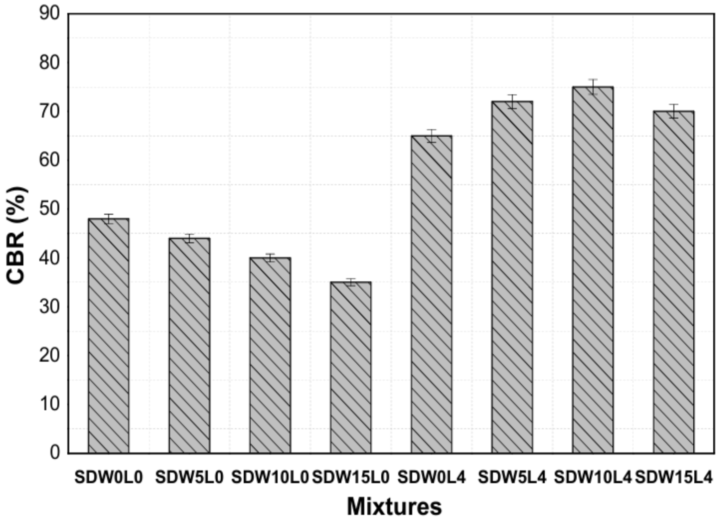


Fig. 10. California bearing ratio values of soil-drilling waste mixtures with and without lime

3.4. Shear Strength

3.4.1 Mohr–Coulomb Failure Line

Fig. 11 shows the Mohr–Coulomb envelopes corresponding to the mixtures without and with lime. The relationship connecting maximum shear strength (τ_{max}) to the normal stress (σ_n), for different soil contents (0, 5, 10, and 15% DW) can be written according to Eq. (1):

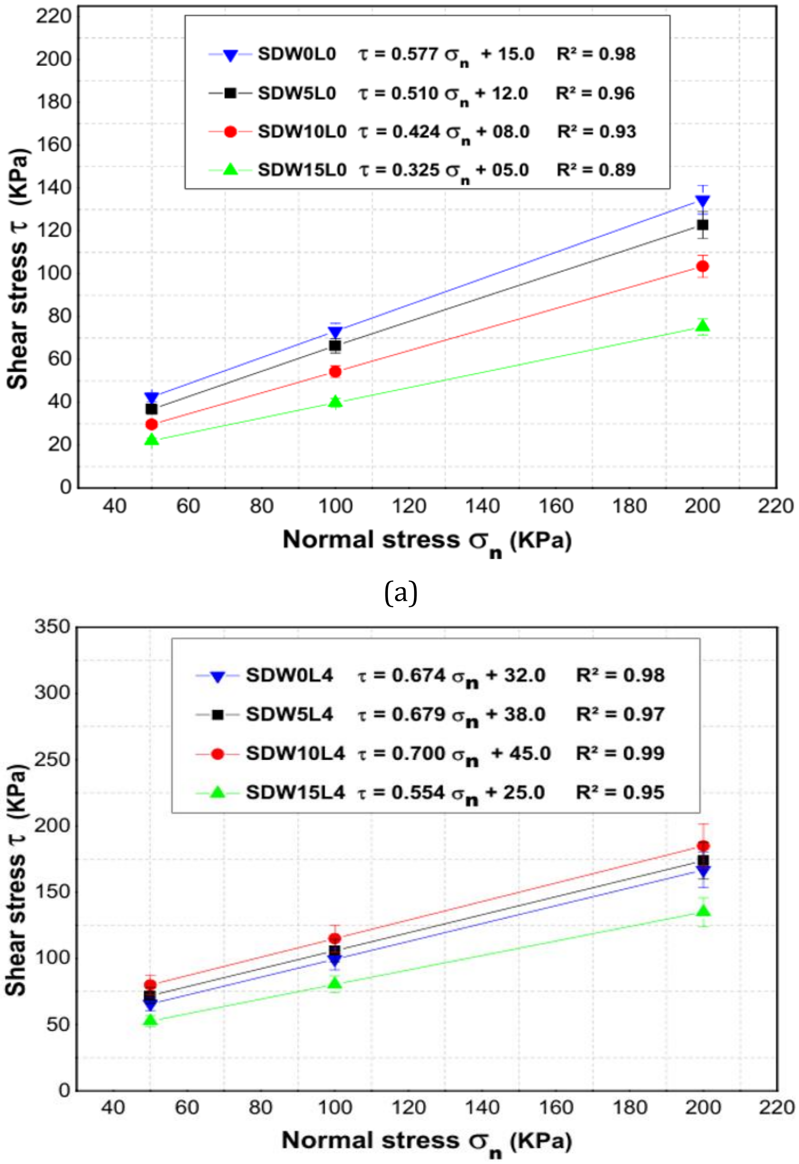
$$\tau_{max} = \sigma_n tg\varphi + c \qquad (1)$$

Where; c: cohesion, φ: internal friction angle, σn: normal stress. These results indicate that adding DW with lime increases the slope of the failure line of soil compared to that without lime. It should be noted that the SDW10L4 mixture has the steepest failure slope.

3.4.2 Cohesion and the Internal Friction Angle

The incorporation of DW into soil mixtures progressively degrades cohesion (c) and friction angle (φ), as illustrated in Fig. 12. For example, in the SDW15L0 mixture, c drops to 5 kPa and φ to 18°, compared to the SDW0L0 mixture (15 kPa and 30°, respectively), reflecting microstructural disruption caused by heterogeneous particles. This aligns with the findings of Shah et al. [56] regarding fuel oil contamination, where decrease cohesion (-66%) and angle of internal friction (-23%) of soil. The addition of 4% lime significantly enhances cohesion (c) and the friction angle (φ), increasing from 32 kPa and 34° (mixture SDW0L4) to 45 kPa and 35° (SDW10L4). This stems from the pozzolanic reactions between lime and DW silica/alumina, forming calcium silicate hydrate gels that densify the soil matrix. On the other hand, lime neutralizes sulfates via stable gypsum ($CaSO_4{\cdot}2H_2O$) formation, while DW particles act as fillers, lowering effective porosity. Al-muaythir et al. [57] found similar results when studying of various types of industrial waste additives to enhance the characteristics of soil. They observed that these additives react with soil minerals in the presence of water to create cementitious compounds, including calcium silicate hydrates (CSH), which serve to link the soil particles together and improve cohesion. The fine particles of the additives occupy the spaces between soil particles, resulting in denser packing and heightened interparticle friction, thereby increasing the internal friction angle.

