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Research Article

Laboratory improvement of clay mineralogical and swelling properties using hydraulic binder treatment

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Abstract

This article outlines the findings from experimental research to improve the mechanical characteristics, notably the swelling potential of a clay sourced from the Boumagueur area in eastern Algeria. In a first part, oedometer tests conducted according to ASTM 4546-03, revealed that increasing binder content significantly reduced swelling properties. From the natural state (without hydraulic binder) to 9% binder content, swelling pressure decreased by 72% for samples treated with lime, 58% for cement, and 62% for the lime-cement mixture. Similarly, swelling potential was notably reduced, with lime treated samples showing an 87% decrease, compared to 57% for cement and 73% for the lime-cement mixture. In the second part of this work, X-ray diffraction analysis confirmed that the reduction in swelling was due to the formation of a cementitious phase, such as hydrated calcium silicate (CSH). Overall, the addition of hydraulic binders effectively improved the swelling behavior of the soil.

1. Introduction

The swelling phenomenon of clay soils is one of the significant problems in geotechnics, referring to the volume increase that occurs when these soils absorb water. This behavior primarily due to the mineralogical composition and structural characteristics of clay particles, which allow strong interactions with water molecules triggering hydration phenomena, resulting in an increase in volume. Clay minerals, such as montmorillonite or smectite, which have a layered structure consisting of alumina (Al_2O_3) and silica (SiO_2), are characterized by weak bonding, allowing water to easily penetrate the interlayer spaces. Consequently, this further weakens the bonds between the layers, causing their separation and leading to significant volumetric swelling [1].

The swelling of certain clay soils, particularly in arid or semi-arid area, causes damage and disorder mainly affecting structures built on the surface and underground [2, 3]. Losses in different types of construction attributed to this phenomenon are very costly. Barbosa et al. [4] reported that the volumetric variation of expansive soils in the state of Acre (Brazil) caused significant financial losses. Similarly, Jones and Jefferson [5] have referred to swelling clays as being the most damaging geohazard in Britain, costing the insurance industry significant financial losses per year. Other

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similar studies of the swelling soils have been made in China [6], Africa [7] and Australia [8]. To clarify the mechanisms at the origin of this phenomenon and to reduce its effect by proposing effective mitigation measures, this phenomenon was widely studied using various techniques by numerous researchers [9, 10]. Meanwhile, many studies have focused on soil stabilization using additives, owing to their ability to improve the geotechnical properties of clay soils [11, 12]. Several and different materials were used as additives to stabilize clay soils and reduce their swelling, such as the incorporation of sand [13, 14], fly ash [15, 16], milk of lime [17, 18], cement [19, 20], lime [21, 22].

The inclusion of lime and/or cement to treat clay soils therefore incentivizes engineers to opt for these stabilizers owing to its beneficial impacts on improving various geotechnical properties of these soils. Many studies have illustrated that treatment with these hydraulic binders, can ameliorate the properties of soils exhibiting subpar physical and mechanical characteristics, such as high plasticity, high swelling, low permeability, and weak mechanical strength, along with susceptibility to water-induced effects. The addition of lime and/or cement into clay soil was observed to diminish its plasticity and compressibility, while augmenting its permeability and mechanical strength, due to hydraulic binder ability to induce soil particle flocculation [23, 24, 29, 26, 27]

Por et al. [28] conducted tests on Na-montmorillonite bentonite. The experimental program involved unconfined compression, vertical free swelling strain, and confined swelling pressure tests. The experimental results show that the cement addition led to marked decreases in the vertical free swelling strain and to the obvious improvement of strength and stiffness of soils. In addition, it was noted that the cement had a greater effect in reducing vertical swelling pressure than the lateral swelling pressure of the soils during one-dimensional swelling. Al-Gharbawi et al. [29], found that the expansive soil treated with cement, has a reduction in free swelling and swelling pressure of about 65 and 76% respectively, compared to untreated soil. In addition to these results, it was also observed in many studies that adding cement reduces the plasticity index and compressibility, while augmenting the mechanical strength of swelling soils [30, 31, 32]. Kemissa et al. [33] present a series of laboratory test results of physical and mechanical characterization obtained on an over consolidated expansive clay treated with lime. They noted an important reduction of its plasticity, which becomes less sensitive to water, resulting in an appreciable mitigation of its potential of swelling. They concluded also that the best performances were obtained for a treatment dosage of 8% lime, which led to a significant improvement of bearing capacity and drained and undrained shear strength of studied soil. Similar results have also demonstrated the effectiveness of adding lime to improve the physical and mechanical properties of swelling soils [34, 35, 36, 37, 38].

For its use in the road works as roadway foundation, Khemissa and Mahamedi [39] investigated a highly plastic swelling clay. The test results demonstrated a significant improvement in the mechanical properties of this swelling clay when treated with varying proportions of a cement-lime mixture and compacted under optimal Proctor conditions. They observed a reduction in the plasticity index and noted that the clay became non-expansive and more compactable. This was accompanied by an increase in CBR values, allowing this fact of increasing the bearing pressure of clay. Additionally, the shear strength of the clay improved, further increasing its bearing capacity. Notably, the best performance was achieved with a combined treatment of 8% cement and 4% lime. Wang and Korkiala [40] conducted incremental loading oedometer tests on soft clay and found that increasing the cement-lime dosage and curing time led to a reduction in the initial void ratio and an increase in the clay dry mass. Their results also revealed a significant increase in the compression index at low cement-lime dosages until a peak value around 3% cement-lime, followed by a significant decrease with higher cement-lime dosage. The most evident effect of chemical treatment was the increase in the elastic limit. The addition of hydraulic binders (lime and/or cement) to soil in the presence of water, initially trigger the flocculation of soil particles, and subsequently, induce a pozzolanic reaction. Calcium cations released from hydraulic binders react with silica (SiO2) and/or alumina (Al2O3) to form cementing agents such as calcium silicate hydrate (CSH), calcium aluminate hydrate (CAH), and calcium aluminosilicate hydrates (CASH) [41, 42, 43, 44, 45]. These compounds interact with clay minerals, altering the soil structure and improve its physical and mechanical properties [46, 47, 48, 49].

This study investigates the effectiveness of lime and cement in stabilizing swelling clay soils, particularly in the Boumagueur – Batna region of eastern Algeria, which is significantly affected by this geotechnical issue. This phenomenon causes differential soil movements, leading to significant damage such as deformations of the roadways; cracks mainly affecting the different elements of the structures (foundations, engineering structures, masonry, etc.) built at shallow depth and without particular precautions. The research evaluates how used hydraulic binders alter the soil mineralogical composition, reduce compressibility, and mitigate swelling effects. By addressing these regional challenges, the study contributes to the literature on soil stabilization, providing practical solutions for similar geotechnical issues in areas prone to swelling soils.

2. Studied Soil and Used Materials

2.1. Studied Soil

The soil under study originates from the urban vicinity of Boumagueur, situated approximately 85 kilometers southwest of the Batna province -Algeria- (see Fig. 1). Several disorders caused by the swelling phenomenon were observed in studied area (see Fig. 2). Generally, these disorders affect light constructions with a single ground floor, which is the most widespread type of construction in this region, and manifest themselves in the form of: detachment of the parts attached to the main parts, detachment and deformation of the exterior slabs as well as various structural cracks with variable openings.

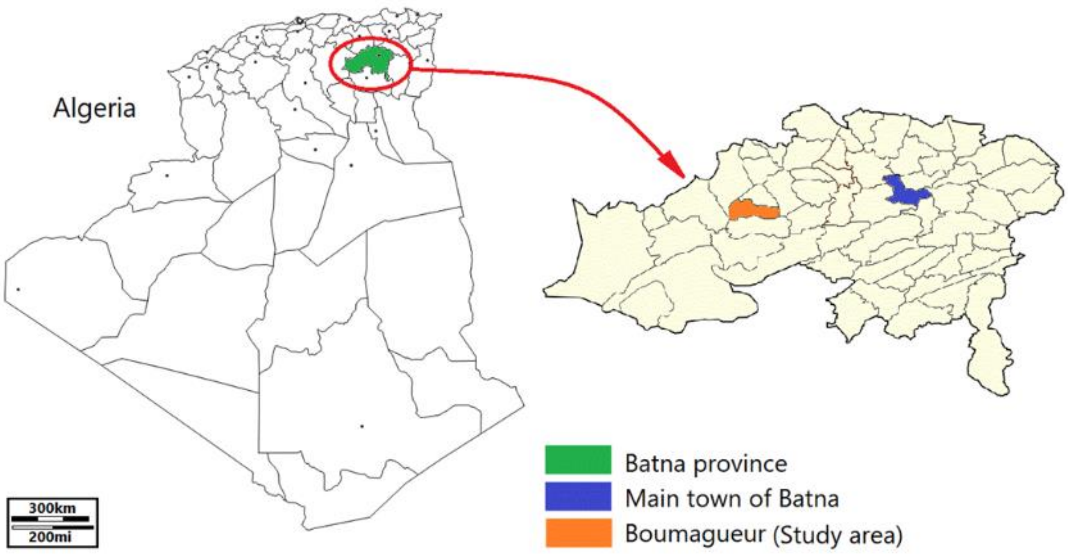


Fig. 1. Geographic location of the Boumagueur region

Geological scrutiny, relying on cartographic data in Fig.3 (1/50 000 geological maps, [50]) and on-site examinations, reveals that the Boumagueur area predominantly features geological formations from the Tertiary and Quaternary periods. These formations consist of:

- Quaternary sedimentary deposits comprising limestone, sand, silt, sandy clay, conglomerates, and gravel.

Tertiary formations include marls, clays, clay marls, and conglomerate limestones. Some marls may exhibit sandy characteristics and contain notable gypsum content.

