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Effects of Sodium Nanoalginate and Lime on Swelling Properties of Expansive Soils

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Abstract: The findings revealed that the addition of nanoalginate and lime had distinct effects on various soil properties. Specifically, the liquid limit (LL) and plastic limit (PL) decreased when sodium nanoalginate and lime were added, while the plasticity index (PI) and shrinkage limit (SL) increased. Furthermore, the soil classification was altered when sodium alginate and lime were introduced to the control soil. Regarding the standard Proctor test, it was observed that adding sodium nanoalginate increased the maximum dry density and reduced the optimal moisture content, whereas lime had the opposite effect by decreasing the maximum dry density and increasing the optimal moisture content. The free swelling and swelling pressure tests indicated that the incorporation of sodium nanoalginate and lime reduced both free swelling and swelling pressure. The most significant reduction was observed in the sample containing 7% sodium nanoalginate and 5% lime. Additionally, the study highlighted the influence of processing time, showing that an increase in the curing time led to a decrease in free swelling and swelling pressure in samples mixed with 3% sodium nanoalginate and lime. The XRD test showed that adding sodium nanoalginate reduced primary minerals, forming SAH, while lime reduced quartz and calcite, creating CSH. Overall, the results suggest that sodium nanoalginate can be a more environmentally friendly alternative to lime for soil stabilization projects.

Keywords: free swelling; swelling pressure; XRD; soil classification

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1. Introduction

Since forest and rural roads are usually built on the earth's natural substrate, understanding the mechanical properties of the soil is necessary and can significantly reduce the costs of constructing and maintaining roads [1]. In the field of soil mechanics studies, the characteristics of the soil as a type of material are scrutinized. Then, based on the knowledge of the characteristics of the soil, proper instructions are provided to minimize additional costs as much as possible. In other words, designing and constructing a road without studying this aspect lacks technical and economic justification. Engineers inevitably encounter substrates of different soil types with varying resistance and characteristics in road construction projects. Different soils have different mechanical, swelling, and resistance properties. Some soils are classified as problematic, and fine-grained soils fall into this category. The volume of these types of soils increases due to water absorption and decreases due to loss of moisture; therefore, they are known as swelling soils, causing issues in road construction arising from unfavorable technical characteristics [2]. The damages caused by these types of soils are estimated to be billions of dollars annually [3]. Therefore, in cases where it is not possible to avoid the construction of superstructures on these types of soils by changing the route of the road, measures should be taken to reduce the swelling of the soil, and the construction of superstructures on these soils without stabilization should be avoided [4,5]. Usually, fine-grained soils bear a significant load when subjected to moisture less than the optimal level, but as the moisture level increases, their resistance

decreases, and more deformations occur in the soil. Ultimately, soil stability is lost [2]. Hence, free swelling and swelling pressure are other critical parameters in evaluating the quality and mechanical characteristics of materials, particularly for road construction.

The damage caused by swelling soils has become a significant challenge for engineers and researchers who are consistently seeking effective techniques to improve swelling characteristics. While many researchers have studied the impact of traditional materials, such as lime, to enhance the engineering properties of expansive soils, there are environmental concerns due to high energy consumption and the depletion of natural resources during the production of these materials [6–9]. Such substances release carbon into the atmosphere [10]. Therefore, it is imperative to develop the use of environmentally friendly materials. For this purpose, in recent years, various studies have investigated the use of eco-friendly additives to stabilize the soil, among which we can refer to nano-stabilizing materials [5,11,12] and low-carbon sodium silicate liquid additives [12], such as formaldehyde [13], polypropylene [14], polyacrylamide [15], tire-derived aggregate (TDA) products [16], polyvinyl acetate [17], lignosulfonate [18], and xanthan gum [19,20]. Research on these materials has indicated that polymers usually have a lower dielectric constant than water. They can reduce the thickness of the double layer of the soil, which reduces the swelling potential of the soil.

Fernandez et al. (2016) investigated the effect of three types of polymers, including calcium lignosulfonate, cationic polyacrylamide, and anionic polyacrylamide, on the swelling potential of the soil, and demonstrated that these materials could reduce the swelling potential of the soil [21]. Other researchers, such as Zumrawi and Mohammed (2019), have also scrutinized the effect of polyvinyl and acetate [22]. In a study conducted by Mousavi et al. (2021) [4], the influence of CBR Plus and RPP on the mechanical properties of swelling soil was explored. The findings indicated that these materials could decrease the plasticity index and swelling potential of swelling soils [4]. In general, considering the relatively low energy requirements for producing these materials, substituting a part of traditional stabilizers with environmentally friendly materials can be even more economical. One such recently introduced and cost-effective additive, with biodegradable properties and environmental approval, is sodium nanoalginate [8]. Sodium nanoalginate is a cheaply available biopolymer and a low-carbon cementing material. It has gained attention for engineering applications due to its characteristics, such as biodegradability, hydrophilic properties, sensitivity to pH, and natural origin. Sodium nanoalginate is a polysaccharide extracted from algae and bacteria [23–25]. In recent years, the use of this material for applications, such as biotechnology, medicine, pharmaceutical, and especially food industries, is increasing [26]. In light of the absence of previous research examining sodium nanoalginate's impact on the behavior of forest soils, this research aims to contrast the impact of a traditional stabilizer, lime, with that of a non-conventional alternative, namely, sodium nanoalginate. The current investigation focuses on analyzing the influence of sodium nanoalginate on the swelling characteristics of clay soil prone to swelling. Afterward, the results were compared with lime, which is one of the essential conventional stabilizers. Moreover, X-ray diffraction (XRD) was employed to scrutinize the microscopic structure of the untreated soil and the soil treated with various concentrations of sodium nanoalginate and lime.