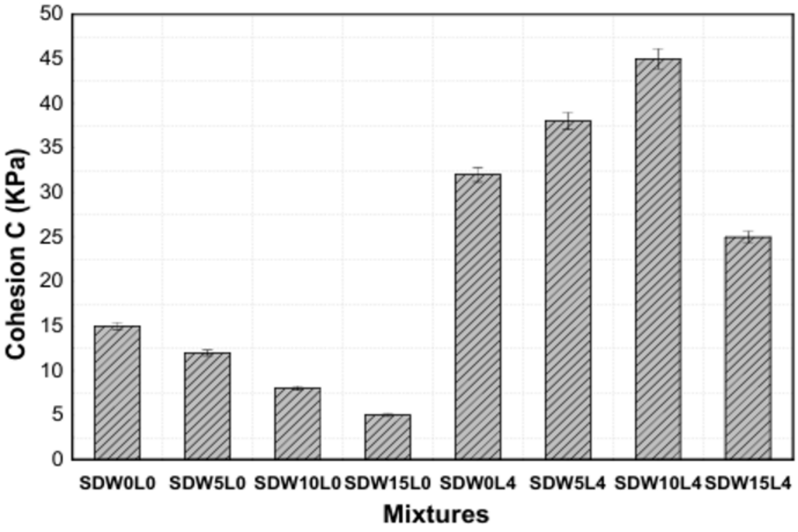
Al-muaythir et al. [57] found similar results when studying of various types of industrial waste additives to enhance the characteristics of soil. They observed that these additives react with soil minerals in the presence of water to create cementitious compounds, including calcium silicate hydrates (CSH), which serve to link the soil particles together and improve cohesion. The fine particles of the additives occupy the spaces between soil particles, resulting in denser packing and heightened interparticle friction, thereby increasing the internal friction angle.



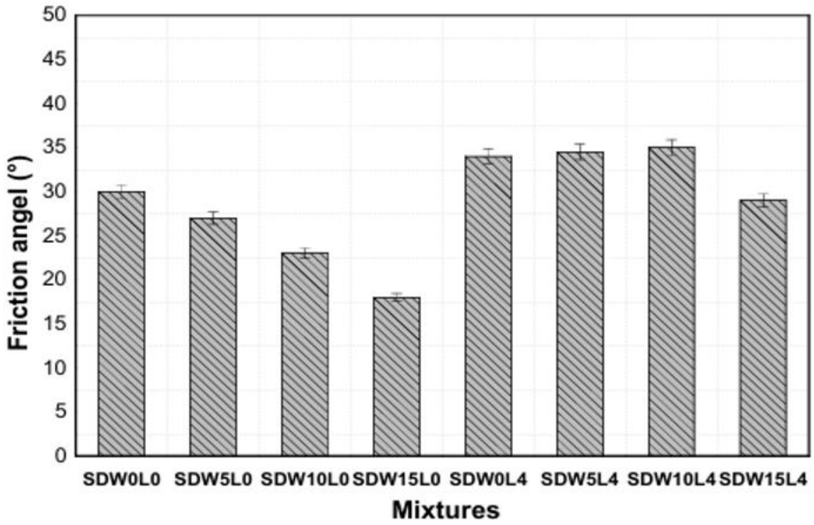
(a)

(b)

Fig. 11. Failure envelopes for the direct shear of soil-drilling waste mixtures: (a) without lime and (b) with lime



(a)

