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The influence of lime powder on the behaviour of clay soil

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Research Paper

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High price of land and importance of modern construction has imposed the need to strengthen weak clay soils. The stabilization of these soils has been conducted using various additives. Due to its low cost, availability, and positive impact on resistance, lime has traditionally been applied for stabilisation of poor and sensitive types of soils. In this research, lime powder, added in the percentages of 0, 2, 4, 8 and 16 of the dry soil weight, was mixed with kaolinite clay soil and its various engineering parameters were investigated during the curing time of 90 days. PH change, Atterberg Limits, optimum water content, and the modified clay maximum dry unit weight, were determined at different percentages of lime during the curing time. In the scope of determination of an optimum lime powder content, the Unconfined Compressive Strength tests (UCS) and CBR tests were conducted. The Young's modulus was determined based on UCS testing and definition of stress-strain curve. The results showed a significant increase in the effective, responsive performance of lime in the soil and a remarkable increase in the maximum compressive strength (q_u), cohesion, and Young's modulus.

Key words:
clay soil, lime powder, optimum percentage, curing time, soil strength parameters

Prethodno priopćenje

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Utjecaj vapnene prašine na ponašanje glinovitog tla

Visoka cijena zemljišta i značenje graditeljstva u modernom svijetu uvjetovali su potrebu za ojačanjem glinovitog tla slabe nosivosti. Stabilizacija takvog tla provodi se dodavanjem raznih aditiva. Zbog svoje niske cijene, dostupnosti i pozitivnog utjecaja na čvrstoću, vapno se tradicionalno koristi za stabilizaciju slabo nosivih i osjetljivih vrsta tla. U ovom se radu vapnena prašina u udjelu od 0, 2, 4, 8 i 16 % od težine suhog tla miješa s kaolinitnim glinovitim tlom te se istražuju razni inženjerski parametri u razdoblju njege tijekom 90 dana. U tom razdoblju njege, za razne postotke vapnene prašine istražuje se promjena pH-vrijednosti, Atterbergove granice, optimalan udio vode i maksimalna suha jedinična težina modificirane gline. U okviru određivanja optimalnog udjela vapnene prašine, provode sei ispitivanja jednoosne tlačne čvrstoće (UCS) te kalifornijskog indeksa nosivosti (CBR). Youngov modul određuje se na temelju pokusa UCS i definicije krivulje naprezanja i deformacija. Rezultati pokazuju znatan porast efektivne učinkovitosti vapna dodanog u tlo te znatan porast maksimalne tlačne čvrstoće (q_u), kohezije i Youngovog modula.

Ključne riječi:
glinovito tlo, vapnena prašina, optimalni postotak, vrijeme njege, parametri čvrstoće tla

1. Introduction

In engineering science, soil is defined as a non-integrated mixture of mineral and organic resid material, while the space in between soil grains is occupied by water and air. Soil as a building material is applied in civil engineering on major projects as well as in the foundations of most structures.

Therefore, civil engineers should study soil properties such as soil origin, gradation, drainage capability, shear strength, and other factors such as settlement, bearing capacity, etc. Fine-grained clay soils are expansive soils characterized by a high volume changes when affected by moisture. These soils are composed of kaolinite, montmorillonite and illite minerals. Considerable efforts have so far been made to overcome negative characteristics of these soils. Replacement with materials insensitive to changes of moisture content, compaction, stabilization with various additives, etc. are some of the efforts made in this respect. Soil stabilisation has been conducted using various additives such as cement, fly ash, lime, bagasse, rice husk, coconut fibres, polypropylene fibres, recycled carpet fibres, and various waste materials. Stabilization with lime is an example of a chemical method for modifying physical and chemical characteristics of soils. Stabilization of relatively fine-grained soils with lime is dependent on the lime and clay reaction. From the macroscopic standpoint, soil stabilized with lime:

- improves characteristics associated with compaction efficiency
- reduces compressibility and sensitivity to change in water content
- increases strength and stiffness of soil.

In this research, various percentages of lime powder, i.e. 2, 4, 8 and 16 percent, were added to the kaolinite clay soil. With a uniform distribution of lime in soil, the pH testing was made and Atterberg Limits were analysed in the curing time from one to 90 days. An optimum lime percentage was defined by determining the plastic limit. Samples containing an optimum rate of lime powder were examined using unconfined compressive strength tests and CBR, and then the positive impacts of lime in increasing the maximum unconfined compressive strength (q_u), and clay soil cohesion was registered.