2. Materials and Methods

2.1. Soil Properties

The soil used for this study was a sample from a forest road located in the Educational and Experimental Forest (Khayroud Forest) of the University of Tehran, Iran. The Khayroud Forest, located at coordinates 36°27′ to 36°40′ north latitude and 51°32′ to 51°43′ east longitude, is situated approximately seven kilometers east of Noshahr in the Mazandaran province of Iran. Notably, the presence of fine-grained soils with a high clay content, displaying high plasticity and swelling potential, poses a significant challenge in road construction within the studied area. Therefore, due to the widespread occurrence of clay soils in the Hyrcanian Forest in Iran and their significant potential for expansion, a soil

sample from this region was chosen for research purposes, whose physical and chemical properties were determined according to the standard and are represented in Table 1.

Table 1. Physical and chemical properties of the soil sample.

Properties	Amount	Properties	Amount	Properties	Amount
Gs (gr/cm^3)	2.85	Na^+ (meq/L)	0.39	LL (%)	64.3
$SO_4{}^{2-}$	1.9	Ca^{2+} (meq/L)	1.7	PL (%)	30.8
$CaCO_3$ (%)	0.74	Mg^{2+} (meq/L)	2.8	SL (%)	21.4
CEC (cmol/kg)	39.09	CL^- (meq/L)	0.8	PI (%)	33.73
EC (ds/m)	121.2	CO_3^{2-} (meq/L)	0	Maximum dry density (kN/m^3)	13.5
OC (%)	1.68	$HCO_3{}^{2-}$	1.88	Optimum water content (%)	24
pH	4.8	K^+ (meq/L)	0.9	Clay (%)	87

Additionally, Table 2 shows the studied soil sample's X-ray fluorescence (XRF) results. Further, the samples were subjected to air drying in the laboratory for subsequent analysis. Following this, they underwent sieving through a two-millimeter sieve (No.10) and were then stored in designated containers for testing purposes. The soil's pH was assessed using a pH meter with a 1:1 ratio, as outlined in [27]. Soil electrical conductivity (EC) was gauged using a conductivity meter, following the methodology in [28]. The soil organic carbon (OC) content in the samples was quantified employing the Walkley and Black method [29], while lime content was determined through calorimetry as per the approach detailed in [28]. The soil's cation exchange capacity (CEC) was ascertained using the Bower method [30]. Besides, the granulation particle size test was performed according to the ASTM D422 standard, which showed that the soil used is fine-grained [31].

Table 2. XRF results of the soil sample.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	Na_2O (%)	MgO (%)	K_2O (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)
52.502	17.734	10.965	0.398	0.295	1.587	2.291	1.185	0.061	0.049
LOI (%)	Cl (ppm)	S (ppm)	As (ppm)	Ba (ppm)	Ce (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Nb (ppm)
2	N	30	644	51	25	178	N	10	2
Pb (ppm)	Rb (ppm)	Sr (ppm)	V (ppm)	Y (ppm)	Zr (ppm)	Zn (ppm)	Mo (ppm)	Ni (ppm)	Pb (ppm)
36	139	84	145	47	203	167	31	36	139

2.2. Sodium Nanoalginate

The commercially available sodium nanoalginate is typically supplied in solid form and is prepared by mixing with water, following the manufacturer's guidelines. Sodium alginate is a natural polysaccharide composed of two interconnected β-D-mannuronic acid (M) and α-L-guluronic acid (G) residues, commonly found in diverse sources, such as seaweeds and bacteria [8]. Its structure often comprises homopolymeric sections of G-residues (G-blocks) and M-residues (M-blocks), interspersed with sections of mixed monomers or MG-blocks [32]. Table 3 outlines the properties of this agent.

Table 3. The physiochemical properties of sodium nanoalginate [31].

Property	Value
Chemical formula	$(C_6H_7O_6Na)_n$
pH	5.5–7.5 for a 1% aqueous solution (at 25 °C)
Matter insoluble in water	1%
Arsenic (As)	<3 ppm
Lead (Pb)	<10 ppm
Sulphated ash	22.6
Sulphur (S)	<0.02%
Phosphor (P)	<0.02%
Molecular weight	216 g/mol
Dynamic viscosity	12 CPS
Appearance	Cream to pale yellowish brown powder

Source: Data from Oxford Laboratory (2011).

2.3. Lime

The lime used in this investigation was calcium oxide (CaO). This material displays significant chemical reactivity and is visually identified as a white powder. CaO possesses a crystalline structure and exhibits alkaline characteristics. Table 4 provides an overview of the characteristics of the lime used in this study.

Table 4. Properties of lime according to the manufacturer [31].

Property	Value
Chemical formula	CaO
pH	12.8
Matter insoluble in water	Chemical reaction, converts to calcium hydroxide
Gs	3.34 g/cm^3
Melting point	2613 °C
Appearance	White powder

2.4. Experimental Methodology

The Atterberg limit assessments, which encompass evaluations for the liquid limit (LL), plastic limit (PL), and plasticity index (PI), were executed in adherence to ASTM D-4319 protocols. Moreover, the shrinkage limit (SL) was determined using the Casagrande method [33]. The soil specimen used in the current investigation was categorized as CH soil type (clay with high plasticity) under the Unified Soil Classification System (USCS, ASTM D2484), as determined by the LL and PI. The soil sample was also identified as comprising high to very high swelling potential clays [34–36]. It was required to determine the maximum dry density and the optimum moisture content (OMC) of the samples. Therefore, standard Proctor compaction tests were performed on both the untreated and treated soil specimens, incorporating varying proportions of sodium nanoalginate (3, 5, and 7%) and lime (3, 5, and 7%), in line with the ASTM D698 standard [31].