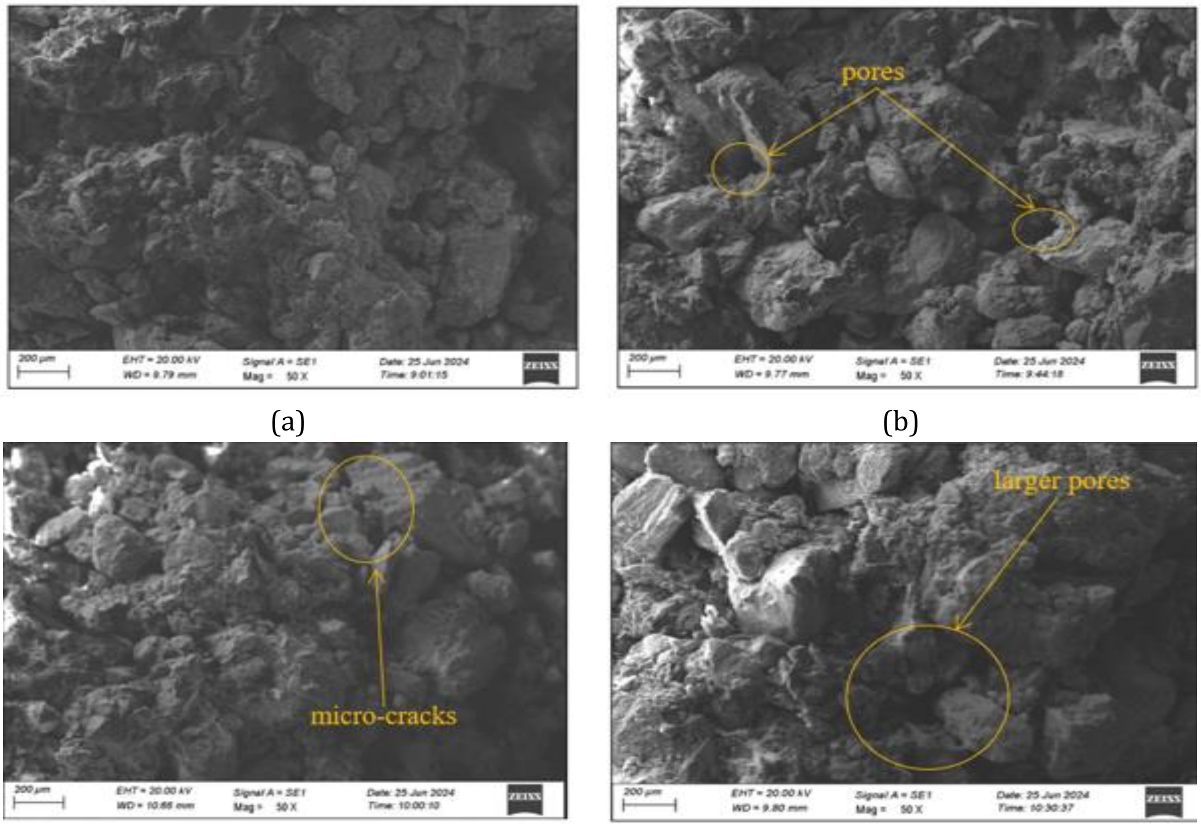


(b)

Fig. 12. Variation of shear parameters of tested mixtures without and with lime: (a) cohesion; (b) the angle of internal friction

3.5. Microstructure analysis

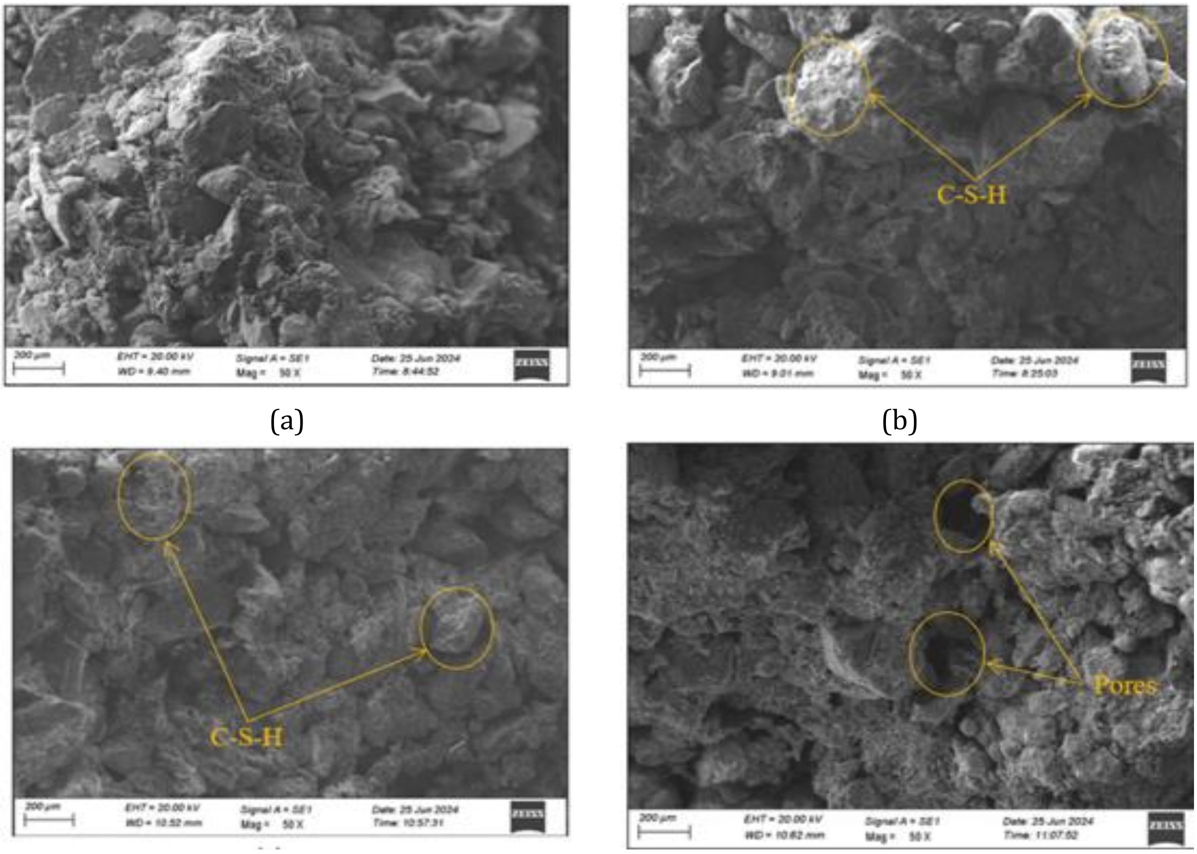
The microstructural analysis by Scanning Electron Microscopy (SEM) of gypseous-calcareous soil and DW mixtures without lime, shown in Fig. 13, reveals that, at 5% of DW, the microstructure remains relatively homogeneous, with only a slight increase in porosity compared to pure gypseous-calcareous soil.



