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Forest Road Subgrade Improvement by Lime and Sodium Nanoalginate Used as Stabilizers for Clay Soils

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Abstract: Fine-grained soils cause problems for forest road construction and often require improvements of their mechanical properties. One of the methods of improving mechanical properties of clay soils is soil stabilization. In this study, the effect of a conventional (lime) and a non-conventional (sodium nanoalginate) stabilizer on improving the characteristics of a high plasticity forest soil was compared. Atterberg limits including liquid limit, plastic limit and plasticity index, standard Proctor, UCS (Unconfined Compression Strength) and CBR (California Bearing Ratio) tests were performed on control (untreated) and soil samples treated with different doses (3%, 5% and 7%) of lime and sodium nanoalginate, according to the standard procedures. Moreover, to evaluate the effect of curing time, additional tests were performed on the soil samples treated with 3% lime and 3% sodium nanoalginate at 7, 14 and 28 days after the treatment. The results indicated that adding sodium nanoalginate and lime to the forest soil improves the Atterberg limits. Additionally, adding sodium nanoalginate to the forest soil increases the maximum dry density (γ_{dmax}) and decreases the optimum moisture content (OMC), whereas adding lime to the forest soil reduces the maximum dry density and increases the optimum moisture content. Adding sodium nanoalginate and lime in different doses (3%, 5% and 7%) increased UCS and CBR as the main indices of soil strength. The increment range of UCS for the soil stabilized with sodium nanoalginate and lime was 42.59%–160.14% and 31.34%–56.65%, respectively, and the range of CBR improvement for soil stabilized with sodium nanoalginate and lime was 28.72%–122.97% and 13.83%–45.59%, respectively. Increasing the curing time improved the mechanical properties of the forest soil in the samples treated with both stabilizers, but sodium nanoalginate performed better in soil stabilization.

Keywords: forest roads; subgrade; mechanical properties; improvement; stabilization; Atterberg limits; CBR; UCS; curing time

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1. Introduction

Successful and sustainable forest management is largely dependent on an efficient road network that should provide easy and permanent connectivity and access to the forests [1]. Hence, forest roads play an important role in the management of forests. However, forest roads may also have negative effects by their existence or if they are faultily designed and constructed [1–3].

Generally, the aim of studying and understanding the mechanical properties of soil is to reduce forest removal to make space for roads, reduce forest road construction costs and soil erosion and to minimize post-construction negative consequences [4]. To meet these criteria, forest roads need good construction methods and materials [5]. Therefore, soil properties are important indicators in estimating the costs of forest road construction and maintenance and in predicting the negative environmental effects of forest roads [6,7]. In this regard, fine-grained soils are problematic and may cause complex engineering problems for forest road construction due to their unfavorable technical properties, in particular, their plastic properties, low permeability, low resistance, changes in pore water pressure, changes in volume, texture, chemical properties and grain structure [2,8–10]. Environmental conditions can increase the severity of these problems in some cases, especially during the rainy season. The best methods for improving and correcting unfavorable soil conditions are those which are the most compatible with the type of soil [11]. These methods are based on soil science studies, which typically produce outcomes that help in selecting options for soil improvement [6]. For soil stabilization, it is important to know the stabilizers and to be aware of their reactions, how they work and their limitations, which helps in deciding on the best stabilizer and the method of soil stabilization [12,13]. Clay soils, which are common in rainforest areas, have low resistance, and when they are exposed to moisture, their resistance drops significantly [14,15]. To build roads on them, it is necessary to alter their mechanical properties and to stabilize them. Among the traditional methods of stabilizing clay soils is to use lime or cement [13,16]. These are the most common conventional stabilizers that are widely used in soil modification and stabilization [17–19]. Nowadays, with the development of new methods for modifying or improving soil properties and, as a result, the production of new non-conventional stabilizers, there are more options for choosing a stabilizer; it is, therefore, necessary to test their effectiveness and the way of using them [15,20].

Soil stabilization has received increased interest in science by studies showing that conventional stabilizers such as lime [5,10], cement [21] and fly ash [22], and nonconventional stabilizers including lignosulfonate [23], husk ashes [24], rice ash [25], various polymers [26,27], maize ash [28] and coal waste [29], improve the mechanical properties of soil, including unconfined compression strength (UCS) and soil swelling. However, so far, limited research has been conducted on soil stabilization for ballast roads, especially using non-conventional stabilizers [26,30].

A nonconventional stabilizer available in the form of a nano material is sodium nanoalginate (SA), which is a linear polysaccharide and a copolymer [31]. The results of recent studies indicated that sodium nanoalginate is a cheap and environmentally friendly material [32,33]. Sodium nanoalginate also holds good thermal and mechanical stability and has a high self-healing capability when exposed to air [34,35]; it is soluble in hot and cold water, obtained by dissolving a liquid with high viscosity, and forms irreversible gels in reaction with calcium salts or acids. Sodium nanoalginate gels hold characteristics such as viscosity and material stabilization properties [36,37]. Given the fact that these materials hold high viscosity, are cheap and environmentally friendly, they can be proposed as an option to improve the mechanical properties of road subgrades. Hence, considering the fact that no research has been conducted on the effect of this material on the behavior of forest soils, in this study, the effects of a conventional (lime) and non-conventional (sodium nanoalginate) stabilizer on the properties of forest soil are compared as a first objective. In other words, this study aimed to gain an understanding of forest soil improvement by lime and sodium nanoalginate. For this purpose, the changes caused by applying lime and sodium nanoalginate were evaluated by the Atterberg limits, standard Proctor compaction, CBR (California Bearing Ratio) and UCS (Unconfined compression strength) tests. The second objective of the study was to check the effect of curing time on the mechanical properties of the soil by considering both stabilizers and three curing periods (7, 14 and 28 days).

2. Materials and Methods

2.1. Study Area and the Soil Used

The study was carried in Kheyroud forest, which is located in northern Iran. The area of the forest is about 8000 ha, covering 7 districts and 60 km of main and secondary forest roads; the altitude ranges from 40 to 2200 m above sea level (a.s.l.) [38]. The mean annual rainfall in the area is 1450 mm, and the minimum and maximum rainfall are recorded in May and October, with 61 and 254 mm, respectively. The mean warmest and coldest temperatures are 26 °C in August and 8 °C in February [39]. The main soil types are clay with low plasticity (CL), clay with high plasticity (CH), silt with low plasticity (ML) and silt with high plasticity (MH), based on the unified soil classification system [2]. To conduct research in the laboratory, a soil specimen (about 100 kg) was collected near a forest road showing repeated stability problems [15]. Physical and chemical properties of the soil were determined and are shown in Table 1. Additionally, a grain size distribution test was carried out based on the ASTM D422 [40] and ASTM D7928 [40] using sieve analysis and a hydrometer. It should be noted that the mechanical or sieve analysis was conducted to determine the distribution of the coarser, larger-sized particles, while the hydrometer method was applied to determine the distribution of the finer particles. The grain size distribution chart of the soil sample used is shown in Figure 1. According to the chart, the soil sample used had 9% sand, 4% silt and 87% clay.

Table 1. Chemical properties of the soil sample.