To provide soil samples for this study, core drilling was conducted in the study area. Tests were carried out on samples taken at a starting depth of 2.5 m. The outcomes of the physical and chemical characterization tests performed on the swelling soil in question are outlined in Table 1 and 2, respectively.

Based on the USCS/LPC classification system, the studied soil is categorized as CH, which refers to a highly plastic clay with low organic matter.

Fig. 2. Some pathological cases observed in the study region

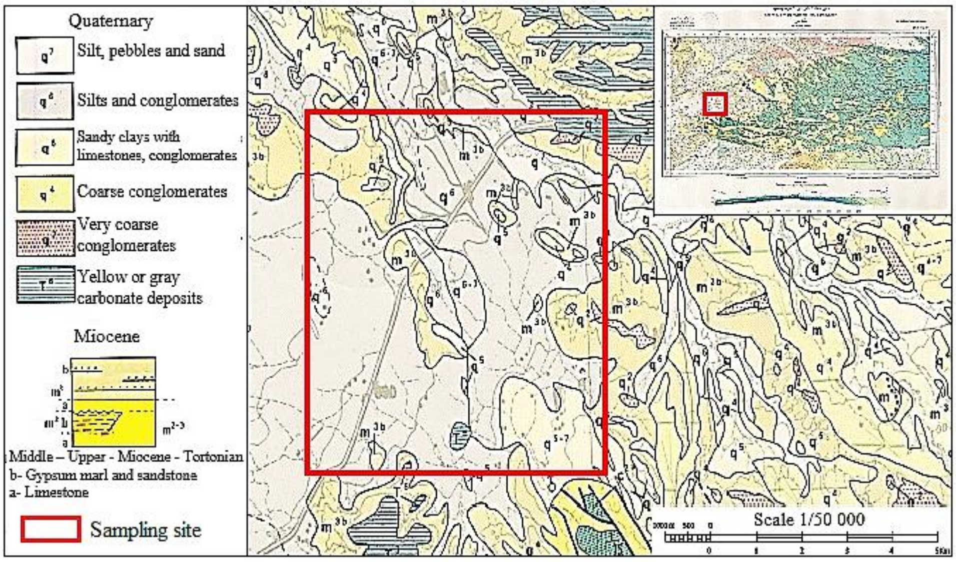


Fig. 3. Extract from the geological map of N'Gaous (1/50000; Source: National Institute of Cartography - Algiers)

Table 1. Physical characteristics of the studied material

Particle size		Atterberg limit			Shrinkage limite	Density of solid grains
Clay		LL	PL	PI	SL	gs
(% < 2 µm)	(% < 80 µm)	(%)	(%)	(%)	(%)	(kN/m3)
60	98	59	28	31	10	26.5

Table 2. Chemical properties of the studied material

Value of methylene blue	Specific surface area	CaCO3 Content	Organic matter	Clay activity
	(m2/g)	(%)	(%)	
7.2	150.7	46	8.5	0.51

The mineralogical composition of the soil under examination was identified through X-ray diffraction analysis (see Fig. 4). The soil consists of 63% clay minerals, comprising 5% illite, 15% kaolinite and 43% smectite. The latter presents a significant variation in volume (swelling) during interaction with water [1]. A detailed percentage distribution of each mineral component is provided in Table 3.

Table 3. Mineralogical composition of the studied soil

Quartz	Calcite	Gypsum	Dolomite	Feldspar	Smectite	Illite	Kaolinite
19%	16%	0.1%	0.5%	1.4%	43%	5%	15%

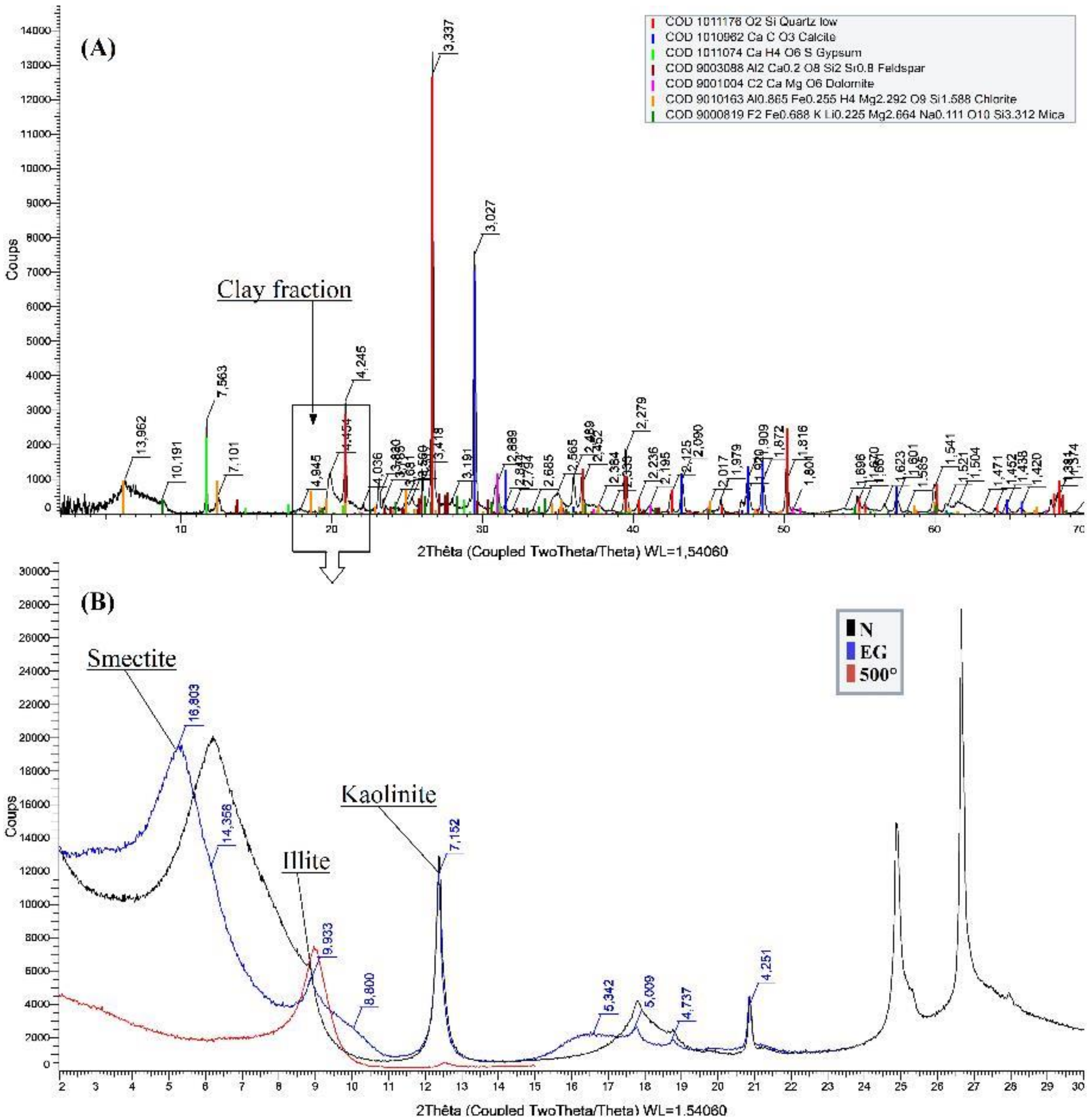


Fig. 4. X-ray diffraction of studied soil: (A) total clay of sample; (B) clay fraction

2.2. Hydraulic Binders Used

2.2.1 Lime

The lime used in this study is a commercial quicklime sourced from a local Algerian production facility. Its composition is predominantly calcium oxide (CaO) at a minimum of 85%, with traces of other impurities, as confirmed by X-ray diffraction analysis (see Fig. 5).

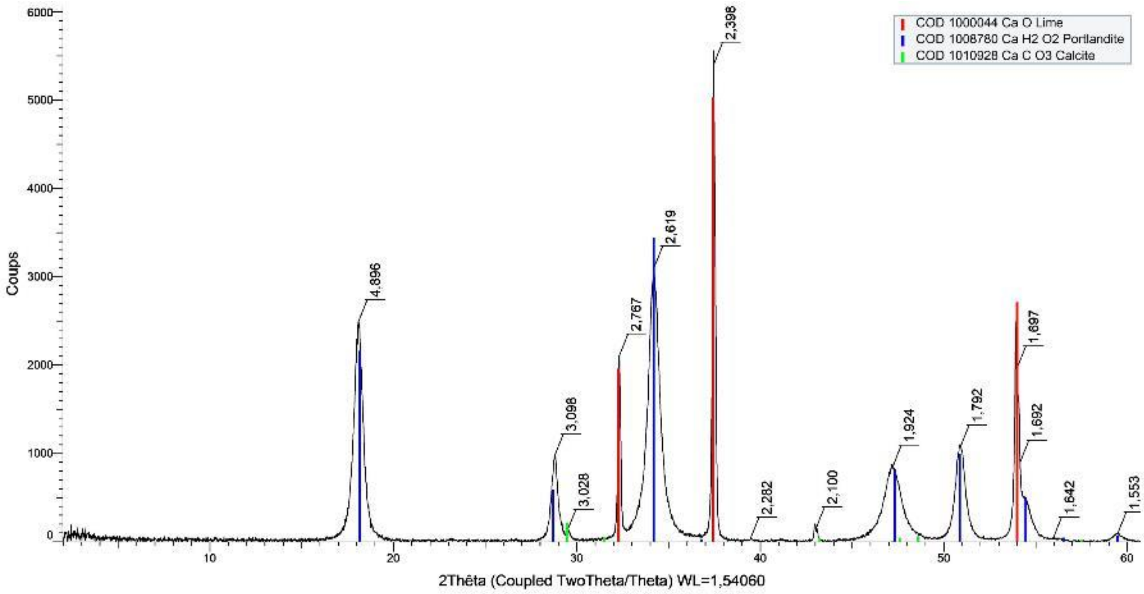


Fig. 5. X-ray diffraction of the used lime

2.2.2 Cement

The employed cement is a Portland cement (CPJ - CEMII / A 42.5 with a minimum of 65% clinker), made at the Ain-Touta cement plant in Batna, and readily available on the market. Its compressive strength at day 28 is between 42.5 and 62.5 N/mm^2. X-ray diffraction tests on the used cement are presented in Fig. 6.