(a) (b)

(c) (d)

Fig. 13. SEM micrographs of mixtures without lime: (a) 0% DW; (b) 5% DW; (c) 10% D; (d) 15% DW



(a) (b)

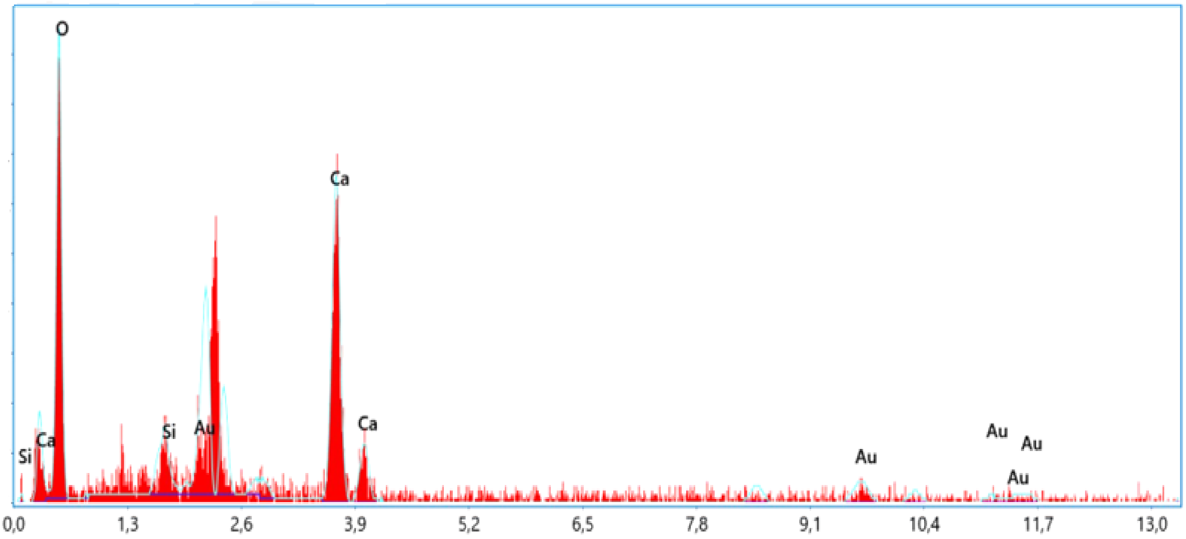
(c) (d)

Fig. 14. SEM micrographs of mixtures with lime: (a) 0% DW; (b) 5% DW; (c) 10% DW; and (d) 15% DW

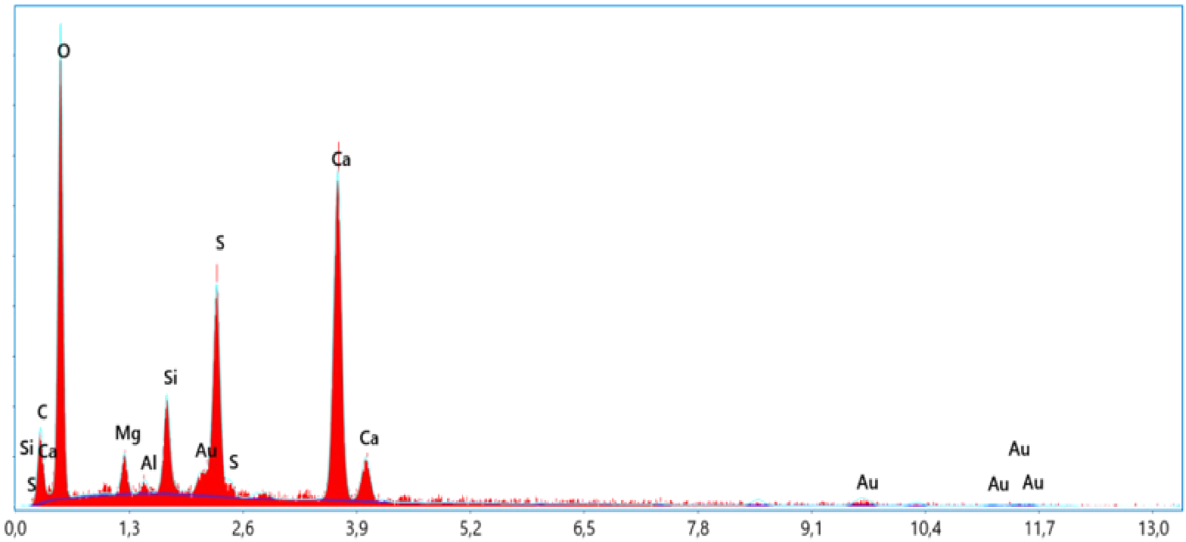
The soil particles appear well integrated without significant alteration of the binding phases. At 10%, porosity increases markedly, accompanied by the emergence of micro-cracks around the soil particles, indicating a weakening of the chemical and mechanical bonds within the matrix. Finally, at 15%, the microstructure becomes heterogeneous, characterized by larger pores and interconnected fissures, which reveals an increased chemical incompatibility and a degraded integration of the soil particles. This phenomenon is explained by the presence of organic or mineral impurities from the petroleum waste, which disrupts the internal arrangement of particles and reduces the mechanical cohesion of the soil. These observations are consistent with the work of Ahmad et al. [58], who demonstrated that the incorporation of diesel and crude oil into soil lead to development of a hydrocarbon coating on the surfaces of the soil particles, which influenced their microstructure.