The control and treated soil samples, infused with varying proportions of sodium nanoalginate and lime, were contained within plastic sheets and stored at a constant temperature of 25 °C for 24 hours in a controlled humidity environment. This was carried out to ensure the uniform moisture absorption of clay particles before subjecting them to the standard Proctor compaction. Notably, the results from the moisture content tests were used in the preparation of swelling and pressure swelling tests.

Following this, free swelling and pressure swelling tests were performed according to ASTM D4546 [33] on the control and treated soil samples, incorporating different percentages of sodium nanoalginate and lime agents. These samples were prepared through static compaction based on the optimum moisture content acquired from the compaction curves.

Using a static compaction method, the control sample and those treated with sodium nanoalginate and lime agents were compacted within consolidation rings measuring 75 mm

in diameter and 20 mm in height. After compaction, filter papers and porous stones were placed within the consolidometer cell and soaked with water. Maintaining static pressure on the samples for 30 min was crucial to prevent rapid swelling of the samples. Subsequently, the specimen and consolidation ring were removed from the compression mold, and the surrounding soil was meticulously cleared. The specimen and ring were then enclosed in plastic sheets to prevent moisture loss until the free swelling tests commenced. These tests continued until the swelling deformation reached a consistent value. The swell potential (S) was defined as $(\Delta h/hi) \times 100$, where hi represents the initial thickness of the sample and Δh is the increase in thickness at a specific time. Swell pressure was determined as the total vertical pressure necessary to achieve zero axial strain, per the swell under load method [4].

X-ray diffraction (XRD) tests [12,37,38] were conducted to evaluate the microstructural and mineralogical properties of the soil samples treated with 3% sodium nanoalginate and lime. These samples were stored in plastic bags for 7, 14, and 28 days. Subsequently, swelling and pressure swelling tests were carried out to ascertain the impact of the curing time on the samples.

3. Results and Discussion

3.1. Atterberg Limit Test

Figure 1 illustrates the outcomes of the Atterberg limit tests for both the control soil and the soil blended with varying proportions of sodium nanoalginate and lime. In the case of the control soil, the liquid limit (LL), plastic limit (PL), shrinkage limit (SL), and plasticity index (PI) values were 64.3, 30.8, 21.40, and 33.73%, respectively. With the addition of sodium nanoalginate and lime, there was a decrease in the LL and PI, while the PL and SL values experienced an increase. By adding 7% of sodium nanoalginate, the LL, PL, SL, and PI were 45.34, 3.66, 32.37, and 9.68%, respectively, and by adding 7% of lime, the LL PL, SL, and PI were 49.15, 33.31, 25.55, and 15.84%, respectively. Additionally, the results of the classification of soil samples mixed with different percentages of sodium nanoalginate and lime showed that the soil class changed upon adding these materials to the control soil (Figure 2). According to the obtained results, it was observed that by mixing sodium nanoalginate and lime into the soil, the ratio of the LL to SL decreased. Figure 3 illustrates that this ratio was lower in samples mixed with sodium nanoalginate compared to those mixed with lime. This is indicative of the fact that sodium nanoalginate is more effective in reducing swelling, compared to lime. Generally speaking, the larger this ratio is, the greater the swelling range of the soil.

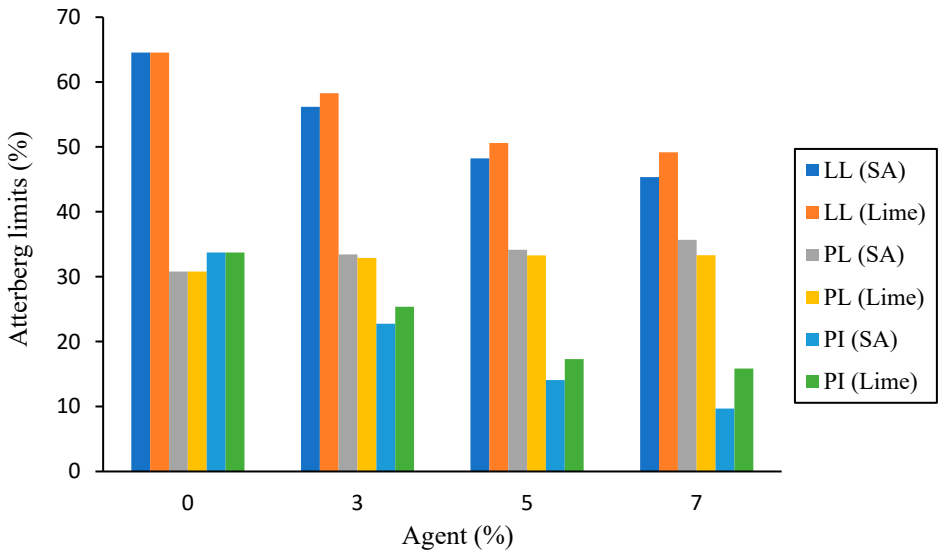


Figure 1. Atterberg limits' outcomes for untreated soil and soil treated with varying proportions of sodium nanoalginate and lime.