Property	Amount
Gs	2.85
SO_4 ($^{2-}$)	1.9
$CaCO_3$ (%)	0.74
CEC	39.09
EC	121.2
OC	1.68
Ph	4.8
Na^+ (meq/L)	0.39
Ca^{2+} (meq/L)	1.7
Mg^{2+} (meq/L)	2.8
Cl^- (meq/L)	0.8
CO_3^{2-}(meq/L)	0.0
HCO_3 ($^{2-}$)	1.88
K^+ (meq/L)	0.9

Note: Gs—specific gravity, SO_4 ($^{2-}$)—sulfate, $CaCO_3$—calcium carbonate, CEC—cation exchange capacity, OC—organic carbon, EC—electrical conductivity, Ph—potential of hydrogen.

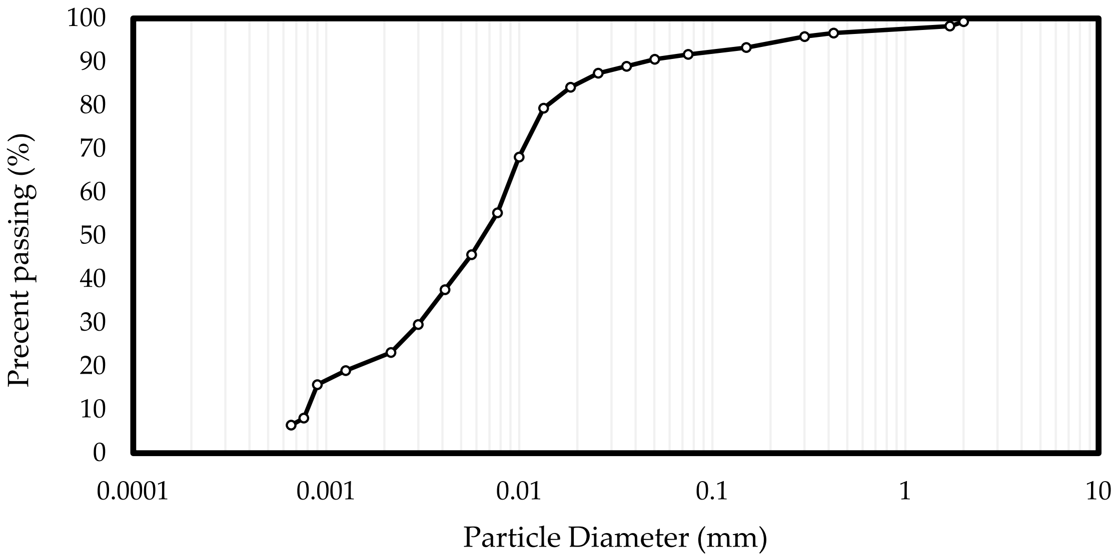

Figure 1. Particle size distribution of the soil sample.

2.2. Description of the Tested Stabilizers

Commercially, sodium nanoalginate is supplied in solid form, and for using it in this study, it was mixed with heated distilled water [41]. Sodium nanoalginate is a natural polysaccharide that consists of two linked acids, namely, β-D-mannuronic acid (M) and α-L-guluronic acid (G), which are residues widely distributed in seaweeds and bacteria [41]. It is often structured as the homo-polymeric regions of G-residues (G-blocks) and M-residues (M-blocks), interspersed with regions of mixed monomers or MG-blocks [42]. The lime used in this study was calcium oxide (CaO). This material has high chemical reactivity and has the appearance of a white powder. CaO has a crystalline structure, and it is alkaline. The properties of sodium nanoalginate and lime used in this research are summarized in Table 2.

Table 2. Physiochemical properties of sodium nanoalginate and lime.

Stabilizer	Property	Value
Sodium nanoalginate	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%
	As	<3 PPM
	Pb	<10 PPM
	Sulphated ash	22.6
	S	<0.02%
	P	<0.02%
	Molecular weight	216 g/mol
	Dynamic viscosity	12 CPS
Lime	Chemical formula	CaO
	Ph	12.8
	Matter insoluble in water	Chemical reaction and converts to calcium hydroxide
	Gs	3.34 g/cm
	Melting point	2613 °C
	Appearance	White powder

Note: C—carbon, H—hydrogen, Na—sodium, As—arsenic, PPM—parts per million, Pb—lead, S—sulfur, P—phosphorus, Ca—calcium, O—oxygen.

2.3. Method

Liquid and plastic limit tests were carried out on the untreated and treated soil samples according to BS [43] and ASTM D4318 [40], respectively, which is equivalent to ISO 17892-12 [44]. Treatment of soil samples was conducted with doses of 3%, 5% and 7% of sodium nanoalginate and lime, respectively. The soil sample used in this study was classified as CH (clay with high plasticity) according to the Unified Soil Classification System (USCS, ASTM D2484).

Standard Proctor compaction tests were carried out on the untreated and treated soil according to ASTM D698 standard and ISO 17892-2 standards [45] to determine the maximum dry unit weight (MDUW) and the optimum moisture content (OMC) of the samples. The Standard Proctor compaction test is a laboratory method of experimentally determining OMC, at which a given soil type will become most dense and achieves its MDUW. It should be mentioned that the results of optimum moisture content were also used for the preparation of CBR and UCS tests on soil samples. Then, CBR and UCS tests were conducted according to ASTM D1883 [40], ISO 12236 [46], ASTM D-1633 [40] and ISO 17892-7 [47] standards, respectively, on the untreated and treated soil samples containing different doses of sodium nanoalginate and lime that were prepared by static compaction, based on the optimum moisture content obtained from the compaction curves.

The CBR test is a measure of a road subgrade's strength or other paved area and of the materials used in its construction. Penetration was measured by applying the bearing load on the sample using a standard needle, with a diameter of 50 mm, at a rate of 1.25 mm/min. The CBR is expressed as a percentage of the actual load causing the penetrations of 2.5 or 5.0 mm to the standard loads on crushed stone, based on which a load penetration curve was drawn. The load values on standard crushed stone are of 13.44 and 20.15 kN at 2.5 and 5.0 mm penetrations, respectively. It should be noted that for the CBR calculation, from the curve, the corresponding stress shall be determined for both 0.1-inch (2.55 mm) and 0.2-inch (5.08 mm) penetrations, and then Equations (1) and (2) are used determine the

CBR value. Generally, $CBR_{0.1in}$ (Equation (1)) is taken as a CBR value. However, for the condition where $CBR_{0.1in}$ is significantly lower than $CBR_{0.2in}$, the test shall be repeated.

$$CBR_{0.1in} = \frac{\text{Stress at 0.1 penetration (N)}}{13386.8} \quad (1)$$

$$CBR_{0.2in} = \frac{\text{Stress at 0.2 penetration (N)}}{19982.2} \quad (2)$$

The UCS stands for the maximum axial compressive stress that a cohesive soil sample can bear under zero confining stress. The UCS test is one of the fastest and cheapest methods of measuring the shear strength of clay soils.