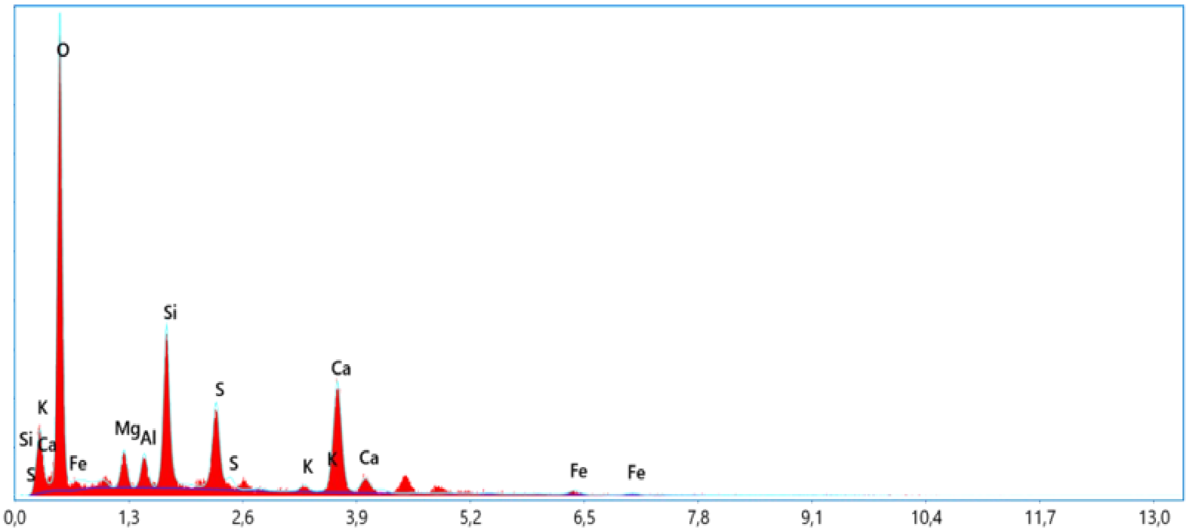
The microstructural analysis, conducted by SEM, reveals notably different microstructural results for the mixtures with 4% lime, as shown in Fig. 14. There was a marked improvement in the microstructure of all mixtures, resulting in a more homogeneous and compact matrix, as well as a significant reduction in internal voids and the waste particles appear properly integrated into the soil. This densification is attributed to the presence of calcium silicate hydrate, resulting from reactions between the lime and the siliceous compounds of treated DW. This result aligns with the conclusions reported by Oluwatuyi et al. [59], who observed similar effects when stabilizing hydrocarbon-contaminated soils using cement and lime.

Fig. 15 presents the Energy Dispersive X-ray Spectroscopy (EDX) analysis results for mixtures of gypseous-calcareous soil and DW with lime. It can be seen, from EDX recordings (a) and (b), that the mixtures SDW0L4 and SDW5L4 have high calcium and sulfate contents due to the nature of the soil and the presence of lime in the mixtures. For the mixture SDW10L4, the calcium content decreases due to its increased consumption during chemical reactions with siliceous compounds of DW. This chemical stabilization, observed by Ezeokpube et al. [60] through mineralogical analyses, confirms the mitigation of structural disorders induced by hydrocarbon contaminants. Finally, mixture SDW15L4 on the EDX record shows a slight increase of sulfate, calcium and silicon peaks accompanied by very low chlorine and sodium contents.

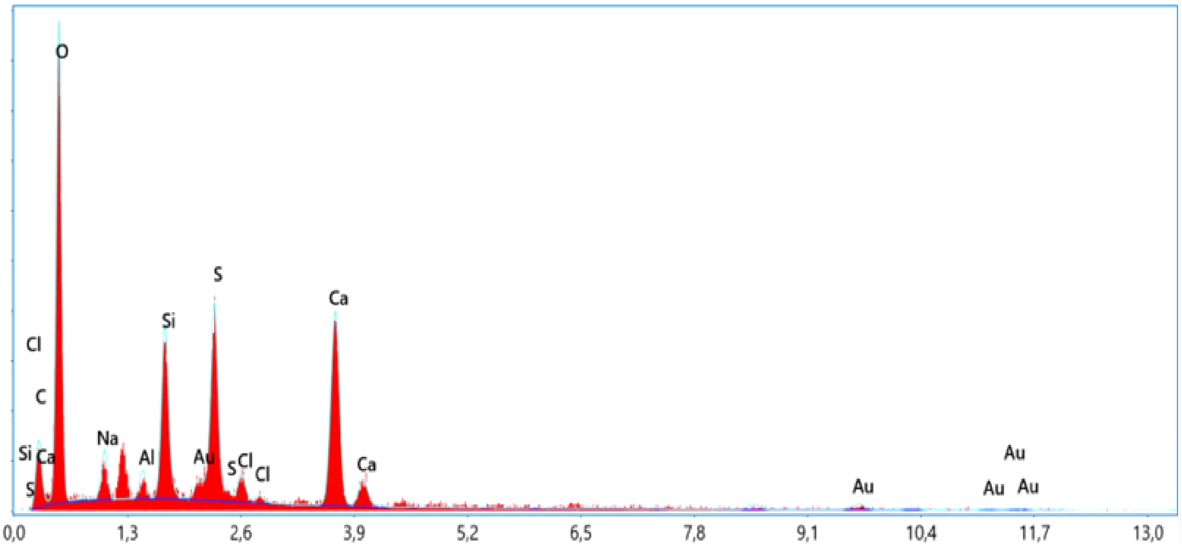


(a)





(c)



(d)

Fig. 15. EDX of mixtures with lime: (a) 0% DW; (b) 5% DW; (c) 10% DW; and (d) 15% DW

4. Conclusions

The results of this study demonstrate the technical and environmental feasibility of valorizing treated oil drilling waste, in combination with gypseous-calcareous soil, for road applications in arid regions. Based on the results of this experimental study, the main conclusions are as stated below.

The addition of DW without lime significantly decreased compressive strength, from 1.1 MPa in the pure soil (SDW0L0) to 0.5 MPa in the soil with 15% DW (SDW15L0). As for the CBR index, a decrease of 27% was observed, from 48% in the pure soil (SDW0L0) to 35% in the soil with 15% DW (SDW15L0). In direct shear tests, both cohesion (c) and friction angle (φ) decreased, regardless of the proportion of DW used. As a result, the soil becomes more sensitive to water and disintegrates quickly. SEM images demonstrated that the microstructure of soil containing oil drilling waste has higher porosity, causes a reduction in the mechanical properties.