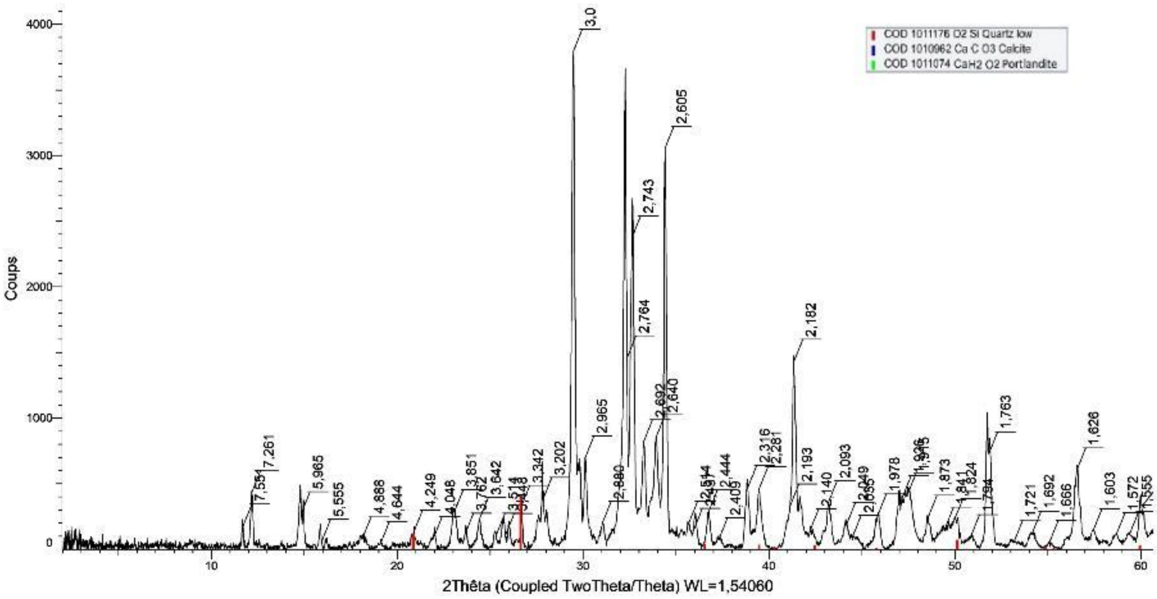


Fig. 6. X-ray diffraction of the used cement

The cement chemical characteristics given by the supplier are summarized in Table 4.

Table 4. Chemical composition of the used cement

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	CaO_{Free}	LOI*
23.50%	5%	4.20%	56.50%	1.80%	0.96%	0.80%	2.60%	0.94%	3.70%

(*) LOI : loss on ignition.

2.2.3 Cement-Lime Mixture

Lime can offer an advantage by reducing the plasticity index (PI) of highly plastic soils (swelling soils), while cement has the advantage of improving mechanical strength in addition to reducing the PI [51]. In this study, a mixture of the same cement and lime was used for treatment of studied soil to investigate and compare its effect on clay soils swelling with the effect of each hydraulic binder alone (lime and cement). The percentages used to prepare the cement-lime mixture are summarized in Table 5.

Table 5. Used percentages to prepare the cement-lime mixture

Binder	Lime	Cement	Lime	Cement	Lime	Cement	Lime	Cement
Binder addition	1 %	2 %	3 %	2 %	5 %	2 %	7 %	2 %
Mixture	3 %		5 %		7 %		9 %	

2.3. The Soil-Hydraulic Binder Mixture

In an oven and at a temperature of at 50°C, the soil studied was first dried, then ground into fine powder after being sieved through a 2 mm mesh. The studied soil and the hydraulic binder used for treatment were mixed using a mechanical mixer at 5 to 10 min until homogenized (NF P94-100 Standard). Following this, distilled water was added to the mixture, with the water content adjusted to match the natural moisture level of the soil (Initial water content w_i = 20%). The mixture obtained from the soil, hydraulic binder and water, was statically compacted in a CBR press by a compaction pressure of 50 kN and at a slow speed of 2 mm/min into rigid steel molds (70 mm in diameter and 20 mm in height). Immediately after preparation, the samples were carefully packed in film paper and sealed with paraffin to minimize moisture loss, then stored at a controlled temperature of 20°C for 28 days.

For each used hydraulic binder (Lime, Cement, Lime + Cement), four hydraulic binder contents (3%, 5%, 7% and 9%) were used in this study. The hydraulic binder contents used in the treatment of the studied soil is calculated using the following expression:

$$Hydraulic\ binder\ contents\ (\%) = \frac{Hydraulic\ binder\ mass}{Hydraulic\ binder\ masse + Dry\ soil\ masse} \tag{1}$$

3. Experimental Methods

3.1. Oedometric Tests

Oedometric tests, following the free swelling method (standard ASTM 4546-03, Method A), were performed on untreated and as well as on treated soil with hydraulic binders to determine the effect of the latter on the studied soil swelling. In these tests, a soil sample measuring 7 cm in diameter and 2 cm in height was placed in a classical oedometer cell with a moving ring. The sample was subjected to a piston load of 1.5 kPa, and finally saturated by immersion.

Vertical strain was recorded using an LVDT type strain sensor, and the swelling potential (ΔH/H) was calculated as the ratio of the maximum deformation after sample saturation to the initial height. Subsequently, the sample was progressively loaded, and the vertical pressure required to restore the sample to its original height was determined as the swelling pressure. The loading mode used in these tests is successive step mechanical loading. The transition from one loading to another takes place when the strains stabilize.

3.2. Mineralogical Analysis

To assess the reactivity of minerals (both clay and non-clay) with the hydraulic binders, the mineralogical composition of the studied material (disoriented powder) and its clay fraction (clay slides <2µm) were analyzed using X-ray diffraction. The diffractometer used is a Bruker D8 Advance diffractometer, operates at a voltage of 40 kV and an intensity of 25 mA, using Cu-Kα1 radiation (λ = 1.5406 Å). The diffraction speed used is 0.6 s/step, rotation speed 2° 2θ/min, covering an angular range "2θ" from 2° to 45°.

3.2.1 Powder Diffractogram

The powder diffractogram method, is used to identify all the minerals present in the sample, including quartz, feldspars, calcite, gypsum, and phyllosilicates. To prepare and analyze the total disoriented powder, the sample was first dried in an oven at 40 °C, then manually ground and sieved at 250 µm. The powdered material was placed on a PVC sample holder, lightly compacted, and the supports were closed to avoid any influence on preferential orientation of the mineral particles. The samples were subsequently subjected to X-ray radiation scanning over an angular range of 2° to 45° 2Θ for the determination of the total mineralogical composition.

3.2.2 Clay Fraction Slide Diffractogram

The clay slides (oriented samples) are prepared by directly depositing a diluted suspension of particles less than 2 µm on a ground glass slide, followed by air drying. The clay suspension used for X-ray diffraction was previously decalcified, and the clay fraction (< 2 µm) was extracted after a decantation process through a sedimentation process based on Stokes law. The first centimeter of the suspension was applied to a glass slide, and dried overnight at room temperature [52]. The type of clay minerals is determined by analyzing three slides subjected to different preparation protocols: air drying (natural state), solvation with ethylene glycol (EG) for 24 hours (to highlight swelling clays), and heating at 500 °C for 4 hours (to induce the destruction of kaolinite).

3.2.3 Qualitative Identification

Qualitative identification was performed by referring to the intermediate spacing values [53] and the intensity of the main reflections observed in the three X-ray diffractograms of each mineral. Semi-quantitative estimates were based on the measurement of the intensities of the characteristic peaks from the X-ray patterns. The semi-quantitative analysis was estimated using correction factors proposed by Cook et al. [54] and Boski et al. [55] for total disoriented powder and those of Fagel et al. [56] for clay minerals.

4. Results and Discussions

4.1. Free Swelling Oedometric Tests

Atterberg limit tests conducted on the studied soil reveal its high plasticity (PI = 31%). Additionally, X-ray diffractograms indicate a significant presence of smectite (43%) in the soil composition. In general, the more clay in a soil, the higher the plasticity, the greater the potential swell, the higher the compressibility [57].

Table 6. Values of the swelling pressure and swelling potential of the different oedometric tests

<table>
<tr><th rowspan="3">Hydraulic binder content (%)</th><th colspan="6">Hydraulic binder used</th></tr>
<tr><th colspan="2">Lime</th><th colspan="2">Cement</th><th colspan="2">Lime-Cement mixture</th></tr>
<tr><th>Ps (kPa)</th><th>ΔH/H (%)</th><th>Ps (kPa)</th><th>ΔH/H (%)</th><th>Ps (kPa)</th><th>ΔH/H (%)</th></tr>
<tr><td>0</td><td>190</td><td>16.60</td><td>190</td><td>16.60</td><td>190</td><td>16.60</td></tr>
<tr><td>3</td><td>120</td><td>4.50</td><td>125</td><td>12.24</td><td>127</td><td>8.40</td></tr>
<tr><td>5</td><td>94</td><td>3</td><td>100</td><td>10.73</td><td>110</td><td>6.40</td></tr>
<tr><td>7</td><td>71</td><td>2.60</td><td>95</td><td>9.20</td><td>90</td><td>5</td></tr>
<tr><td>9</td><td>54</td><td>2.20</td><td>80</td><td>7.15</td><td>72</td><td>4.50</td></tr>
</table>

This is due to the fact that certain families of clay minerals, particularly smectite, exhibit particularly weak bonds between their constituent layers, to the extent that the amount of water likely to be adsorbed within the clay particles themselves can be substantial, leading to significant volume changes [1].To monitor the changes in the swelling parameters of the studied soil according to the hydraulic binders used for the treatment, oedometric tests were conducted on both untreated and treated samples (different hydraulic binders' contents), at room temperature. The results of these tests, including the swelling pressure and swelling potential, are summarized in Table 6. Fig. 7, 8 and 9 show the variation of the void ratio as a function of the total vertical stresses of all conducted oedometric tests.