In addition, soil samples prepared with 3% of lime and sodium nanoalginate (according to the recommended value by the manufacturer) were kept in plastic bags in a special curing cabinet under constant temperature (20 ± 5 °C) and relative humidity conditions, allowing them to cure for 7, 14 and 28 days. This curing protocol has also been previously adopted by researchers such as [48,49]; following the curing periods, compaction, CBR and UCS tests were repeated to determine the effect of curing time on the samples. Three replicates were taken for each experiment. To give an overview on how the quantity of stabilizer used may affect the magnitude of change in the soil's mechanical properties, in addition to the results reported for the main tests and for the effect of curing time, linear regression models were developed by taking the dose of stabilizers used as a predictor. These indicative results were reported in the Appendix A section, along with their main statistical descriptors.

3. Results

3.1. The Effect of Stabilizers on the Atterberg Limits

The results on the Atterberg limits of the soil treated with different doses of sodium nanoalginate (SA) and lime are compared to the control soil in Table 3. As shown, by adding sodium nanoalginate and lime to the soil, the liquid limit (LL) of the treated samples decreased, the plastic limit (PL) increased and, finally, the plasticity index (PI) decreased in such a way that by adding 3% to 7% SA to the soil, the results showed a decrease of 14.88% to 42.32% in the LL. Additionally, the PL of the samples treated with SA increased from 8.53% to 15.77%. On the other hand, by adding the same percentage of SA, the PI decreased by 48.32% to 248.4%. By adding 3% to 7% lime to the soil, the LL and PI decreased by 10.78%–31.29% and 33.00%–112.94%, respectively, and the PL increased by 6.78%–8.14%.

Table 3. Atterberg limits of the control soil sample and of the treatment with different doses of sodium nanoalginate and lime.

Treatment	Dose (%)	LL (%)	PL (%)	PI (%)
Control	0	64.53	30.80	33.73
Sodium nanoalginate	3	56.17	33.43	22.74
	5	48.22	34.15	14.07
	7	45.34	35.66	9.68
Lime	3	58.25	32.89	25.36
	5	50.58	33.27	17.31
	7	49.15	33.31	15.84

3.2. The Effect of Stabilizers on the Parameters of the Standard Proctor Compaction Test

The results of the Standard Proctor test on control and on the soil treated with different doses of sodium nanoalginate and lime are given in Figure 2. As shown, adding sodium nanoalginate to the soil increased its maximum dry unit weight (γ_{dmox}, kN/m^3) and decreased the optimal moisture content (OMC, %). Adding 3 and 5% sodium nanoalginate to the soil increased γ_{dmox} by 3.7% and 15.55%, respectively. By adding 7% SA, γ_{dmox} increased by 20% compared to the control soil. Additionally, by adding 3%, 5% and 7% sodium nanoalginate, the OMC decreased by 4.34%, 9.09% and 41.17%, respectively. The results of soil stabilization using lime also indicated that adding 3%, 5% and 7% lime decreased γ_{dmox} of the soil by 2.96%, 4.44% and 6.66%, respectively, and increased the OMC by 4.16%, 8.33% and 16.66%, respectively.

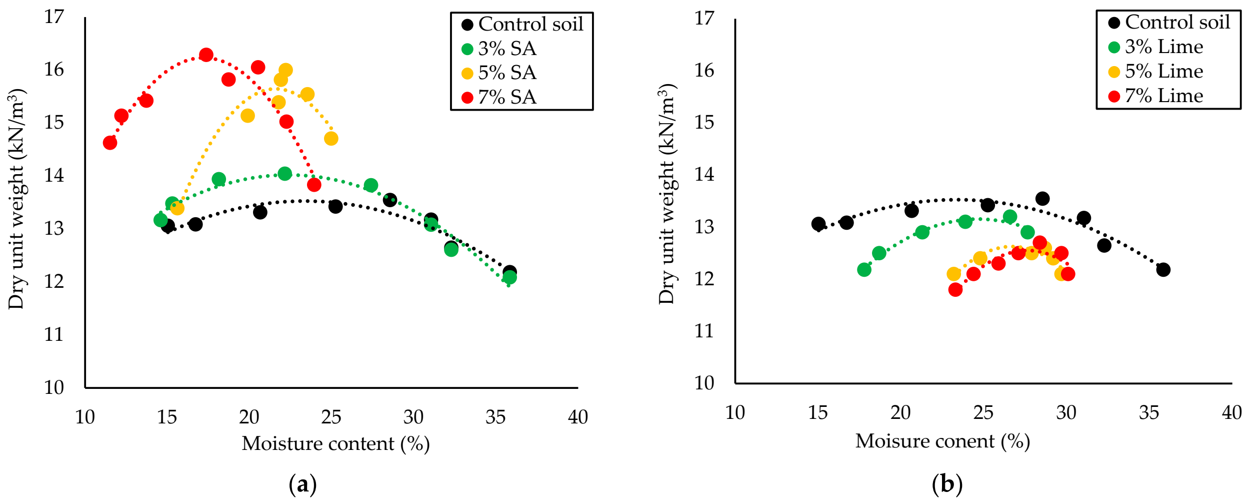

Figure 2. Standard Proctor compaction curves of the control soil and of the soil treated with sodium nanoalginate (**a**) and lime (**b**). Legend: SA stands for sodium nanoalginate.

3.3. The Effect of Stabilizers on the Parameters of the CBR Test

The results of the CBR test on the control and treated soils are shown in Figure 3. The results indicated that adding 3% sodium nanoalginate to the soil increases the CBR by 28.46%. Additionally, by adding 5% and 7% sodium nanoalginate, CBR increased by 60.47% and 122.97%, respectively. On the other hand, by adding 3% and 5% lime to the soil, the CBR increased by 13.83% and 72.27%, respectively, and subsequently, by adding 7% lime to the soil, the CBR increased by 45.59% compared to the control soil.

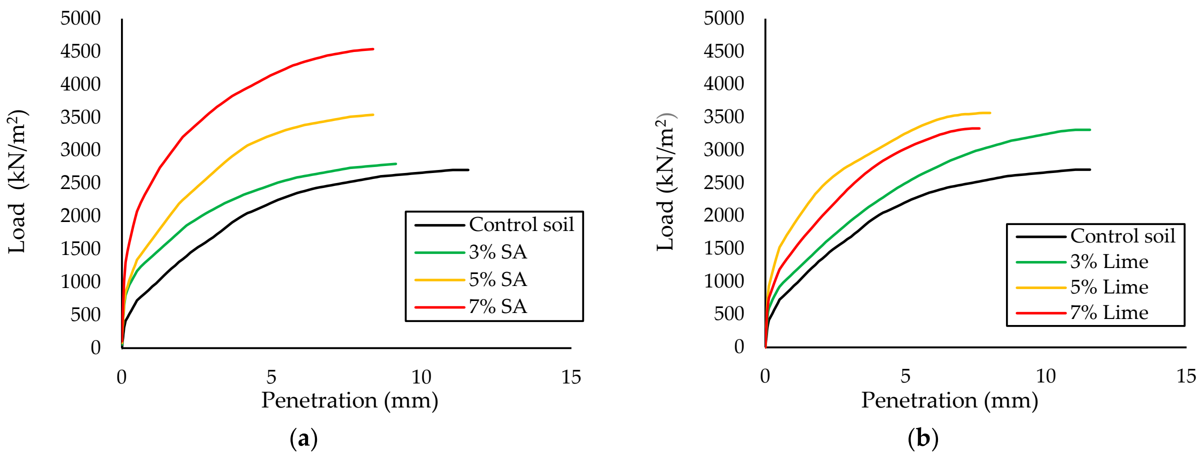

Figure 3. Variation of pressure and penetration for the control soil and for the soil stabilized with different doses of sodium nanoalginate (**a**) and lime (**b**). Legend: SA stands for sodium nanoalginate.