The incorporation of 4% lime into mixtures containing DW significantly improved the compressive strength compared to mixture SDW0L4, reaching optimal values after 90 days of curing. Regarding the sensitivity to water, it was observed that the sample appears well integrated without alteration and compressive strength improved after immersion. Additionally, a 13% improvement in bearing capacity occurred, as CBR index increased from 65% (in mixture SDW0L4) to 75% (in the mixture with 10% DW). The cohesion and the friction angle improved proportionally, with an increase in the DW content of up to 10%, followed by a decrease, and then a further increase in the DW of up to 15%. The SEM-EDX analysis revealed that the presence of reactive oxides in DW (such as SiO_2) and the addition of lime (CaO) favors pozzolanic reactions, leading to the formation of cementitious compounds that reduce porosity and limit micro-cracks, thereby enhancing the soil texture and internal structural density, contributing to greater cohesion and resistance under load.

The SDW10L4 mixture achieved the highest performance, showing a compressive strength of 2.45 MPa and a CBR index of 75%. The parameters of cohesion (c) (45 kPa), and friction angle (φ) (35°) meet the requirements for Saharan road infrastructure, which is subject to extreme climatic conditions.

In summary, the usage of gypseous-calcareous soil with DW mixtures offers a dual benefit: From an environmental standpoint, this approach offers a sustainable solution for managing and reducing the ecological impact of petroleum waste, while optimizing the use of local resources in desert road infrastructure projects.

Future research should focus on evaluating the long-term durability of the stabilized mixtures under environmental conditions such as wetting–drying and freeze–thaw cycles, as well as assessing their performance under field conditions. Such investigations would help confirm the suitability of oil drilling-waste-based mixtures for road construction applications.

References

[1] Ghazi M, Quaranta G, Duplay D, Hadjamor R, Khodja M, Ait Amar H, Kessaissia Z. Life-cycle impact assessment of oil drilling mud system in Algerian arid area. Resources, Conservation and Recycling, 2011; 55(12): 1222-1231. https://doi.org/10.1016/j.resconrec.2011.05.016

[2] Almudhhi SM. Environmental impact of disposal of oil-based mud waste in Kuwait. Petroleum Science and Technology, 2016; 34(1): 91-96. https://doi.org/10.1080/10916466.2015.1122630

[3] Pereira LB, Sad CM, Castro EV, Filgueiras PR, Lacerda V. Environmental impacts related to drilling fluid waste and treatment methods: A critical review. Fuel, 2022; 310: 122301. https://doi.org/10.1016/j.fuel.2021.122301

[4] Nasir U, Saeed MA, Yousif SM. Environmental impact assessment of heavy metals in surface disposed drilling waste. Journal of Geoscience and Environment Protection, 2021; 9(9): 227-238. https://doi.org/10.4236/gep.2021.99012

[5] Ilinykh G, Fellner J, Sliusar N, Korotaev V. A life cycle assessment of drilling waste management: A case study of oil and gas condensate field in the north of western Siberia, Russia. Sustainable Environment Research, 2023; 33(1): 9. https://doi.org/10.1186/s42834-023-00171-0

[6] Manian R. Bioremediation of polycyclic aromatic hydrocarbons contaminated soils: Recent progress, perspectives and challenges. Environmental Science and Pollution Research, 2023; 30: 1-17.

[7] Rahman ZA, Hussain A, Ismail T. Influence of oil contamination on geotechnical properties of basaltic residual soil. American Journal of Applied Sciences, 2010; 7(7): 954-960. https://doi.org/10.3844/ajassp.2010.954.961

[8] Samad S. Utilization of petroleum drill cuttings as sustainable construction material. Sustainable Materials and Technologies, 2020; 25: e00162.

[9] Al Dhamri HS, Abdul-Wahab SA, Velis C, Black L. Oil-based mud cutting as an additional raw material in clinker production. Journal of Hazardous Materials, 2020; 384: 121022. https://doi.org/10.1016/j.jhazmat.2019.121022

[10] Abdul-Wahab SA, Al-Dhamri H, Ram G, Black L. The use of oil-based mud cuttings as an alternative raw material to produce high sulfate-resistant oil well cement. Journal of Cleaner Production, 2020; 269: 122207. https://doi.org/10.1016/j.jclepro.2020.122207

[11] Ayati B, Molineux C, Newport D, Cheeseman C. Manufacture and performance of lightweight aggregate from waste drill cuttings. Journal of Cleaner Production, 2019; 208: 252-260. https://doi.org/10.1016/j.jclepro.2018.10.134

[12] Bernardo G, Souza P, Santos J. The use of oil well-derived drilling waste and electric arc furnace slag as alternative raw materials in clinker production. Resources, Conservation and Recycling, 2007; 52: 95-102. https://doi.org/10.1016/j.resconrec.2007.02.004

[13] Anghelescu L, Cruceru M, Diaconu B. Building materials obtained by recycling coal ash and waste drilling fluid and characterization of engineering properties by means of artificial neural networks. Construction and Building Materials, 2019; 227: 116616. https://doi.org/10.1016/j.conbuildmat.2019.07.342

[14] Chen TL, Lin S, Lin ZS. An innovative utilization of drilling wastes as building materials. Proceedings of the SPE Health, Safety, Security, Environment and Social Responsibility Conference, Galveston, USA, 2007. https://doi.org/10.2118/106913-MS

[15] El-Mahllawy M, Osman TA. Influence of oil well drilling waste on the engineering characteristics of clay bricks. Journal of American Science, 2010; 6(7): 48-54.