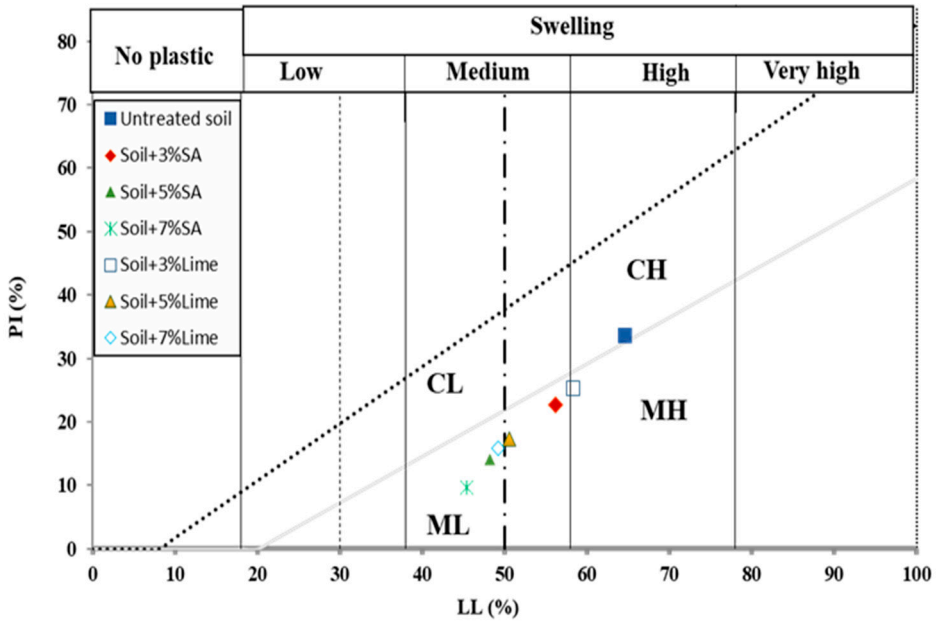


Figure 2. Classification of control soil sample and soil samples mixed with different percentages of sodium nanoalginate and lime, based on USCS: CL (clay with low plasticity), CH (clay with high plasticity), ML (silt with low plasticity), MH (silt with high plasticity).

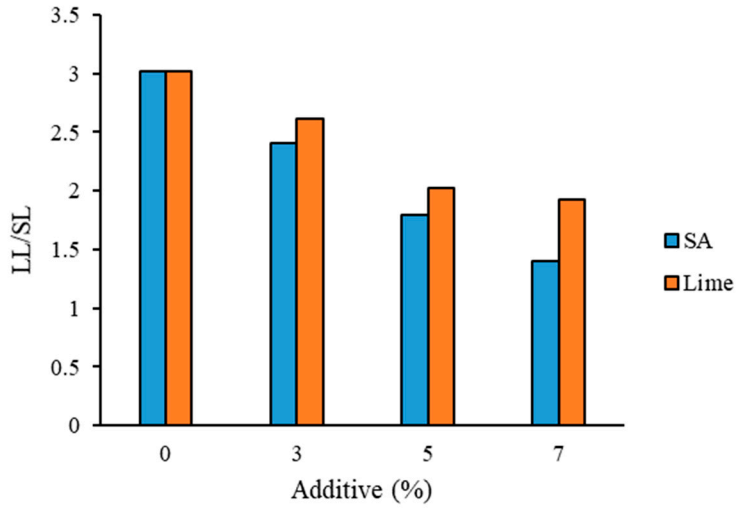


Figure 3. Comparison of changes in the LL/SL ratio for two materials: nanoalginate sodium and lime.

To put it another way, a larger LL/SL ratio may indicate that the soil in a particular location is susceptible to undesirable volume changes due to variations in humidity, and some cracks will likely be seen in the foundations that are newly built on these soils due to contraction or expansion caused by seasonal humidity changes [39]. Since sodium nanoalginate has a high specific surface area [8], this characteristic leads to the creation of ionic bonds with soil clay particles and reduces PL. Generally, electrostatic interaction is one of the main mechanisms of soil stabilization, particularly between cationic polymers (polycations) and clays, because the surfaces of clay minerals have negative loads. Polycations are readily adsorbed on the surfaces and edges of clay minerals, altering the water absorption near the clay surface, and forming large and stable flocculant particles. Studies have indicated that small-sized polymers are uniformly distributed in the soil microparticles due to their remarkable ability to penetrate fine pores [40,41]. Moreover, substances with an elevated molecular weight, such as sodium nanoalginate, have the potential to improve interactions with the soil. Nevertheless, the efficacy may be affected

by the constrained penetration of the polymer into the soil surface and the challenge of achieving consistent cumulative absorption.

Conversely, studies have indicated that biopolymer materials with smaller sizes can establish uniform soil-stabilizing polymer networks [40,41]. The reduction in the LL and PI, coupled with the rise in the PL and SL observed in the lime-stabilized samples, can be attributed to the ion exchange reaction occurring due to the combination of soil and lime. This reaction diminishes the plastic characteristics of the soil, thereby improving the overall soil efficiency [42].

3.2. Free Swelling Test

The results of the soil swelling test for the control soil and the samples mixed with different percentages of sodium nanoalginate and lime (i.e., 3, 5, and 7%) are depicted in Figure 4. The findings revealed that sodium nanoalginate can reduce free swelling across all concentrations. The percentage of free swelling decreased from 16.9% to 10.9% in samples treated with 3%, 5%, and 7% sodium nanoalginate. Moreover, as the percentage of sodium nanoalginate in the soil increased, the swelling rate decreased. The decrease in soil swelling, compared to the control soil, after adding sodium nanoalginate may be attributed to the prevention of water absorption in the soil structure. Since sodium nanoalginate has numerous COO- groups, when dissolving in water, it quickly combines with water and forms a hydrogel, which causes adhesion [43]. Consequently, after adding sodium nanoalginate to the soil, polymer cementitious materials were created in the soil's pores, which reduced the dielectric constant and the double layer of water around the clay particles. On the other hand, the lower the water absorption, the more robust bonds were created between the clay particles and the polar end groups of sodium nanoalginate, which reduced the swelling potential of the soil owing to the formation of the matrices of granular clay particles by sodium nanoalginate.