3.4. The Effect of Stabilizers on the Parameters of the UCS Test

The results of the UCS test on control soil and soil treated with different doses of sodium nanoalginate and lime are shown in Figure 4. The results showed that adding 3%, 5% and 7% sodium nanoalginate to the soil increased the UCS by 42.59%, 128.94% and

160.14%. By the addition of 3% and 5% lime, the UCS initially increased by 31.34% and 86.88% and then decreased by adding 7% lime.

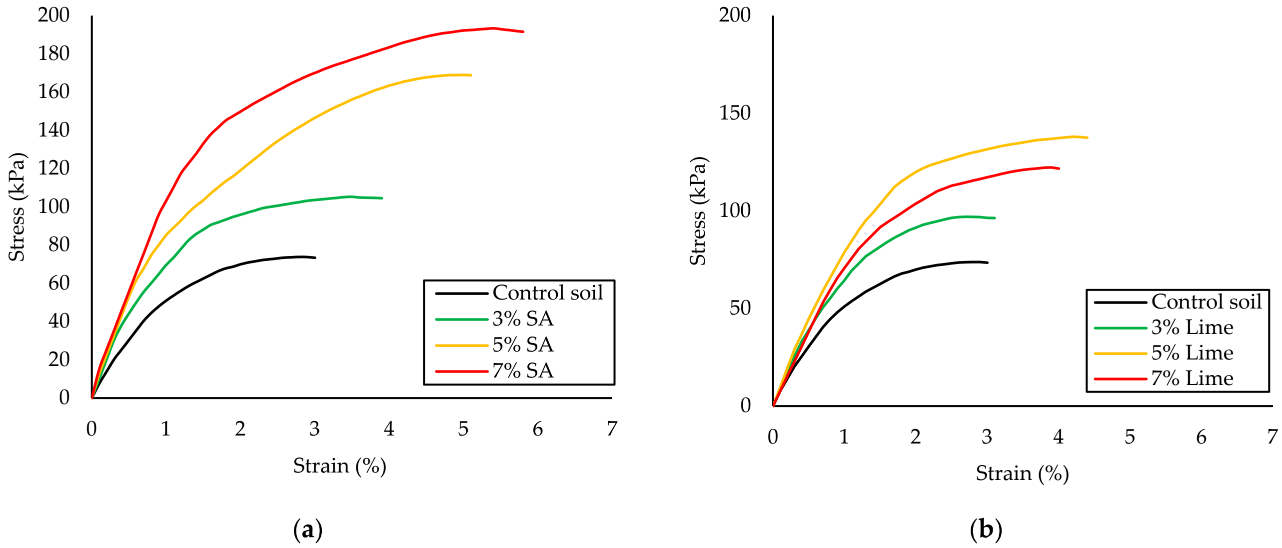

Figure 4. The results of UCS tests for the control and for the soil treated with different doses of sodium alginate (**a**) and lime (**b**). Legend: SA stands for sodium alginate.

3.5. The Effect of Curing Time on Atterberg Limits

The effect of curing time at 0, 7, 14 and 28 days on the Atterberg limits of the soils treated with 3% sodium nanoalginate and lime, respectively, are shown in Figure 5. By increasing the curing time, the liquid limit of the samples treated with both stabilizers decreased. On the other hand, by increasing the curing time in all the treated samples, the plastic limit increased and the plasticity index decreased.

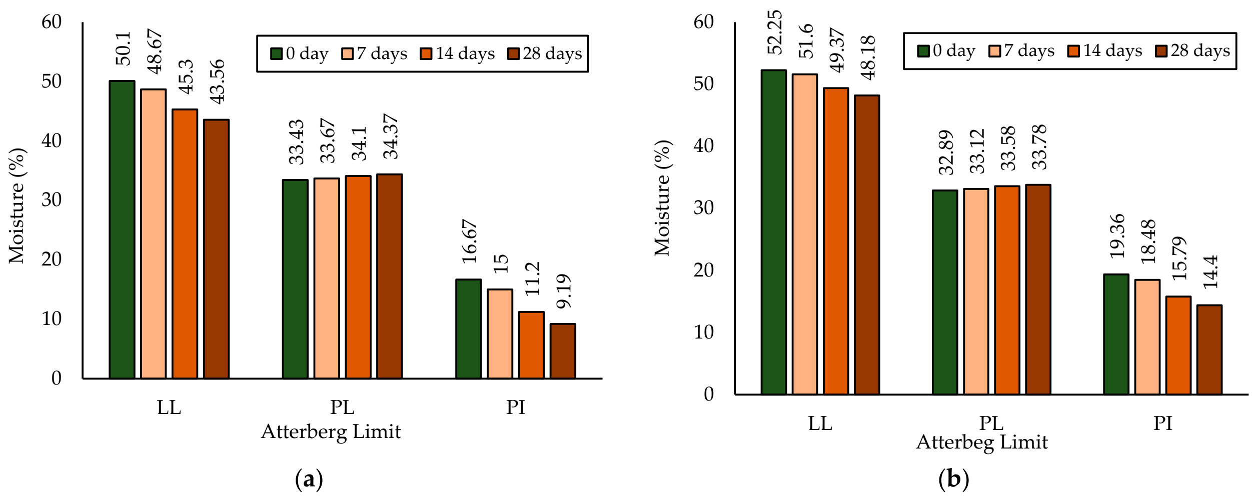

Figure 5. The effect of curing time on the Atterberg limits of the soils treated with 3% sodium nanoalginate (**a**) and lime (**b**).

3.6. The Effect of Curing Time on the Parameters of Standard Proctor Test

Figure 6a shows the results on the effects of curing time on the OMC and γ_{dmox} of the soil treated with 3% sodium nanoalginate. The results indicate that by increasing the curing time, γ_{dmox} of soil increases and the OMC level decreases; γ_{dmox} of the soil increased by 7.85%, 15.71% and 20.71% at curing times of 7, 14 and 28 days, respectively. Additionally, the OMC of the soil decreased by 4.54%, 15% and 21.05% at curing times of 7, 14 and 28 days, respectively. Figure 6b shows the results on the effect of curing time on the OMC and γ_{dmox} of the soil treated with 3% lime. By increasing the curing time, γ_{dmox} of soil increased and the OMC level decreased in such a way that γ_{dmox} of the soil increased by 7.85%, 15.71% and 27.14% at curing times of 7, 14 and 28 days, respectively. Additionally, the OMC of the soil decreased by 2.22%, 9.52% and 21.05% at curing times of 7, 14 and 28 days, respectively.