[16] Mostavi E, Asadi S, Ugochukwu E. Feasibility study of the potential use of drill cuttings in concrete. Procedia Engineering, 2015; 118: 1015-1023. https://doi.org/10.1016/j.proeng.2015.08.543

[17] Wasiuddin PW, Ali N, Islam MR. Use of offshore drilling waste in hot mix asphalt concrete as aggregate replacement. Proceedings of the Energy Technology Conference and Exhibition, Houston, USA, 2002. https://doi.org/10.1115/ETCE2002/EE-29168

[18] Tuleun L Z, Wasiu J. Mechanical behavior of silty-clayey lateritic soil stabilized with recycled municipal solid waste ash. Res. Eng. Struct. Mater, 2025; 11(3): 1121-1138. http://dx.doi.org/10.17515/resm2024.204me0303rs

[19] Zaini MSI, Hasan M. Effects of industrial and agricultural recycled waste enhanced with lime utilisation in stabilising kaolinitic soil. International Journal of Sustainable Construction Engineering and Technology, 2023; 14(4): 332-353. https://doi.org/10.30880/ijscet.2023.14.04.025

[20] Li W, Yi Y, Puppala AJ. Effects of curing environment and period on performance of lime-GGBS-treated gypseous soil. Transportation Geotechnics, 2022; 37: 100848. https://doi.org/10.1016/j.trgeo.2022.100848

[21] Sezer A, Inan G, Yilmaz HR, Ramyar K. Utilization of a very high lime fly ash for improvement of Izmir clay. Building and Environment, 2006; 41(2): 150-155. https://doi.org/10.1016/j.buildenv.2004.12.009
[22] Almuaythir S, Abbas MF. Expansive soil remediation using cement kiln dust as stabilizer. Case Studies in Construction Materials, 2023; 18: e01983. https://doi.org/10.1016/j.cscm.2023.e01983
[23] Sanijya G, Bala M R, Samatha C P. Sustainable stabilization of native subgrade soil for low-volume roads using copper slag and cementitious materials. Res. Eng. Struct. Mater, 2025; 11(4): 1683-1702. http://dx.doi.org/10.17515/resm2025-682ma0214rs
[24] Al-Khafaji R, Dulaimi A, Jafer H, Mashaan NS, Qaidi S, Obaid ZS, Jwaida Z. Stabilization of soft soil by a sustainable binder comprising GGBS and CKD. Recycling, 2023; 8(1): 10. https://doi.org/10.3390/recycling8010010
[25] Arulrajah A, Kua TA, Suksiripattanapong C. Stiffness and strength properties of spent coffee grounds-recycled glass geopolymers. Road Materials and Pavement Design, 2019; 20(3): 623-638. https://doi.org/10.1080/14680629.2017.1408483
[26] Kassa A, Sekine R, Dorji T, Pathak GK, Hayano K, Yamauchi H, Mochizuki Y. Insights into water absorption characteristics of various waste-based inorganic additives and their application for soil stabilization. Journal of Cleaner Production, 2024; 446: 141470. https://doi.org/10.1016/j.jclepro.2024.141470
[27] Pastor JL, Tomás R, Cano M, Riquelme A, Gutiérrez E. Evaluation of the improvement effect of limestone powder waste in the stabilization of swelling clayey soil. Sustainability, 2019; 11(3): 679. https://doi.org/10.3390/su11030679
[28] ALRUBAYE AJ, HASAN M, FATTAH MY. Effects of using silica fume and lime in the treatment of kaolin soft clay. Geomechanics and Engineering, 2018; 14(3): 247-255.
[29] Zaini MSI, Hasan M. Effectiveness of silica fume, eggshell ash and lime use on the properties of kaolinitic clay. International Journal of Engineering and Technology Innovation, 2023; 13(4): 337-352. https://doi.org/10.46604/ijeti.2023.11936
[30] Liu Y, Su Y, Namdar A, Zhou G, She Y, Yang Q. Utilization of cementitious material from residual rice husk ash and lime in stabilization of expansive soil. Advances in Civil Engineering, 2019. https://doi.org/10.1155/2019/5205276
[31] Djili K, Daoud Y, Ayache N. Analyse de la distribution verticale et spatiale du calcaire dans les sols de l'Algérie septentrionale. Étude et Gestion des Sols, 1999; 6(3): 201-213.
[32] Cherrak M, Bali A, Silhadi K. Concrete mix design containing calcareous tuffs as a partial sand substitution. Construction and Building Materials, 2013; 47: 318-323. https://doi.org/10.1016/j.conbuildmat.2013.05.051
[33] Cherrak M, Morsli M, Boutemeur M, Bali A. Valorization of the use of calcareous tuff and dune sand in Saharan road design. Journal of Civil Engineering and Architecture, 2015; 9: 665-676. https://doi.org/10.17265/1934-7359/2015.06.004
[34] Morsli M, Benyelles B, Seddik A. Étude du durcissement d'un tuf d'encroûtement de Hassi-Messaoud (Algérie). Revue Européenne de Génie Civil, 2007; 11(9-10): 1219-1240. https://doi.org/10.3166/regc.11.1219-1240
[35] Goual I, Ben El Hadj A, Boulanouar M. Improvement of natural tuff properties used in Saharian road engineering by addition of sand limestone. European Journal of Environmental and Civil Engineering, 2012; 16(6): 744-763. https://doi.org/10.1080/19648189.2012.667653
[36] Khellou A, Abdeldjouad L, Madun A, Firdaus M, Aminuddin KM, Mokhtari A, Dehmani M. Improvement of the mechanical properties of an encrusting tuff treated with sewage sludge bottom ash and lime. International Journal of Sustainable Construction Engineering and Technology, 2024; 15(3): 230-242. https://doi.org/10.30880/ijscet.2024.15.03.020
[37] Abaas RF, Fattah MY, Naif MH, Hafez M. Collapsible gypseous soil stabilization by calcium carbide residue and sulfonic acid. Sustainability, 2024; 16(22): 9974. https://doi.org/10.3390/su16229974
[38] Sadeghi E, Nikudel MR, Ghasemi S, Bayat N. Chemical and thermal stabilization of gypseous loess soils: Comparative study of natural environmentally friendly materials and cement. Case Studies in Construction Materials, 2025; 23: e04945. https://doi.org/10.1016/j.cscm.2025.e04945
[39] Mahawish AM. Chemical stabilization of gypseous subgrade soils for road construction in Iraq. Journal of Engineering and Sustainable Development, 2013; 17(4): 1-13.
[40] Balegh B, Selaf H, Hadjmostefa A. Effect of ceramic waste on mechanical and geotechnical properties of tuff treated by cement. Case Studies in Construction Materials, 2020; 13: e00368. https://doi.org/10.1016/j.cscm.2020.e00368
[41] Daheur EG, Zhong SL, Demdoum A, Taibi S, Goual I. Valorisation of dune sand-tuff for Saharan pavement design. Construction and Building Materials, 2023; 366: 130239. https://doi.org/10.1016/j.conbuildmat.2022.130239
[42] Akacem M, Moulay OH, Abbou M, Mekerta B, Semcha A. Valorisation des sables de dunes en mélange avec le tuf dans le corps de chaussée: Application à la région d'Adrar. African Review of Science Technology and Development, 2018; 3(1): 18-26.