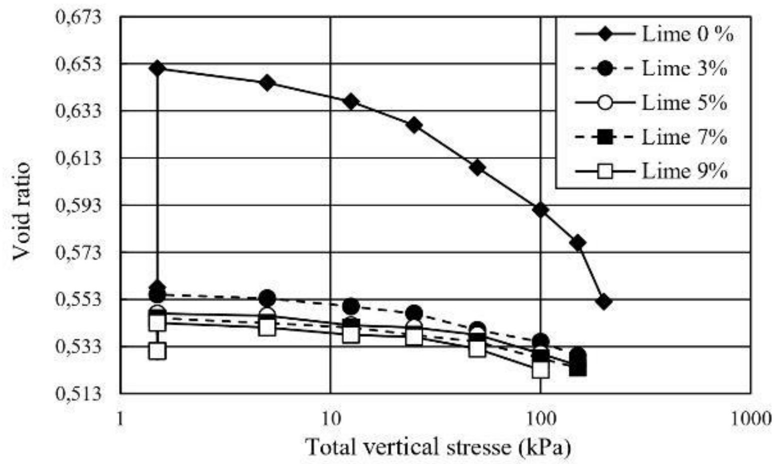


Fig. 7. Oedometric tests curves of treated soil with different lime contents

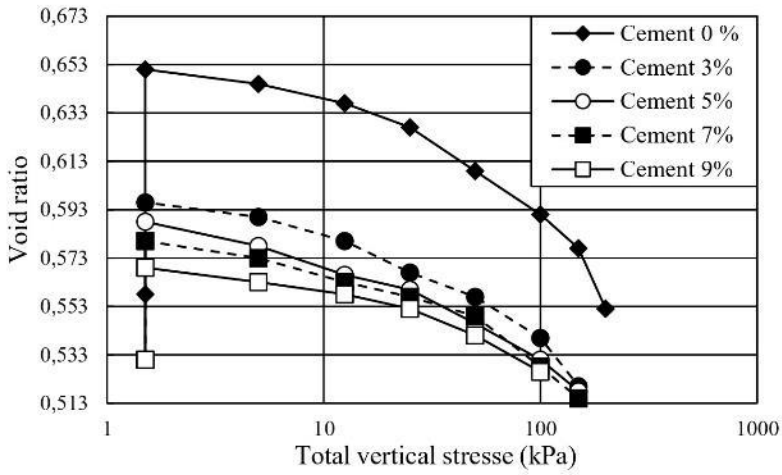


Fig. 8. Oedometric tests curves of treated soil with different cement contents

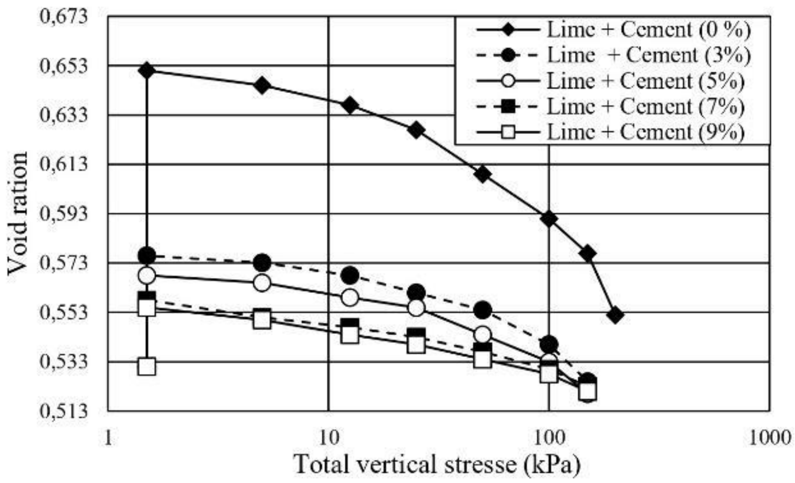


Fig. 9. Oedometric tests curves of treated soil with different mixture (lime-cement) contents

The variations in swelling pressure as a function of hydraulic binder content were plotted in Fig. 10. We note that the untreated sample exhibits a swelling pressure of around 190 kPa. We note also a decrease in the swelling pressure with hydraulic binder content increasing. Concerning the lime treatment, the results show that the effect of lime is greater than that of other binders (cement and the Lime-Cement mixture). The samples treated with lime showed a reduction in swelling pressure of around 72%, for a binder content of 9%. Fig. 11 represents the variations in the swelling potential as a function of the hydraulic binder content. It is also noted that the swelling potential is significantly influenced by variation in hydraulic binder content, so that an increase in the latter is accompanied by a decrease in the swelling potential. From the natural state (without hydraulic binder) to a binder content of 9%, the samples treated with lime showed a reduction in swelling potential of around 86%. For samples treated with cement and with Lime-Cement Mixture, the decrease in swelling potential is 57% and 73%, respectively.

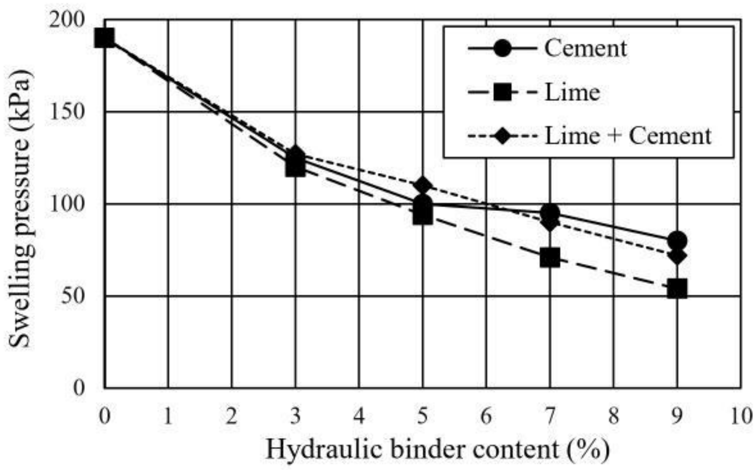


Fig. 10. Variations of swelling pressure as a function of used hydraulic binder content

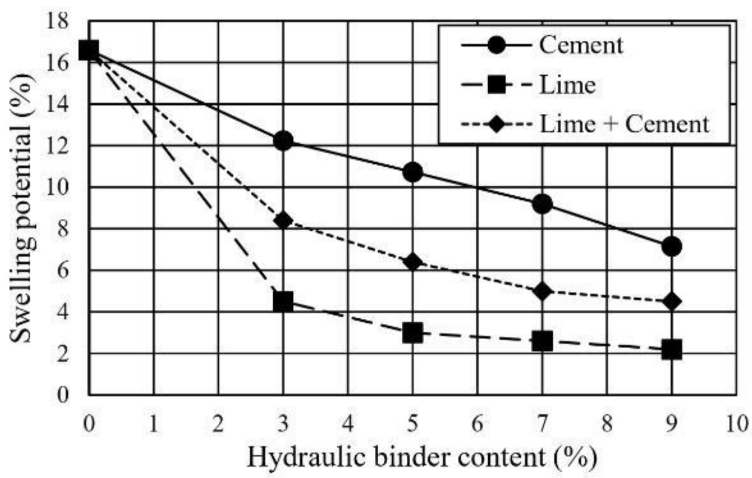


Fig. 11. Variations of swelling potential as a function of used hydraulic binder content

From the obtained results, we note that the swelling soils compressibility decreases with the hydraulic binder content increasing (lime and/or cement). The use of hydraulic binders such as lime or cement has proven effective in the treatment of clays. Abdalla et al. [58] demonstrated that the addition of a hydraulic binder such as lime induces flocculation of clay particles, reducing and limiting swelling. In addition, pozzolanic reactions generated by hydraulic binders produce cementitious compounds such as calcium silicate hydrates (CSH), which stiffen the soil structure and improve its mechanical properties [59]. These transformations also help reduce the swelling of clay soils to minimize disorders associated with volumetric variations.