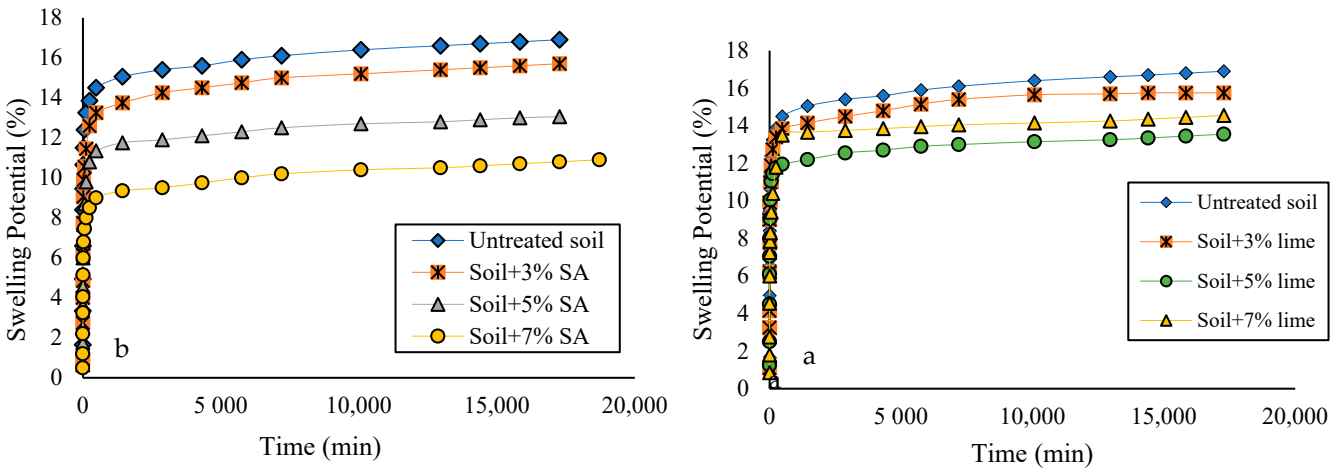


Figure 4. The effect of sodium nanoalginate (**a**) and lime (**b**) with different percentages on soil swelling.

Similarly, the reduction rates of free swelling in the soil mixed with 3, 5, and 7% lime were 7.30, 24.72, and 16.15%, respectively, compared to the control soil. After adding lime to the soil, excess water was removed from around the clay–lime structure by rapidly hydrating CaO to $Ca(OH)_2$, generating significant heat. Then, a rapid cation exchange occurred on the clay particles' surface. At this stage, the double layer of water around the clay particles between divalent cations and monovalent cations was eliminated, and the electrostatic charges around the clay particles were balanced. Simultaneously, at this stage, the mineral effective surface of the clay decreased, and initial pozzolanic reactions occurred, which limited the aggregates' subsequent dispersion. At the end of this stage, the first pozzolanic reaction products were placed at the contact points between the clay particles.

The produced compounds filled the soil holes and reduced the porosity and permeability. Owing to the creation of a complex structure and the solidification of particles produced by adding lime to the soil, the effective surface of clay minerals decreased, reducing the soil's swelling [44]. Additionally, the results demonstrated that the optimal percentage of lime to reduce soil swelling was 5%, and with the increasing percentage of lime, the swelling rate increased. Moreover, sodium nanoalginate outperformed lime in reducing soil swelling.

3.3. Swelling Pressure

The results of the soil swelling pressure test for the control soil sample and the samples mixed with different percentages of sodium nanoalginate and lime (i.e., 3, 5, and 7%) are represented in Figure 5. In this figure, the X-axis represents the change in sample height (ΔH, assuming zero lateral deformation) on the initial height of the sample (H), and the Y-axis indicates the swelling pressure (P). Figure 5a shows that the swelling pressure of the sample treated with 3, 5, and 7% sodium nanoalginate decreased from 1020 to 100 kPa. The reduction of the swelling pressure of soil mixed with 3, 5, and 7% of lime was from 1020 to 520 kPa. These results are in line with the free swelling results. Additionally, the swelling pressure more intensively decreased with the addition of sodium nanoalginate compared to lime; therefore, sodium nanoalginate performed better.

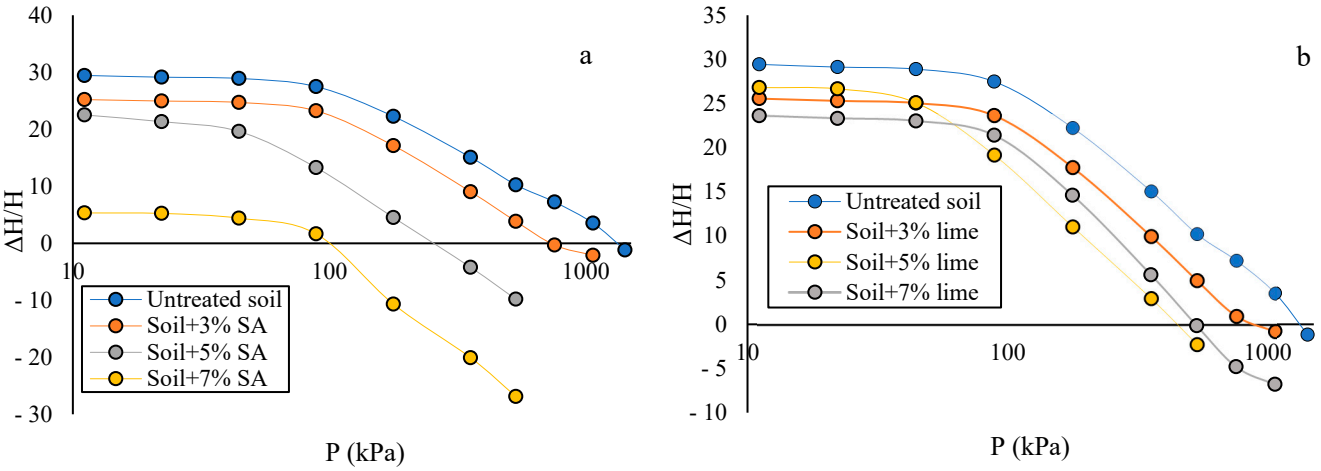


Figure 5. The effect of sodium nanoalginate (**a**) and lime (**b**) with different percentages on soil swelling pressure.