[43] Omar HM, Zentar R, Akacem M, Mekerta B, Mouli M. Co-valorization of tuff and sandy residues in roads construction. Open Civil Engineering Journal, 2022; 8(5): 1029-1045. https://doi.org/10.28991/CEJ-2022-08-05-013

[44] Décret Exécutif n°06-141. Définissant les valeurs limites des rejets d'effluents liquides industriels. Journal Officiel de la République Algérienne, 2006; 4-9.

[45] James J, Sivapriya SV, Ali S, Madhu TR, Singh B. Wetting and drying resistance of lime-stabilized expansive soils modified with nano-alumina. Electronic Journal of the Faculty of Civil Engineering Osijek-e-GFOS, 2021; 12(22): 70-80. https://doi.org/10.13167/2021.22.6

[46] EN ISO 17892-7. Geotechnical investigation and testing - Laboratory testing of soil - Part 7: Unconfined compression test. 2020.

[47] EN 13286-47. Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of the California Bearing Ratio, immediate bearing index and linear swelling. 2021.

[48] EN ISO 17892-10. Geotechnical investigation and testing - Laboratory testing of soil - Part 10: Direct shear tests. 2018.

[49] Abdallah T, Mustapha A, Hassan M O, Lyacine B, Larbi A. Co-valorization of local materials tuff and red brick waste mixture for use in road construction. Res. Eng. Struct. Mater., 2026; 12(1): 535-547. http://dx.doi.org/10.17515/resm2025-906ma0517rs

[50] Al-Amoudi OSB, Khan K, Al-Kahtani NS. Stabilization of a Saudi calcareous marl soil. Construction and Building Materials, 2010; 24(10): 1848-1854. https://doi.org/10.1016/j.conbuildmat.2010.04.019

[51] Moayyeri N, Oulapour M, Haghighi A. Study of geotechnical properties of a gypsiferous soil treated with lime and silica fume. Geomechanics and Engineering, 2019; 17(2): 195-206.

[52] Goual I, Goual MS, Gueddouda MK, Ferhat A. Effect of treatment with lime and cement on the mechanical behavior of calcareous tuffs for pavement layers in Laghouat, Algeria. International Conference on Construction and Building Technology, Malaysia, 2008.

[53] Abdulrasool AS, Kadhim ST, Khattab MM, Khaleel TA. Role of cement-micro silica on mechanical behavior of collapsible soils under long-term soaking. AIP Conference Proceedings 2024; 3219(1): 020014. https://doi.org/10.1063/5.0237784

[54] Alavéz-Ramírez R, Montes-García P, Martínez-Reyes J. Use of sugarcane bagasse ash and lime to improve durability and mechanical properties of compacted soil blocks. Construction and Building Materials, 2012; 34: 296-305. https://doi.org/10.1016/j.conbuildmat.2012.02.072

[55] Sharifi TE, Mirzababaei M, Karimiazar J, Arjmandzadeh R, Mahmoudpardabad K. Gypsum and rice husk ash for sustainable stabilization of forest road subgrade. Quarterly Journal of Engineering Geology and Hydrogeology, 2024; 57(1): qjegh2023-008. https://doi.org/10.1144/qjegh2023-008

[56] Shah SJ, Shroff AV, Patel JV, Tiwari KC, Ramakrishnan D. Stabilization of fuel oil contaminated soil: A case study. Geotechnical and Geological Engineering, 2003; 21(4): 415-427. https://doi.org/10.1023/B:GEGE.0000006052.61830.1a

[57] Almuaythir S, Zaini MSI, Hasan M, Hoque MI. Sustainable soil stabilization using industrial waste ash: Enhancing expansive clay properties. Heliyon, 2024; 10(20): e39124. https://doi.org/10.1016/j.heliyon.2024.e39124

[58] Ahmad S, Al-Amoudi OSB, Mustafa YM, Maslehuddin M, Al-Malack MH. Stabilization and solidification of oil-contaminated sandy soil using Portland cement and supplementary cementitious materials. Journal of Materials in Civil Engineering, 2020; 32(8): 04020220. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003169

[59] Oluwatuyi OE, Ojuri OO, Khoshghalb A. Cement-lime stabilization of crude oil contaminated kaolin clay. Journal of Rock Mechanics and Geotechnical Engineering, 2020; 12(1): 160-167. https://doi.org/10.1016/j.jrmge.2019.07.010

[60] Ezeokpube GC, Ahaneku IE, Alaneme GU, Attah IC, Etim RK, Olaiya BC, Udousoro IM. Assessment of mechanical properties of soil-lime-crude oil contaminated soil blend using regression model for sustainable pavement foundation construction. Advances in Materials Science and Engineering, 2022; 2022: 7207842. https://doi.org/10.1155/2022/7207842