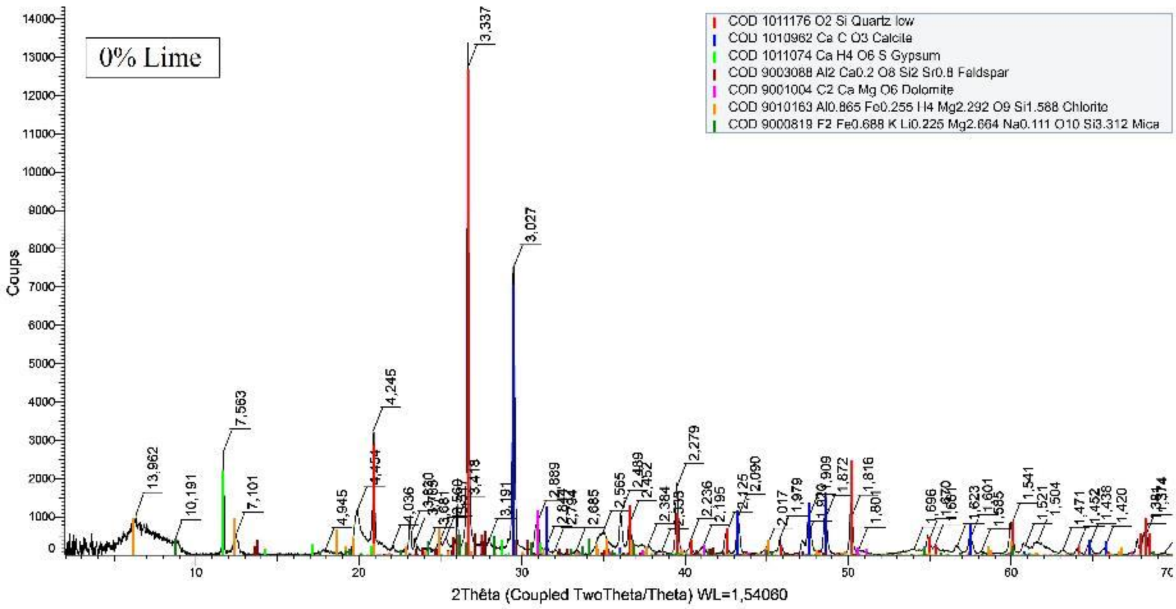
4.2. Impact of Hydraulic Binders on the Mineralogical Characteristics of the Studied Material

The studied samples, untreated and treated at different values of hydraulic binder content, are characterized mineralogically in order to evaluate the reactivity of minerals (clay and non-clay) with hydraulic binders and the formation of cement phases. The evolution of chemo-mineralogical properties during treatment was studied using X-ray diffraction, to highlight crystallized phases such as portlandite and CAH, CASH and CSH type phases.

4.2.1 Treatment Effect on The Entire Studied Material

Fig. 12, 13 and 14 show the different results of the X-ray diffraction analysis of the untreated and treated samples with the different used hydraulic binders. The results shows that the samples were subjected to a mineralogical change and the formation of new minerals after treatment with hydraulic binders. The comparison of the diffractograms of the untreated and treated samples with the different used hydraulic binders (lime, cement and lime-cement mixture) at different hydraulic binder contents (3% and 5%) reveals the emergence of new peaks, indicating the formation of pozzolanic products (CSH) in the treated samples. We also note in the diffragtograms of the different treated samples, a reduction in the clay fraction intensity with the increase of hydraulic binder content. This reduction in the clay fraction is attributed to the formation of pozzolanic type reaction products (CSH) during curing time. These products result from the reaction between silicon released by clay minerals and hydraulic binders (lime, cement, and lime-cement mixture) [60, 61]. The formation of this cementitious compound (CSH) binds clay particles tightly, leading to improved mechanical properties and enhanced stability against swelling [62, 63].

Conversely, the other cementitious compounds (CAH) and (CASH) were not detected in the treated samples, this absence can be attributed to the fact that the progression of pozzolanic activity is strongly influenced by the mineralogy of the clays [64]. The lack of these compounds (CAH and CASH) may be linked to the mineralogical composition of the clay minerals, particularly the presence of smectite, which supplies silica for the formation of (CSH) compounds. Similar results were obtained by De Windt et al [65], who showed that the ongoing dissolution of smectite during pozzolanic reactions serves as a source of silica, facilitating the formation of (CSH) compounds. In Fig. 12 and for sample treated with a lime content of 5%, the presence of portlandite ($Ca(OH)_2$), resulting from the hydration of lime, is observed with a very low intensity. When lime (CaO) introduced into the soil, an exothermic reaction occurs within the first few hours, involving the hydration of lime to form calcium hydroxide ($Ca(OH)_2$).



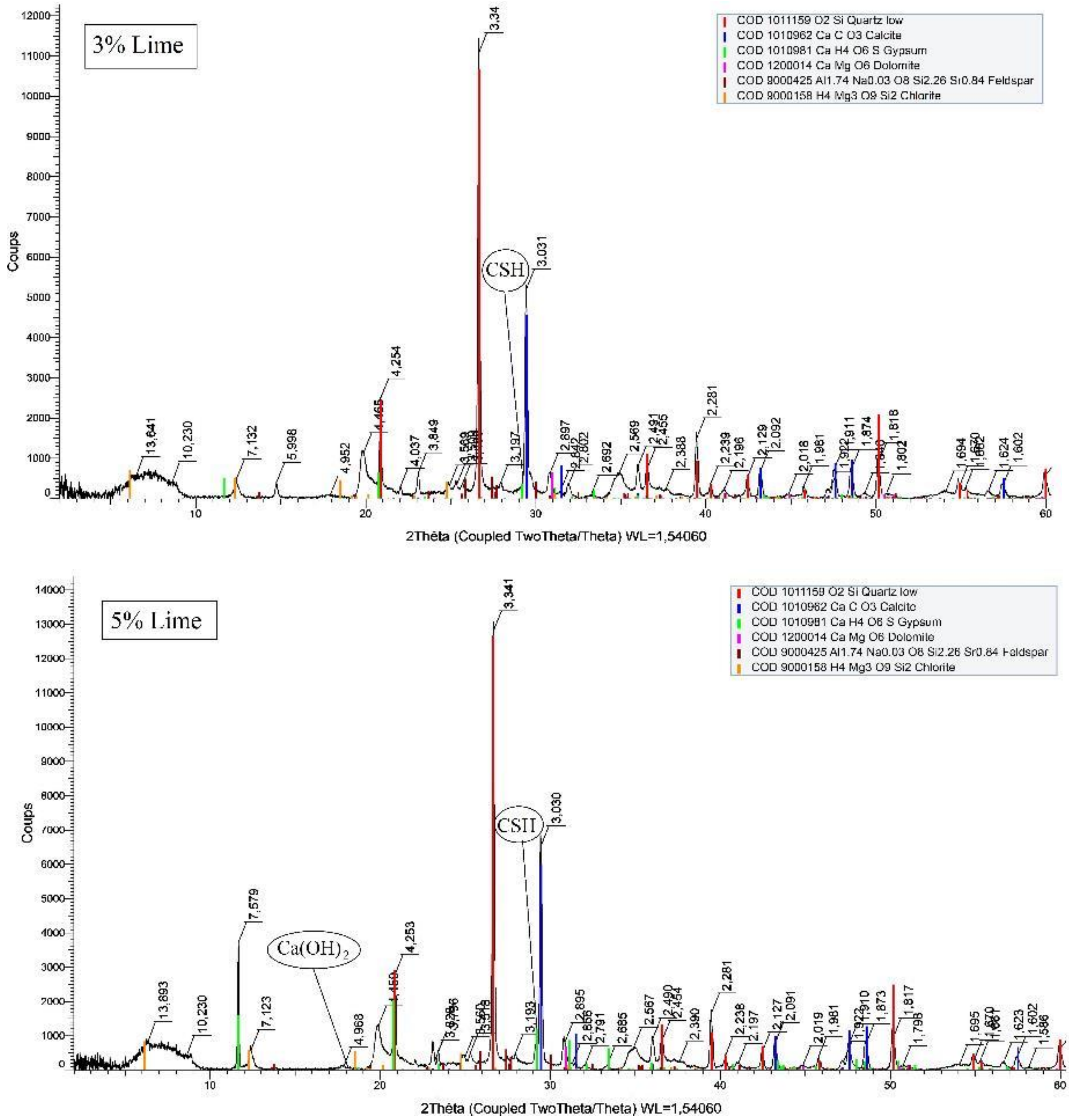


Fig. 12. X-ray diffractograms of total untreated and treated clay with lim

The very low intensity of portlandite is explained by the fact that, at higher lime doses, the amount of interstitial water is insufficient to fully hydrate all the added lime. For samples treated with a lime content of 3%, the absence of portlandite is noted, which is attributed to the complete consumption of the added lime through reactions after 28 days of hardening [66]. Regarding the intensity and relative abundance of other non-clay minerals (Quartz, Calcite and Gypsum), no reduction was observed during treatment with the various hydraulic binders. This indicates that these minerals remained unaffected by the binders used.