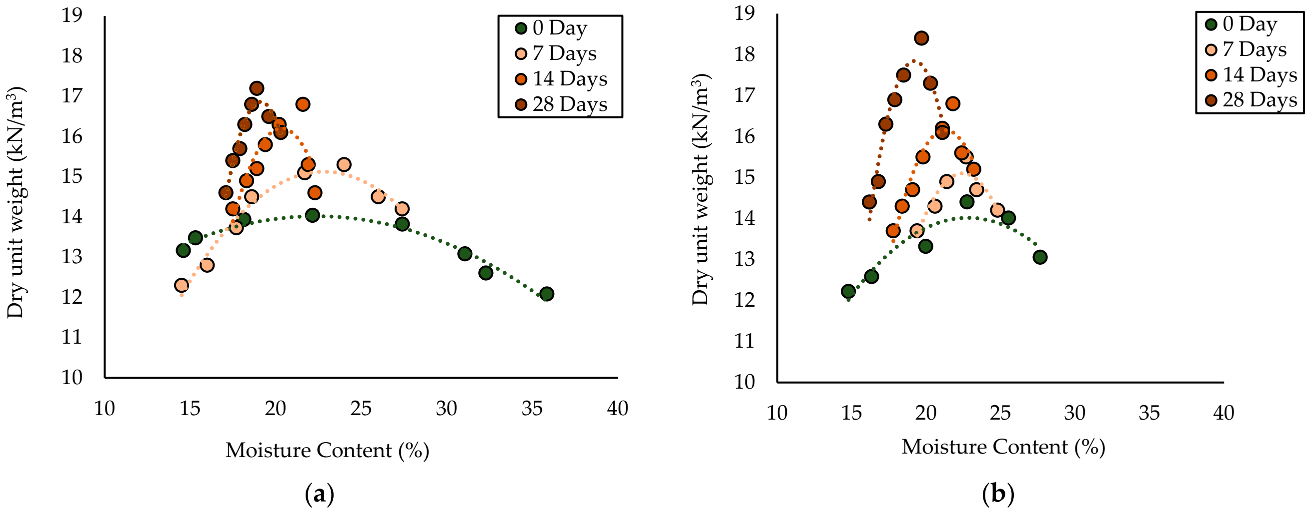

Figure 6. The diagram of the standard Proctor test of the soil treated with 3% sodium nanoalginate (**a**) and 3% lime (**b**) at curing times of 7, 14 and 28 days.

3.7. The Effect of Curing Time on the Parameters of the UCS Test

Figure 7a shows the results on the effect of curing time on the parameters of the UCS test of the soil sample treated with 3% sodium nanoalginate. The results showed that the UCS of the soil increased when increasing the curing time. UCS increased by 17.62%, 47.28% and 63.83% at curing times of 7, 14 and 28 days, respectively. Figure 7b shows the results on the effect of curing time on the parameters of the UCS test of the soil treated with 3% lime. The results demonstrated that the UCS of the soil increased with increasing the curing time; UCS increased by 16.18%, 32.57% and 42.28% at curing times of 7, 14 and 28 days, respectively.

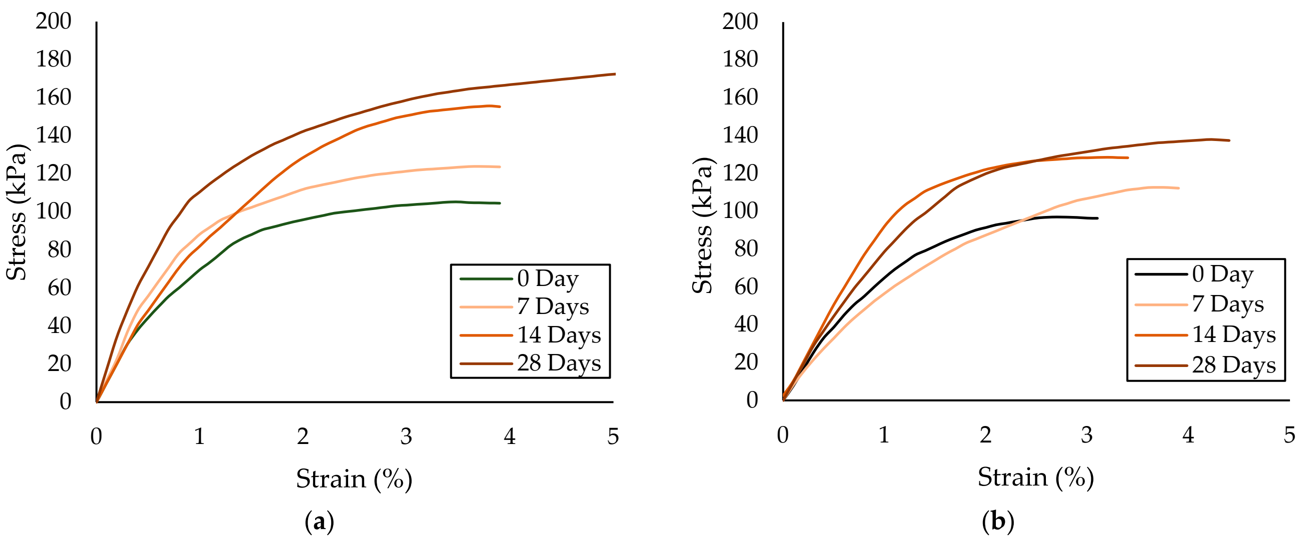

Figure 7. UCS diagrams of the soil samples treated with 3% sodium nanoalginate (**a**) and lime (**b**) at different curing times.

3.8. The Effect of Curing Time on the Parameters of the CBR Tests

Figure 8 shows the results on the effect of curing time on the CBR of samples stabilized with 3% sodium nanoalginate (Figure 8a) and lime (Figure 8b). For both samples, the CBR increased by increasing the curing time; for the sample treated with 3% sodium nanoalginate, CBR increased by 3.4%, 20.2%, and 51.96% after 7, 14 and 28 days, respectively. Additionally, for the samples treated with 3% lime, the CBR increased by 8.3%, 38.29% and 49.86% at curing times of 7, 14 and 28 days, respectively.