3.4. The Effect of Curing Time on Swelling

Figure 6a represents the effect of the curing time on the free swelling of soil treated with 3% sodium nanoalginate at different curing times. The results indicated that with the increasing curing time, the percentage of free swelling decreased by 14.2, 16.17, and 30.29 percent at the curing times of 7, 14, and 28 days, respectively. Additionally, Figure 6b shows that the effect of the curing time on the free swelling of soil treated with 3% lime decreased by 7.14, 14.54, and 19.31 percent at the curing times of 7, 14, and 28 days, respectively.

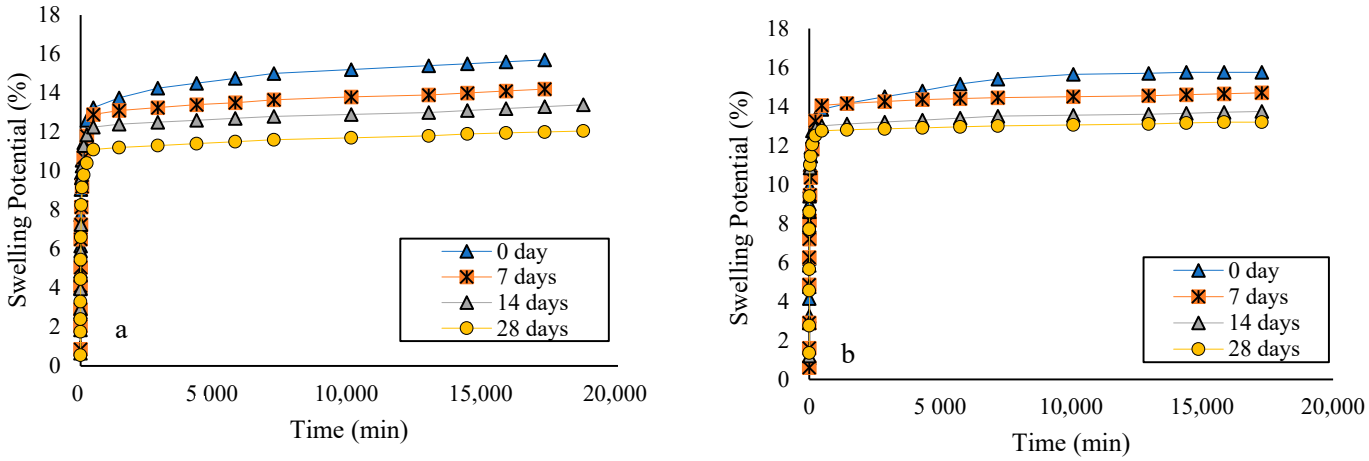


Figure 6. The effect of the curing time on free swelling of soil samples mixed with sodium nanoalginate (**a**) and lime (**b**).

Figure 7 represents the curing time's effect on the soil's swelling pressure when treated with 3% sodium nanoalginate and 3% lime. In this figure, the X-axis represents the change in sample height (ΔH, assuming zero lateral deformation) on the initial height of the sample (H), and the Y-axis indicates the swelling pressure (P). Figure 7a shows that the swelling pressure of the soil treated with sodium nanoalginate was reduced from 14.2 to 12.05% at the curing times of 7, 14, and 28 days, respectively. These values were from 14.7 to 13.2% for the soil treated with lime at the curing times of 7, 14, and 28 days, respectively. Hence, it can be said that the curing time reduced the free swelling and swelling pressure of the soil treated with sodium nanoalginate and lime. Previous studies indicated that after adding sodium nanoalginate to the soil, first, the pores between the soil particles were filled with the colloids formed by this substance, which reduced the soil porosity to a great extent [8]. At this stage, the contact between the particles had changed from point contact to surface contact, and the contact surface significantly increased. In the next step, a coating effect was created on the clay particles and, in fact, most of the clay particles were surrounded by a film-like gel substance, which increased the size of the particles. Hence, larger particles can easily stand next to each other. In addition, due to coagulation, the clay particles remained aggregated in the soil and, by sticking together, created larger particles and agglomerates [45]. The created agglomerates increased the average size of the soil particles. This changed the size distribution of the soil particles and, finally, the soil's free swelling and swelling pressure decreased. Therefore, it can be concluded that after adding biopolymer materials to the soil, molecular changes physically occurred. The position of chemical compounds in the soil structure was altered, and it became more significant with curing. The results showed that by adding lime to the soil, pozzolanic reactions started quickly, and these reactions increased with time. By changing the crystalline structure of the soil, pozzolanic reactions reduced the swelling and swelling pressure of swollen soils, which reduced the swelling potential of the soil over time [46,47].