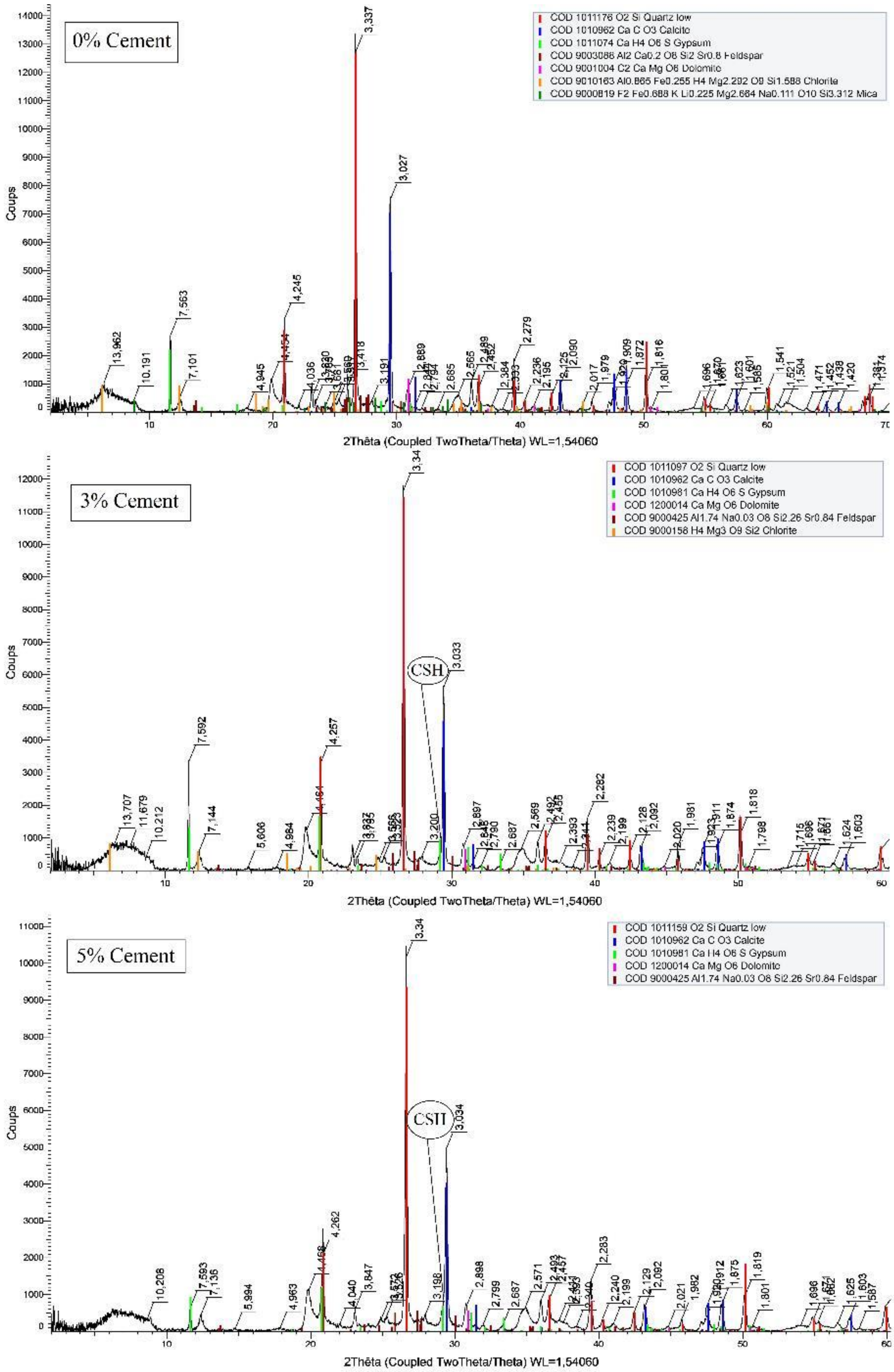


Fig. 13. X-ray diffractograms of total untreated and treated clay with cement

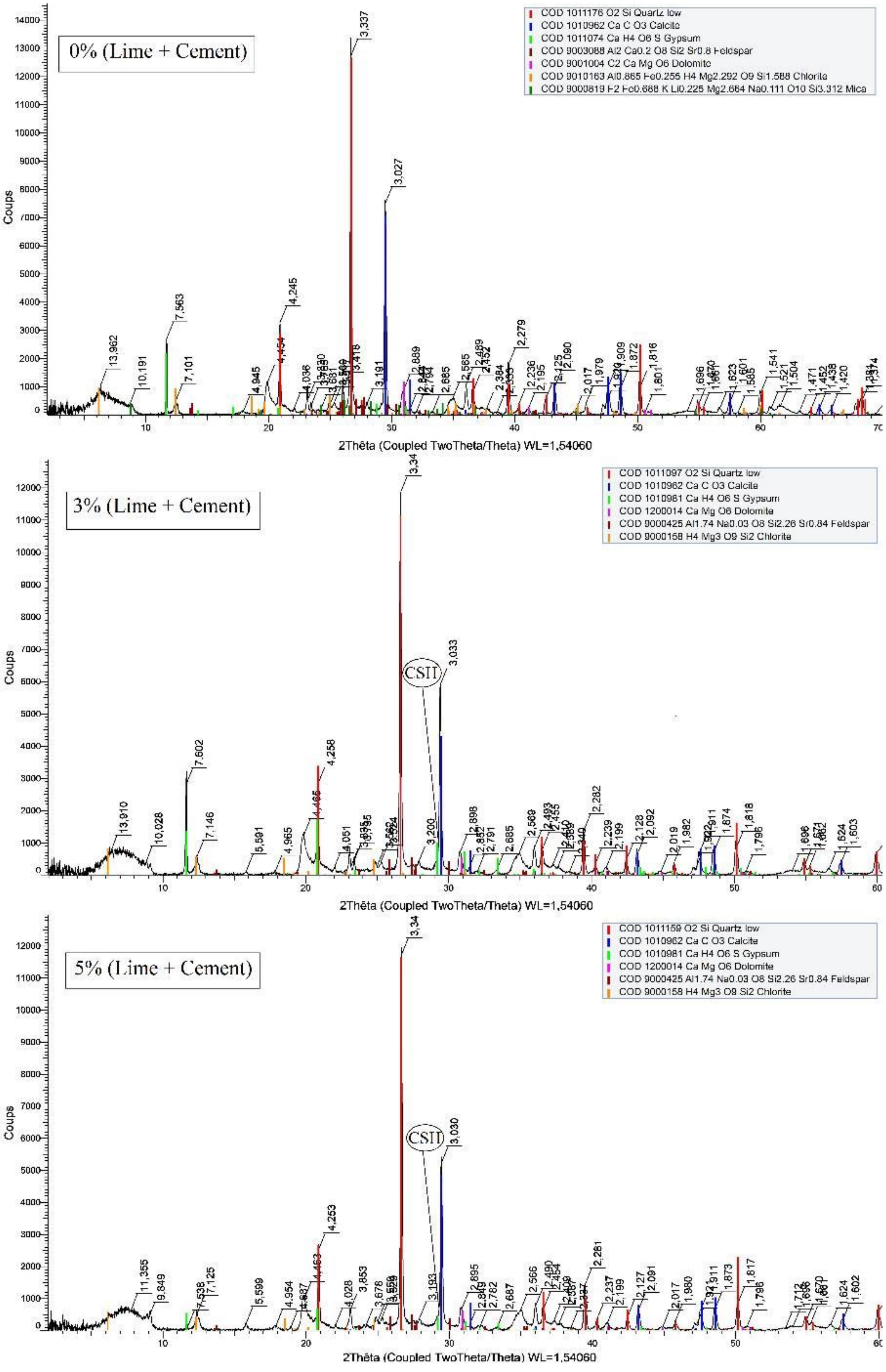
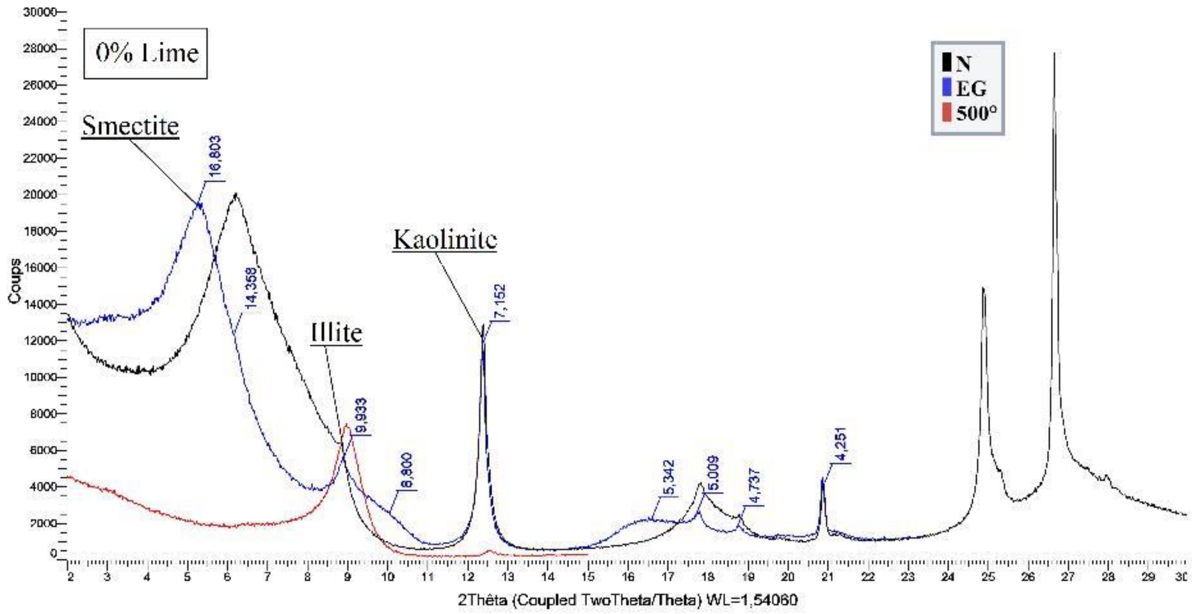