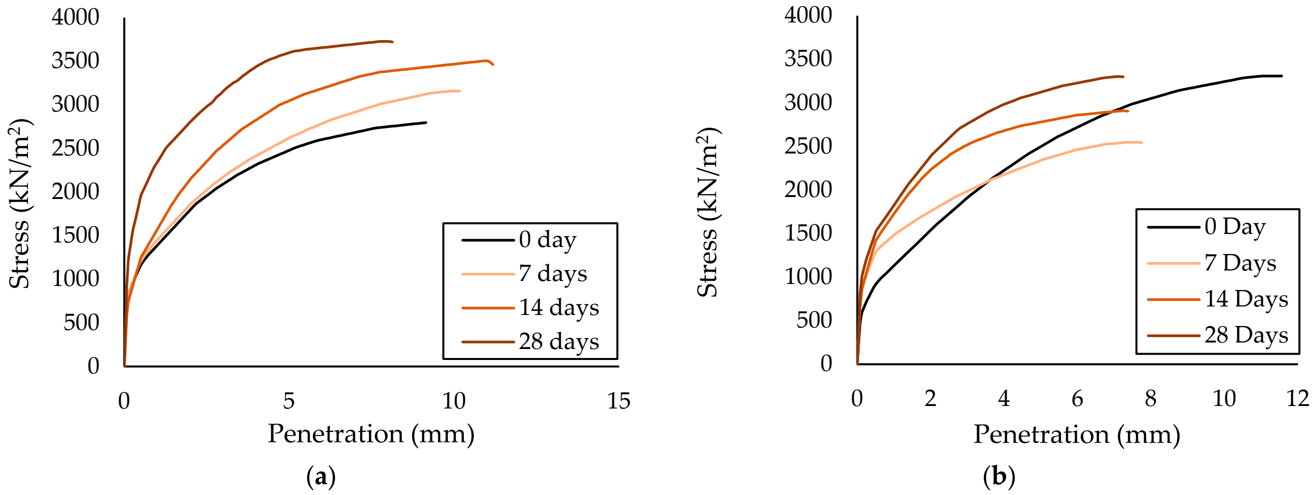

Figure 8. CBR diagrams of the soil samples treated with 3% sodium nanoalginate (**a**) and lime (**b**) at different curing times.

4. Discussion

Forest roads are important for forest management as well as for other activities and leisure [50]. Since the demand for forest-based products and services is rising, traffic on forest roads is expected to become more intense. As a consequence, forest roads have to be constructed and maintained by considering appropriate standards. Unfortunately, many of the forests are located on swelling soils; therefore, forest roads have to be constructed in these areas, meaning that in some cases, road construction will need subgrade stabilization that may provide long-term strength and reduction in plasticity and swelling [51]. Although increasing the long-term strength of the forest soil is the most important goal of stabilization, in very wet and loose soils, lowering the plastic limits to increase the efficiency of forest road construction is usually one of the aims of stabilization, and this is commonly scrutinized by Atterberg limit tests [52]. The results of Atterberg limit tests demonstrated a decrease in the liquid limit, an increase in the plastic limit and, finally, a decrease in the plasticity index of the soil after adding sodium nanoalginate, which was in line with the results of [36]. They showed that adding sodium nanoalginate to soil reduces the liquid limit, increases PL and subsequently decreases PI, which can change the soil class. The lower the clay mineral content, the lower the plasticity index value of the soil [8]. The aggregation in the soil samples mixed with sodium nanoalginate decreases the specific surface and thickness of the diffuse double layer and then water holding capacity [53]. On the other hand, by reducing the fluidity limit of the soil and the plasticity index, electric charges on the surface of particles and the percentage of thin particles reduce. Since the percentage of this type of thin and flake-like particles has a significant effect on the compressibility of the soil, it is the liquid limit that indicates the compressibility of the soil [34,36]. According to the results of this study, adding 3% to 7% sodium nanoalginate increases the maximum dry unit weight and decreases the optimal moisture content of the soil, results which agree with the findings of [36] and can be useful for practical purposes [34,36]. Previous research has indicated that the molecular structure of the soil can be altered by ion exchange; therefore, it can enhance the maximum dry unit weight and reduce the optimal moisture content [49,54]. As the dose of the stabilizer increased, the maximum dry unit weight and the optimal moisture content increased and decreased more intensively, results of which are in line with the findings of [36].

The results of the UCS tests demonstrated that adding sodium nanoalginate to the soil increased the stiffness of the samples treated with this stabilizer, which was consistent with the results of [34,36]. These researchers stated that the reason for the increase in the UCS of the samples treated with sodium nanoalginate is the flocculated structure of the treated soil sample. According to other studies, clay soils with a flocculent structure show a more fragile behavior compared to clay soils with dispersed structure, indicating the high peak strength and stiffness in the samples treated with sodium nanoalginate [55]. These results were in line with the findings of [34,56]. Bakhshizadeh et al. [34] came to the conclusion that sodium nanoalginate is able to improve the UCS of soil samples even at one day of curing. Based on the results of this study, sodium nanoalginate may be added to fine-grained soils, where it improves the mechanical properties, which occurs due to cation exchange between metal ions dependent on the surface of clay particles and sodium ions of the material used [34,36]. In other words, by adding sodium nanoalginate to the soil, polymer cementitious particles are created in the pores of the soil, and, consequently, an insoluble cement material is created due to cross-linking in the presence of metal cations in the aqueous environment [33]. The formation of polymer also fills the pores of the soil, and it causes the cation of the clay particles to connect to the charged clay particles [2]. These charged cations react with sodium nanoalginate and form an insoluble polymer [37]. As a result, this process improves the composition of clay and alginate. On the other hand, the presence of abundant free cations in clay that react with sodium nanoalginate creates a gelling film that fills the pores of soil particles [36,37]. The diffuse double layer around clay particles is reduced by ion exchanges. In other words, the clay particles become closer to each other and form a flocculated structure [55]; hence, the soil particles stick together. Moreover, when ion exchanges occur, sodium nanoalginate creates a cemented gel material due to cross-linking in sodium nanoalginate, and as long as this gel is in contact with ion exchanges, soil resistance will increase.

In fact, the gel formed in the soil treated with sodium nanoalginate causes the creation of cementitious polymer materials, which in turn increases the welding forces between the soil particles and the filled spaces in the soil. In addition, the behavior of fine-grained soil improves through hydrogen or electrostatic bonding with charged clay surfaces [57]. Additionally, the results of this study indicated that adding sodium nanoalginate to soil increases the CBR 1.28 to 2.22 times compared to untreated soil. According to other studies, sodium nanoalginate is able to change the soil surface properties by its ions [36,37,58]. Hence, the most important mechanism for the increase in the CBR level of soil stabilized with sodium nanoalginate is that of ion exchange reactions because sodium nanoalginate often improves the mechanical properties of clay soils through cation substitution [59]. In fact, sodium nanoalginate can increase the clastation process of clay minerals by acting as a catalyst [60]. These results are consistent with those reported in [56,61], which indicated that sodium nanoalginate as a biodegradable material holds the ability to increase the CBR. Moreover, Sawwaf et al. [61] indicated that increment in the CBR of soil samples treated with sodium nanoalginate is directly related to the dose used; also, they pointed out that sodium nanoalginate can be used as a sustainable stabilizer to replace the traditional agents.

As observed, adding lime to soil reduces the liquid limit, increases the plasticity index and decreases the plastic limit of the soil, the main reason of which is the ion exchange reaction caused by the combination of soil with lime. In fact, these reactions reduce the clay properties of soil and, finally, increase the efficiency of soil [15,62]. On the other hand, the results indicated that adding lime to soil decreases the maximum dry unit volume weight and increases the optimal soil moisture content. In previous research, due to the different type of clay soils and also due to the difference in the amount of lime used, the results showed some differences; however, the process of changing the density characteristics of the soil in this study was similar to that of previous studies [39,62].