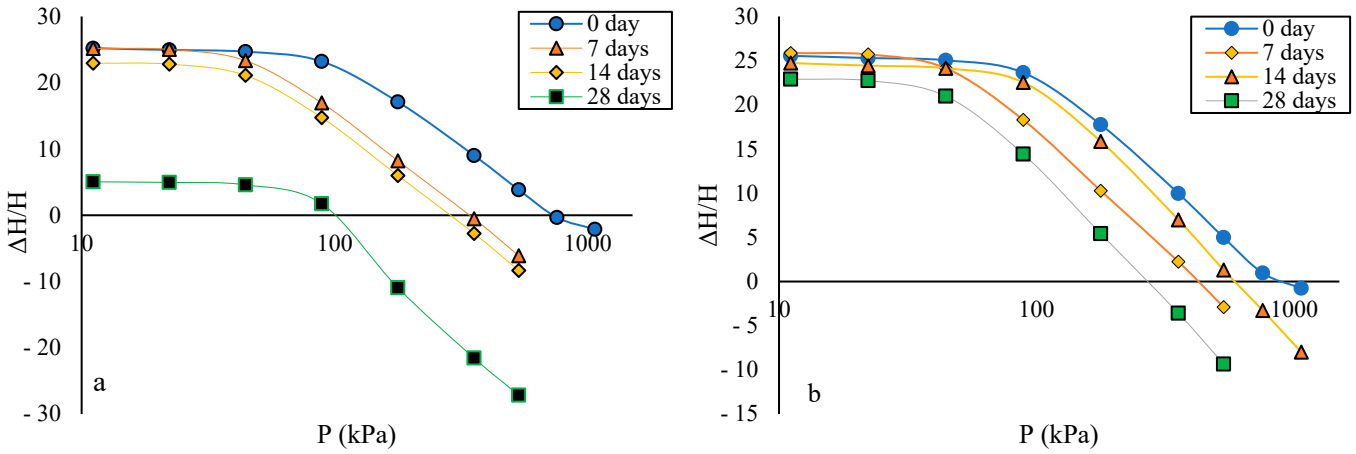


Figure 7. The effect of the curing time on the swelling pressure of soil treated with sodium nanoalginate (**a**) and lime (**b**).

3.5. Microscopic Observations

Figure 8 illustrates the results of the XRD test for the control soil and soil mixed with different percentages of sodium nanoalginate. Based on XRD analysis, the control soil sample was found to contain high amounts of silicon (Si) elements in different crystalline phases. Important minerals, including calcite (calcium carbonate ($CaCO_3$), 2θ = 19.5°, 24.5°, and 40°), zeolite (2θ = 7.5°), and quartz (silicon dioxide (SiO_2), 2θ = 21°, 28.5°, 50°, and 68.5°), were identified in the control soil sample. According to the results, after adding sodium nanoalginate, the main minerals, including quartz, calcite, and zeolite, decreased, which may be due to the consumption of clay minerals in the pozzolanic reaction. Besides, the results demonstrated that after adding sodium nanoalginate, a new product that was not present in the untreated soil was produced at a 2θ = 25°, 36.5° angle. Furthermore, it was observed that as the percentage of sodium nanoalginate increased, the quantities of quartz, calcite, and zeolite decreased, while the amount of the new product (SAH) increased.

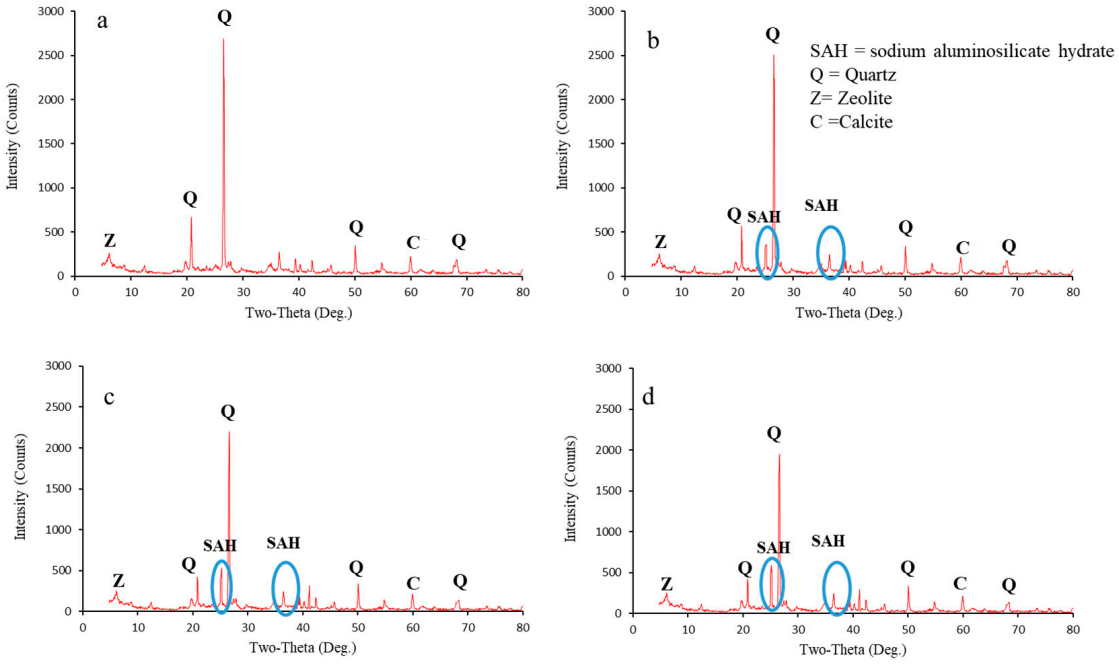


Figure 8. XRD patterns of (**a**) untreated soil, (**b**) soil treated with 3% sodium nanoalginate, (**c**) soil treated with 5% sodium nanoalginate, and (**d**) soil treated with 7% sodium nanoalginate.

Figure 9 displays the XRD test results for the control soil and soil treated with different percentages of lime (i.e., 3, 5, and 7%). The primary constituents of the minerals of the control soil sample were quartz (SiO_2), calcite ($CaCO_3$), and zeolite. A reduction in the peak of quartz and calcite was evident upon adding lime to the soil. In the XRD interpretation of the sample stabilized with lime it can be noted that the addition of lime to the soil increased the pH of the soil environment. With an elevated pH, a portion of the clay minerals in the soil was dissolved, after which the intensity of the X-ray diffraction peaks of the clay minerals dissolved. This dissolution provides the basis for the formation of pozzolanic reactions. Cation exchange caused by the substitution of calcium ions for sodium and potassium ions, on the one hand, and the formation of gels by pozzolanic reactions, on the other hand, provide the necessary conditions for the compression and continuity of the double layer of clay. During this mechanism, pre-consolidation stress increased, and the compression coefficient decreased. Adding lime produced new compounds, which can be attributed to the formation of compounds, including calcite, nicolite, calcium silicate hydrate in the form of CSH, and calcium aluminate hydrate in the form of CAH. These materials filled most of the soil holes or covered the surface of the clay flakes.