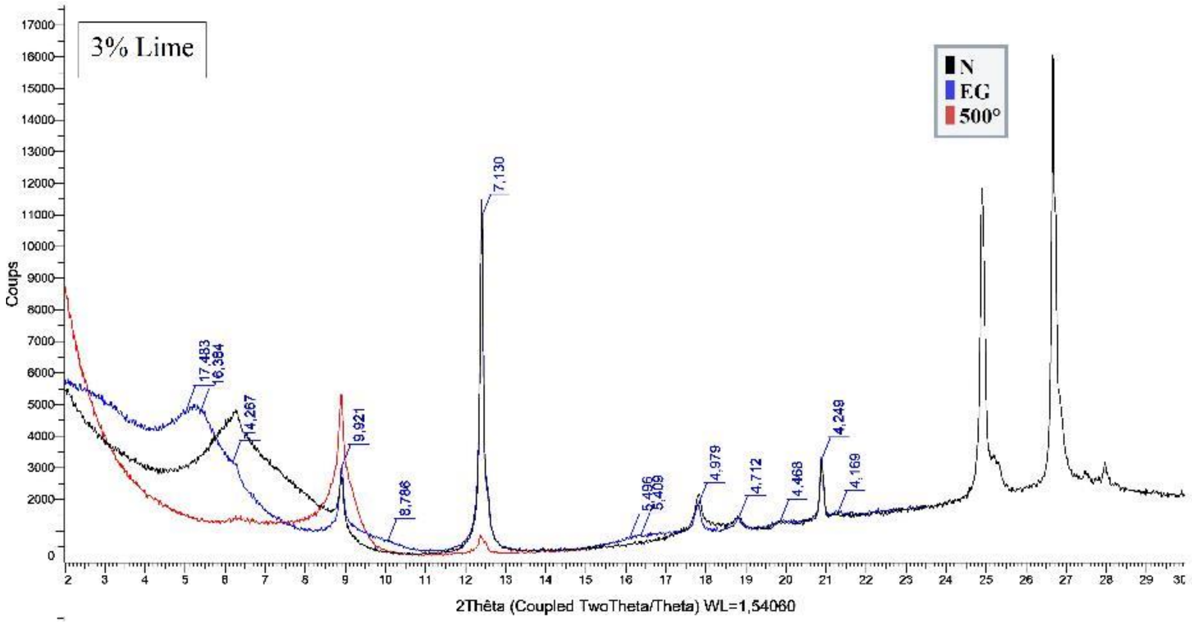
Fig. 14. X-ray diffractograms of total untreated and treated clay with lime-cement mixture

4.2.2 Treatment effect on the clay fraction

The changes in the intensity of clay minerals in the analyzed soil, depending on the content of the applied hydraulic binder, are illustrated in Figures 15, 16, and 17. The results reveal significant variations in the soil mineralogical composition, particularly regarding clay minerals. Initially, the soil exhibits a high clay content (63%), of which 43% consists of smectite, a highly swelling mineral.

The addition of lime results in a reduction in the proportion of smectite, decreasing from 43% to 13.3% with 3% lime, and then to 12.28% with 5% lime. Illite also shows a slight decrease of 4.5% at a lime content of 3%, and a more pronounced decrease to 2.85% at 5% lime. In contrast, kaolinite remains relatively stable, maintaining a constant proportion of 15% at a lime content of 3%, and a slight decrease of 13.53% at 5% of lime. Consequently, the total percentage of clay minerals decreases significantly, from 63% to approximately 29-33%, depending on the lime dosage (see Figure 15). Similarly, the addition of cement induces a gradual reduction in smectite (see Fig. 16), although less pronounced than that observed with lime: with 3% cement, the proportion of smectite decreases to 28.66%, and further to 16.38% with 5% cement.





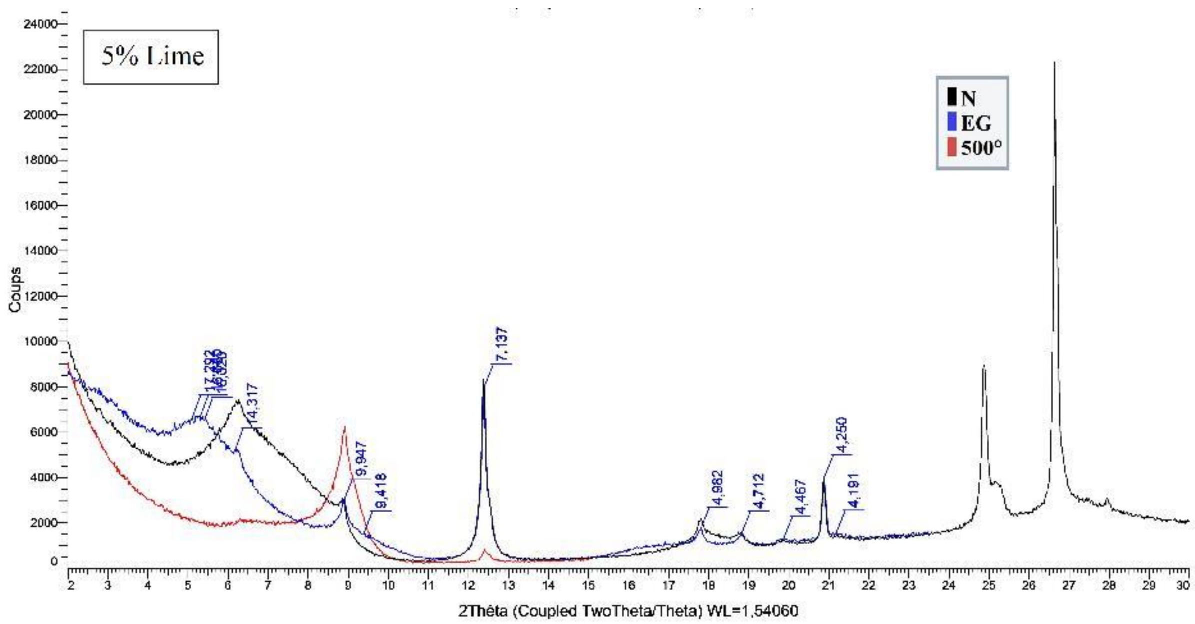


Fig. 15. X-ray diffractograms of clay fraction of untreated and treated studied soil with lime

This effect is primarily attributed to pozzolanic reactions between the cement and clay minerals, which transform the particle structure and stiffen the soil. With the addition of 3% cement, the proportion of illite slightly decreases to 4.16%, and further declines to 2.90% with 5% cement, while the kaolinite peak remains stable. However, the total percentage of clay minerals remains slightly higher than with lime alone, ranging around 34–48%.

The effect of the lime - cement mixture (Fig. 17) reveals a particularly interesting synergy. At 3%, the mixture does not bring any notable improvement: the 43% of smectite and 5% of illite remain high at 40.95% and 4.57%, respectively, while the kaolinite remains stable at 15% for the both mixture content (3% and 5%), suggesting this dosage is insufficient to trigger effective chemical reactions. However, at 5%, the mixture proves to be highly efficient, reducing the same fraction of smectite and illite to 14.20% and 3.33%, respectively, and consequently, a reduction of the clay fraction of about 33%.

The obtained results show that the used hydraulic binders (lime and/or cement) in this study, have a significant effect on the mineralogy of the studied soil. During the treatment, the significant reduction in the intensity of smectite and illite is due to the high reactivity of these two minerals with the used hydraulic binders (lime and/or cement). This high reactivity leads to the formation of pozzolanic reaction products (CSH) during the hardening process. These products are formed through the reaction between the hydraulic binders and the silica released from smectite and illite.

Concerning the intensity of kaolinite, which did not exhibit a clear reduction during the treatment, this indicates that the reactivity of this mineral with the hydraulic binders used is limited. Therefore, it can be concluded that kaolinite was not significantly affected by this type of hydraulic binder during the treatment.

In summary, lime is highly effective even at low dosages, especially on the most active clay minerals. Cement requires a higher dosage to achieve comparable effectiveness. The contents of 5% of lime-cement mixture or of lime offers the best solution, allowing for a significant reduction in clay mineral content. It should be noted that the 15% of kaolinite fraction remains constant in nearly all cases, suggesting that this category is less reactive to the applied treatments. Variations in the 5% fraction are moderate but still confirm the treatment's effectiveness, particularly with the high concentration of lime (5%), which represents the best performance observed.