Reducing the maximum dry unit volume weight of soil owing to the addition of lime to the soil can occur due to calcification of clay. Negi et al. [63] mentioned that lime forms hydrated calcium aluminates and calcium silicates that include soluble silicate aluminate, then organizes a bond upon crystallization that is named pozzolanic reaction. Therefore, increasing the optimal soil moisture in samples stabilized with lime occurs due to the hydration and pozzolanic reaction between soil and lime, as well as the hydrophilicity of lime [18]. Additionally, the drop in density is associated to the replacement of particles [64]. According to the results, adding lime to clay soil increases the UCS and CBR of the soil, which was in line with the results of other studies [62,65].

However, the maximum UCS and CBR was obtained in the samples stabilized with 5% lime, indicating that the optimal dose of lime used in the present study so as to stabilize the tested clay soil is 5 percent weight of the dry soil; adding lime beyond the dose of 5% brings no further improvements in resistance and CBR of the soil, but the mentioned parameters also decrease, owing to the saturation of the mixture with lime. This is caused by the mechanism of the reaction of lime with clay soil particles, which is because after adding lime to clay soil, this material breaks down into calcium and hydroxide ions. On the other hand, silicon and aluminum ions resulting from the dissolution of clay silicates and aluminates combine with calcium hydroxide and lime ions and create hydrated calcium silicates and aluminates (CSH and CAH), which cause cementation of the soil and, consequently, increase soil strength [66]. Therefore, the reason for the increase in soil strength can be the increase in pozzolanic reactions. The pozzolanic reactions between silica or silica aluminate components of a pozzolan occur in the presence of calcium hydroxide when exposed to moisture and show adhesion and cementation properties. The aforementioned reactions are a function of time and will continue as long as hydrated calcium silicate and aluminate are present. As a result of these reactions, cement compounds are also produced and increase the strength of the soil stabilized with lime. It should be noted that the short-term strength of the soil stabilized with lime is due to the cation exchange reaction and the long-term strength is due to the pozzolanic reaction [67]. Yin et al. [64] also mentioned that increasing CBR values are related to cations and the pozzolanic reaction between soil and lime. In addition, previous studies indicated that the pozzolans have no cementing value unless mixed with lime in the presence of water [54,68]. Hence, by adding lime to the soil up to the optimal percentage, changes in clay minerals occur due to cementation and pozzolanic reactions, and, as a result, the soil strength enhances. Therefore, it can be said that the decrease in resistance and CBR with the addition of more than 5% lime is due to the stopping of the pozzolanic reaction, owing to the exhaustion of the reactants.

Generally, in the first stage, the polymer-based stabilizers disrupt the concentration of pore water. Subsequently, ion substitution reactions occur, and this causes the accumulation and integration of clay minerals. As a stronger attraction is created between the clay minerals, the cations released from the ionic electrolyte of the pore water cause the collapse of clay minerals and their transformation into more stable forms. In this process, the double layer of water is also drained from each side. The general result of such a reaction is an increase in UCS, CBR and soil granularity [60].

The results of the effect of curing time on the soil sample stabilized with 3% sodium nanoalginate and lime at curing times of 0, 7, 14 and 28 days indicated that by increasing the curing time, the liquid limit in the samples stabilized by lime decreased more. On the other hand, by increasing the time, the plastic limit increased more, and finally, the plasticity index of the soil showed a further decrease, which caused a change in the soil class. Additionally, the results indicated that by increasing curing time, the soil strength increased in both samples in such a way that the highest strength was observed after 28 days; these results were consistent with those of [19,69]. It should be noted that according to Scholen's theory, polymeric materials such as sodium nanoalginate change the environmental conditions from alkaline to acidic, which can complete the changes in the molecules of the material. However, these changes require a long curing time [60]. Hence, the reason for improving the physical and mechanical properties of soil stabilized with sodium nanoalginate is the same. Generally, strength increment over time in stabilized soils can be explained by the growth of cementitious products, which weld the soil particles and fill the pore space in clay soil matrices [70].

On the other hand, the strength obtained in clay samples stabilized with lime is caused by the creation and expansion of bonds between particles created by the pozzolanic reaction, which is a function of the quantity of lime used, silica and alumina in the composition, and the curing time [18]. Pozzolanic reactions change the crystalline texture of clay, and consequently, major changes in the physical properties and mechanical behavior of the soil occur, and this reaction takes place over time. Hence, the physical and mechanical properties of soil that is stabilized with lime improves as a function of curing time [18,69,71]. Generally, the results of this study indicated that sodium nanoalginate performed better in improving the mechanical properties of the soil, including Atterberg limits, CBR and unconfined compression strength.

Nowadays, with the sharp increase in road construction costs and the damage caused to the environment due to the extraction of gravel from forest sites or riverbeds, the use of alternative methods has emerged as an important issue. Therefore, it is necessary to look for alternative materials to minimize the extraction of road construction materials from nature. This study was carried out by considering a specific location within a larger area exhibiting a variety in forest soil conditions. Additionally, this study used a sample characterizing a single class of soils (CH), which is its main limitation. Since there are important differences in mechanical properties of soils as well as in their potential reaction to stabilizers, the effect of lime and sodium nanoalginate on other soil classes should be explored further. Therefore, it is suggested to study the effects of these stabilizers on other types of soils in the future.

In addition, in this study, soil mechanical tests were performed on the soil samples treated with 3%, 5% and 7% sodium nanoalginate, providing evidence on improvements only in this range of doses used; however, the results are encouraging for testing the effects of higher doses, provided that such attempts would be economical for scaling in practice. Since the stabilization of soil by sodium nanoalginate increases the CBR of the soil, the thickness of gravel pavement layer required to undertake the traffic load will decrease, which will likely reduce the costs of road pavement. In addition, the maintenance cost of stabilized forest roads will be reduced in the coming years. Nevertheless, an end-to-end economic assessment of potential cost saving by using the stabilizers tested in this study would depend on the long-term behavior of the forest roads. As such, follow-up studies are encouraged to check whether this solution is economical by considering the entire life cycle of a forest road.

5. Conclusions

This study was carried out with the aim of scrutinizing the effect of sodium nanoalginate and lime on the mechanical properties of clay soils. Moreover, the effect of curing time with the two types of stabilizers was examined. The following conclusions may be drawn:

- Adding sodium nanoalginate and lime to the soil decreased the liquid limit, increased the plastic limit and, finally, reduced the plasticity index. It should be noted that sodium nanoalginate showed better results compared to lime.
- Adding sodium nanoalginate to the soil increases the maximum dry unit weight and decreases the optimal moisture content, and as the percentage of the stabilizer increases, the dry unit weight of the soil increases and the optimal moisture content decreases more intensively. On the other hand, adding lime to the soil decreased the maximum dry unit weight and increased the optimal moisture content, but increasing the lime content to more than 5% provided no additional benefits.
- Adding different doses of sodium nanoalginate and lime increased the UCS of the soil, but using sodium nanoalginate provided better outcomes compared to lime. It is noteworthy that with increasing the dose of sodium nanoalginate, the UCS increased more intensively, as opposed to adding lime.

- Adding sodium nanoalginate and lime to the soil increased the soil's CBR, but sodium nanoalginate performed better. The highest CBR was observed in the sample treated with 7% sodium nanoalginate and 5% lime, and increasing the dose of lime at 7% decreased the soil's CBR.
- Increasing the curing time improved the mechanical properties of the soil in the samples treated with both stabilizers, but the results indicated better results with increasing the curing time in the samples treated with sodium nanoalginate.