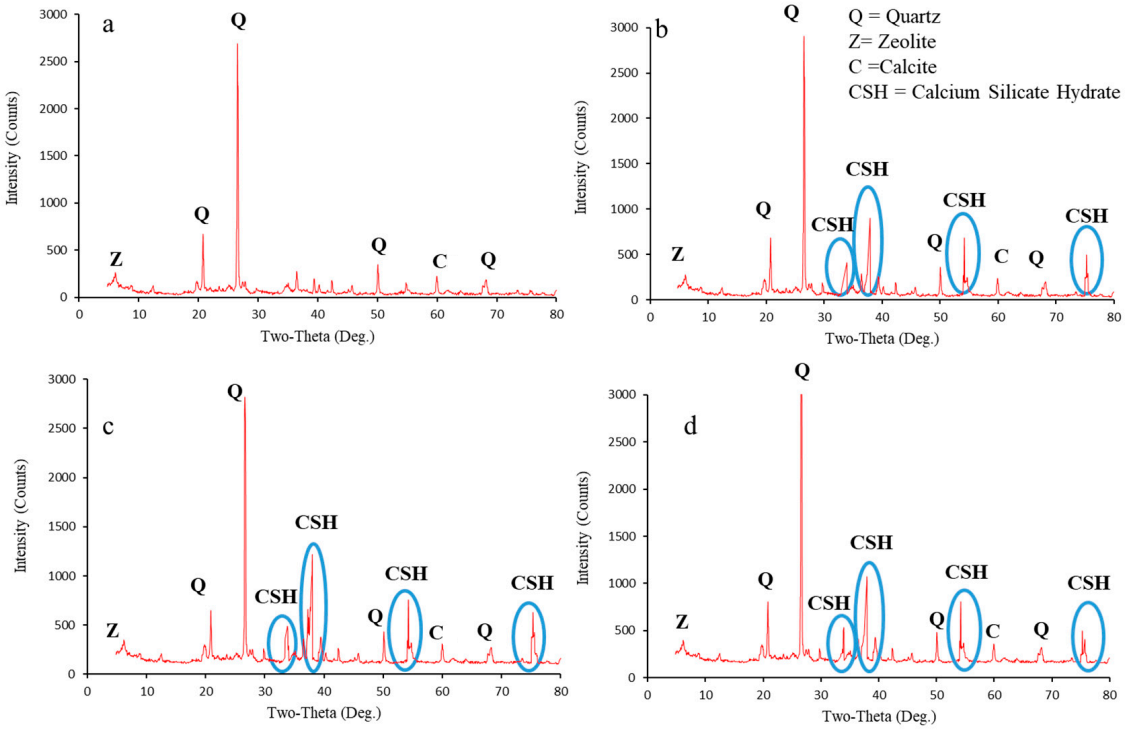


Figure 9. XRD patterns of (**a**) untreated soil, (**b**) soil treated with 3% lime, (**c**) soil treated with 5% lime, and (**d**) soil treated with 7% lime.

As a result, the void ratio and permeability change decreased with an increase in the amount of lime. The reason for reducing clay mineral peaks in the presence of lime can be attributed to a combination of short-term and long-term reactions. The formation of complex structures of soil particles (cation exchange) and the consumption of clay particles in pozzolanic reactions, facilitated by the solubility of silica and alumina in an environment with a high pH, and their covering by CSH cement materials reduced the amount of X-ray reflection, which finally decreased the intensity of the clay mineral peak.

The XRD test results are indicated in Table 5. According to the results, it should be noted that SAH, produced by sodium nanoalginate, enhanced properties such as viscosity, stability, emulsion, and mechanical characteristics. On the other hand, CSH and CAH, produced by lime, are primary components of the hydrated mixture, contributing to its strengthening and enhancement of mechanical properties. According to the results, the

SAH produced due to the addition of sodium nanoalginate to the soil was more effective in reducing soil swelling.

Table 5. The XRD test results.

Soil Sample	Important Minerals	2θ (angle)
Control soil	Calcium carbonate ($CaCO_3$)	19.5°, 24.5°, 40°
	Zeolite	7.5°
	Quartz (silicon dioxide (SiO_2))	21°, 28.5°, 50°, 68.5°
Soil sample mixed with sodium nanoalginate	SAH	25°, 36.5°
Soil sample mixed with lime	CSH, CAH	33°, 37°, 39°, 75°

4. Conclusions

This study examined the impact of sodium nanoalginate and lime on the swelling characteristics of expansive clay soil. Additionally, it investigated the influence of the processing time on the soil's swelling properties. The following conclusions were drawn from the research:

1 Addition of both sodium nanoalginate and lime to the soil resulted in a decreased LL, increased PL, and ultimately decreased the PI of the soil. The use of sodium nanoalginate produced more favorable outcomes compared to lime.

2 The addition of different concentrations of sodium nanoalginate and lime reduced soil swelling, with sodium nanoalginate demonstrating superior results compared to lime. It is worth noting that increasing the percentage of the sodium nanoalginate additive led to higher values of free swelling and swelling pressure. However, with more than 5% of lime, the soil's free swelling and swelling pressure decreased.

3 Increasing the curing time decreased the soil's free swelling and swelling pressure when treated with both agents. With the increasing curing time, sodium nanoalginate performed better compared to lime.

4 The XRD tests showed that sodium nanoalginate reduced soil swelling by filling pores, binding particles, and altering the mineral composition. Lime addition to the soil reduced quartz and calcite peaks, forming new compounds, such as calcite, nicolite, CSH, and CAH.

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