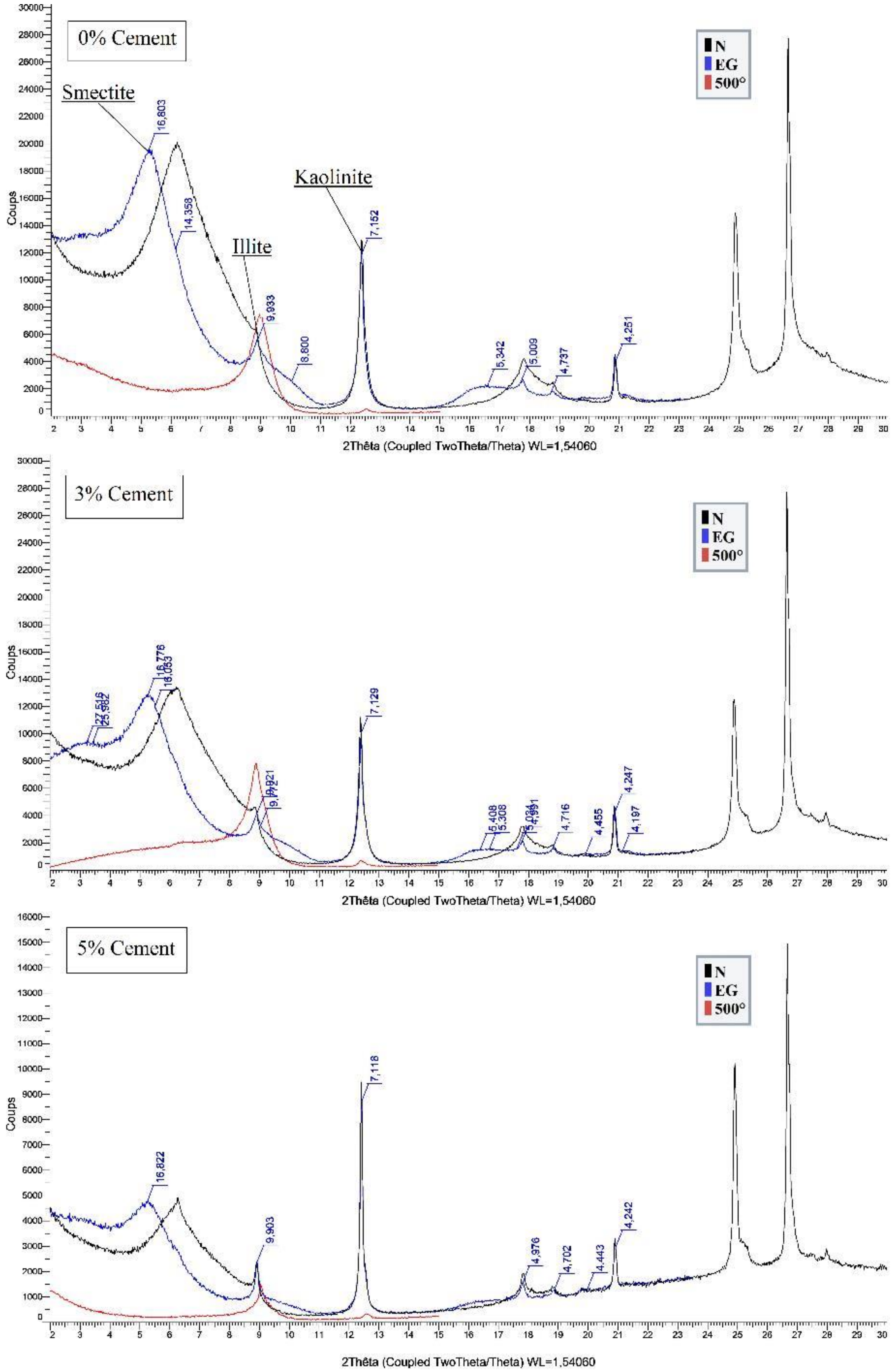


Fig. 16. X-ray diffractograms of clay fraction of untreated and treated studied soil with cement

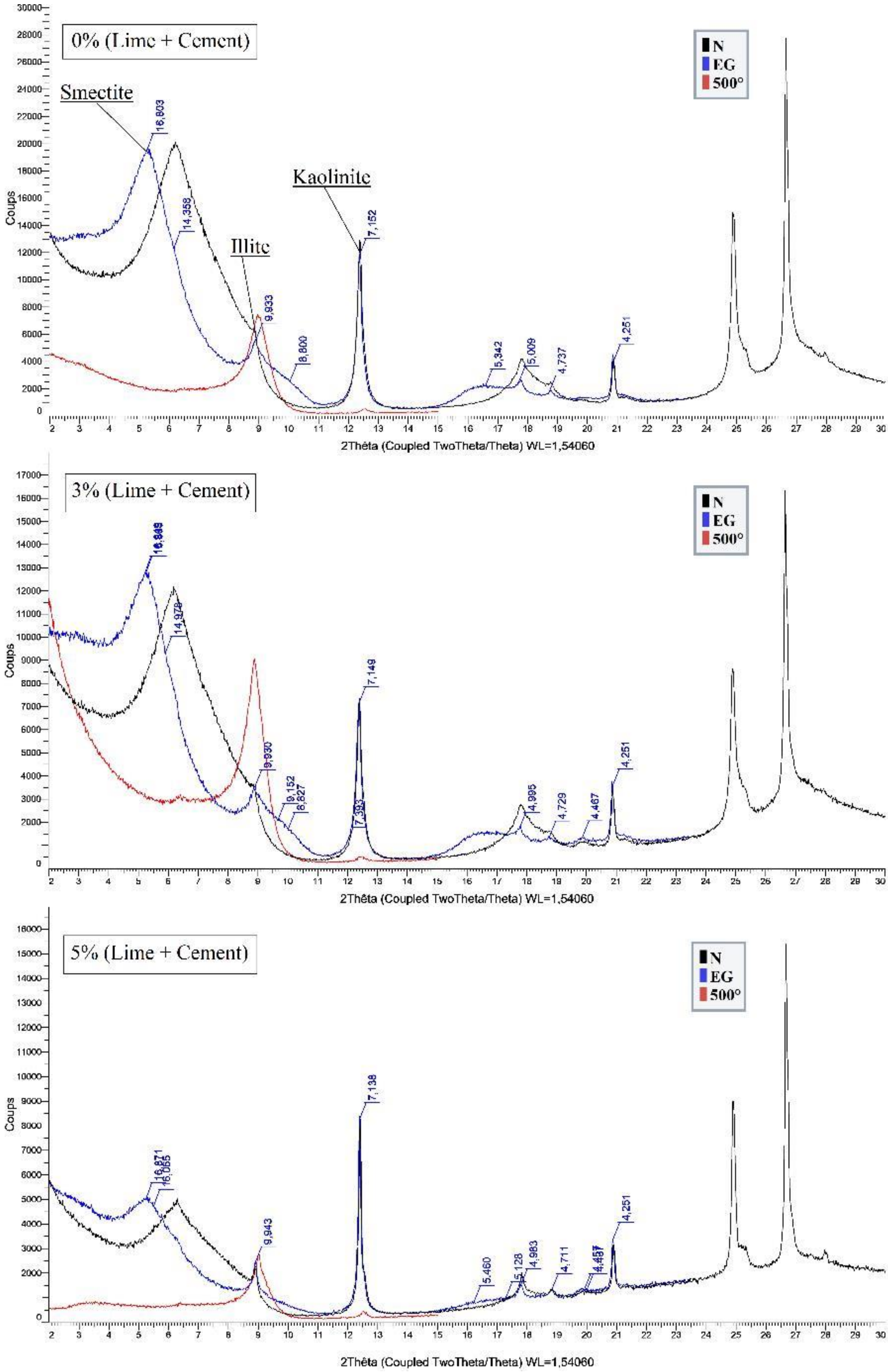


Fig. 17. X-ray diffractograms of clay fraction of untreated and treated studied soil with lime-cement mixture

5. Conclusions

The swelling behavior and mineralogical characteristics of clay soils were investigated during treatment with hydraulic binders, including lime, cement, and a lime-cement mixture. The study aimed to evaluate the impact of these additives on the soil sensitivity to water and its swelling potential. The results highlight how the addition of these binders influences the soil mineralogical composition and its interaction with water, ultimately affecting its swelling properties.

The soil in the study area of Boumagueur is predominantly clayey, exhibiting high plasticity and a significant potential for swelling. This sensitivity to swelling has resulted in numerous damages and deteriorations in various building elements such as foundations, structures, and masonry. The grain size distribution analysis of the soil reveals a substantial percentage of fines, approximately 60%, while oedometric tests confirm its high swelling potential. Additionally, the mineralogical composition of the soil, determined through X-ray diffraction, indicates a clay mineral content of 63%, with smectite constituting 43% of this composition.

The oedometric tests results of the treated soil illustrate the influence of different types and percentages of hydraulic binders on the swelling behavior of a clayey soil (swelling potential and swelling pressure). Without any binder hydraulic (0%), the soil exhibits a high swelling potential of 16.6% and a pressure of 190 kPa, indicating a swelling nature. The addition of lime, even at a low dosage (3%), significantly reduces the swelling: the potential drops to 4.5% and the pressure to 120 kPa. This improvement continues with increasing dosage, reaching a minimum swelling potential of 2.2% and a pressure of 54 kPa at 9%.

Cement, on the other hand, shows less efficiency compared to lime. At 3%, it reduces the swelling potential to 12.24% and the pressure to 125 kPa. At 9%, these values decrease to 7.15% for the potential and 80 kPa for the pressure. The lime-cement mixture yields approximately similar results to those of cement regarding the swelling pressure values. At 3%, the mixture reduces the swelling potential to 8.4% and the pressure to 127 kPa, at 9%, values reach 4.5% for swelling potential and 72 kPa for swelling pressure.

The X-ray diffraction analysis reveals a mineralogical transformation in the samples and the emergence of new minerals following treatment with hydraulic binders.

A comparison of the diffractograms between untreated and treated samples with various hydraulic binders (lime, cement, and lime-cement blend) reveals the emergence of new peaks, indicating the formation of pozzolanic products, such as calcium silicate hydrates (CSH), in the treated samples.

Furthermore, the diffractograms of the treated samples exhibit a decrease in the intensity of the clay fraction as the content of hydraulic binder increases. This reduction in the clay fraction stems from the formation of pozzolanic reaction products (CSH) during the hardening process. These products result from the reaction between hydraulic binders and silicon released by clay minerals.

For samples treated with a lime content of 5%, the presence of portlandite ($Ca(OH)_2$) is observed with very low intensity. This phenomenon can be attributed to the high lime dosage, where the quantity of pore water is insufficient to fully hydrate the added lime.

The addition of hydraulic binders to swelling soils serves to decrease their sensitivity to water and fosters the formation of strong bonds between particles, mitigating the swelling phenomenon. As a result, treatments involving hydraulic binders such as lime, cement, and lime-cement mixture prove to be effective in stabilizing of this type of clayey soils and improving their geotechnical properties.

In conclusion, the study clearly demonstrates the effectiveness of lime in altering the clay mineral composition of the soil. It offers the best performance in reducing active clay minerals, with smectite content decreasing sharply from 43% to 13.3% with 3% lime, and further to 12.28% at 5%. Overall, lime reduces the total clay fraction from 63% to as low as 29%. The persistence of kaolinite around 15% across all treatments confirms its limited reactivity.

Based on the results of this study, several practical recommendations can be proposed for the effective application of hydraulic binders in stabilizing clay soils, particularly in the Boumagueur region:

- The performance of lime, especially at moderate dosages (3–5%), suggests its preferential use in road subgrades, foundation platforms, and earthworks where control of swelling is essential. Its effectiveness in reducing active clay minerals like smectite and minimizing swelling potential makes it a reliable stabilizer with economic efficiency.
- Before large-scale application, it is essential to carry out tests to assess field performance; moisture sensitivity tests to simulate local hydrological conditions as well as shrinkage and cracking assessments, especially for surface layers.
- Lime stabilization, due to its cost-effectiveness and local availability, may offer a better return on investment for large-area applications.

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