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Appendix A

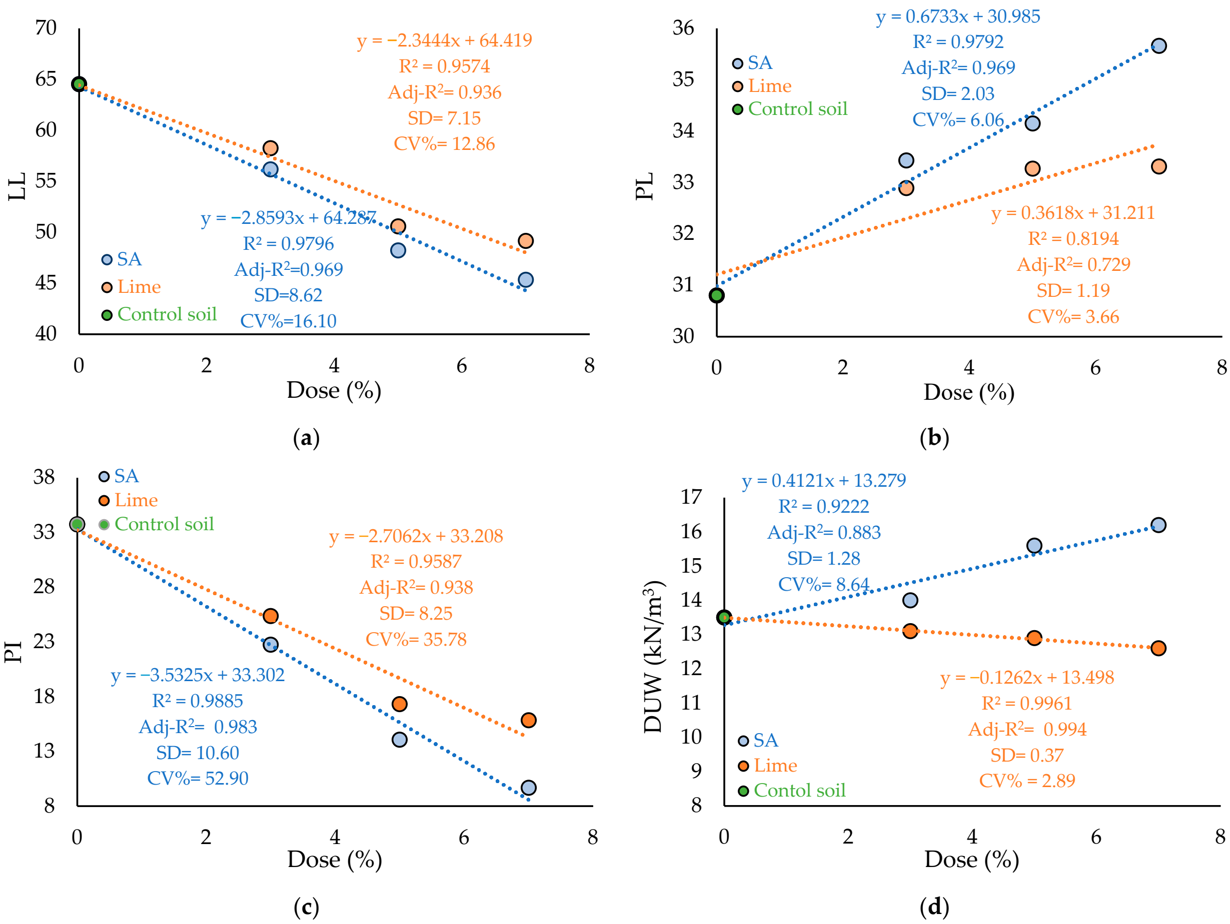
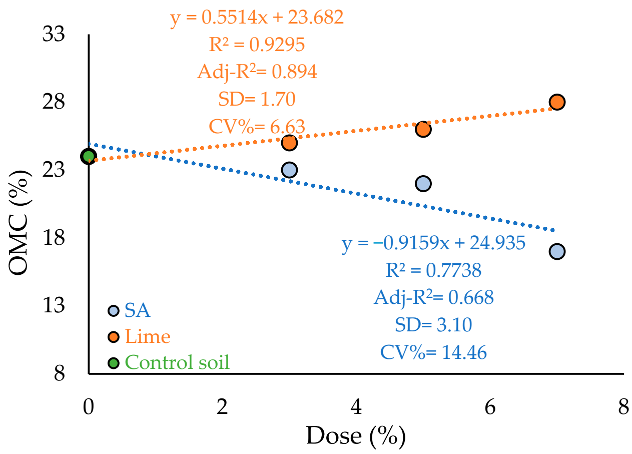
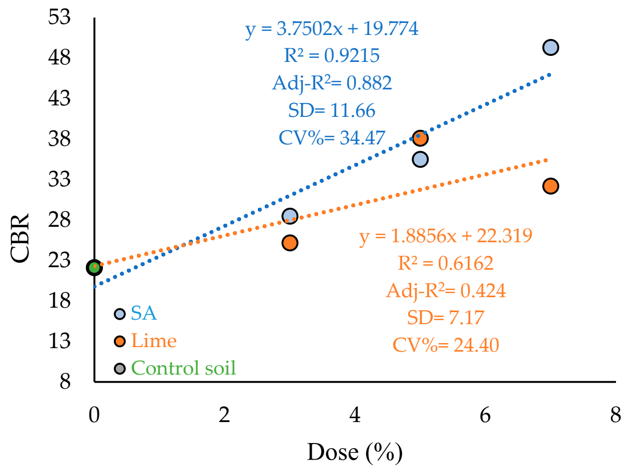


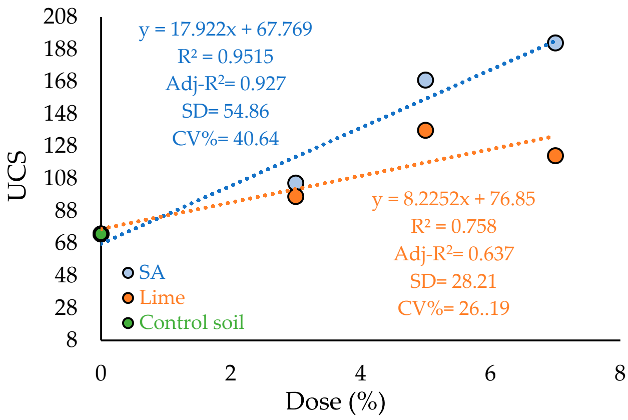
Figure A1. *Cont.*



(**e**)



(**f**)



(**g**)

Figure A1. Linear regression equations showing the relationships between the mechanical properties and the dose of stabilizer used: (**a**)—liquid limit (LL), (**b**)—plastic limit (PL), (**c**)—plasticity index (PI), (**d**)—dry unit weight (DUW), (**e**)—optimum moisture content (OMC), (**f**)—California Bearing Ratio (CBR), (**g**)—unconfined compression strength (UCS), SA—sodium nanoalginate, SD—Standard Deviation, CV—Coefficient of variation, Adj-R^2—Adjusted R^2.

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