2. Previous research on soil stabilization using lime

Bell [1] reports that the soil water content decreases rapidly by adding lime to the soil. The water content reduction increases if quicklime is used instead of hydrated lime. From the beginning up to 24 hours after mixing lime with soil, the following two physical-chemical mechanisms occur:

- live lime turns into hydrated lime by soil water absorption
- water evaporates from the soil as an exothermic reaction

Rogers et al. [2] show that after reducing the water content, the plasticity of soil modified with lime reduces due to modification of natural soil physical properties, three to four days after addition of lime. Compared to natural soil, the soil modified with lime is less sensitive to swelling and shrinking.

Boardman et al. [3] and Parsons et al. [4] investigated development of stabilization and solidification in lime-clay mixes. This occurrence was probably due to reduction of thickness of absorbed water layer in clay soil. The stabilization of soil with lime occurs over time, and in fact, it was not an instantaneous phenomenon. A thorough understanding of the nature and performance time of these effects is still lacking and, in fact, this issue needs further study.

Many studies on the impact of soil stabilization with lime have focused on the long term shear strength of fine-grained soil. Beverley et al. [5] consider that the cement or lime reduces soil-metal mobility through precipitation, adsorption, pozzolanic reactions, and cementation.

Marshall Thompson [6] studied an impact of lime stabilization on the shear strength and elastic properties for three types of illite based soil and one type of montmorillonite soil. In addition, he conducted a set of triaxial low compression tests for stabilized soil with different percentages of lime during the curing time of up to 6 days. He revealed a significant increase in shear strength of soil due to an increase in soil cohesion. Shear strength and stiffness improvements were registered several weeks after addition of lime, and so time is considered to be an important parameter in the analysis of soil stabilized with lime.

The stabilization with lime is employed broadly because of improvement of physical and mechanical properties of soil but, in particular, this stabilisation is used to improve properties of fine-grained soil. The lime based soil stabilization results in significant improvement of all soil strength parameters. However, these effects have been proven to increase during the curing time [7-10].

Blood et al. [11] investigated the freeze–thaw deterioration process using two different test procedures (an open system with water uptake during thawing, and a closed system with only initial water content) to measure the strength, gas permeability, mineralogical and microstructural properties of lime-treated gypseous soil. Their results showed that tested characteristics of soil samples depended considerably on the water available during the freeze–thaw procedure, and on the gypsum content. The water content of soil samples is a key parameter of the stability of earth structures under freeze–thaw conditions.

The impact of soil stabilization with lime is greatly dependent on the plasticity index and soil reactivity. The type and amount of clay particles influence the stability of natural soils and lime addition. Atterberg Limits give us the necessary information on limits linked with the content of water (moisture) in clay and silts. But in soil stabilization with lime, and without attention to an increase or decrease of the liquid limit, a significant reduction of plasticity index (PI) will always occur. In the first hours after adding lime to soil, the particle size distribution will significantly

change, and after flocculaton long term reactions will continue [12-15].
Liu et al. [13] conducted dynamic triaxial tests on cement and lime-modified soils with different blend ratios. Their results showed that after repeated freeze–thaw cycles, the modified soils exhibit better performance than before modification, the cement-modified clay was superior to the lime-modified clay, and all of the soils' mechanical properties were visibly improved. Moreover, an optimal blend ratio was determined. Also, a critical deviator stress attenuation coefficient, ηf, was introduced to determine an optimum modification method and the appropriate mixture proportions to be used when soils were subjected to freeze–thaw conditions.
The impact of curing time on the particle size distribution was quite visible. The addition of lime reduced clay particles rapidly, after the subsidence of reaction. After this process was stopped and after longer periods of time it resulted with the soil becoming more heterogeneous. Density parameters changed with the stabilisation of soil with lime. For a specified water content, the dry unit weight of lime-modified soil was always lower compared to natural soil. At the same time, the increased water content for compaction is needed to achieve the maximum dry unit weight of lime-modified soil. But the overall shape of their compaction curve was almost identical [15].
Bozbi et al. [16] examined the effects of different levels of lime in clay soil during the curing time of 7 to 56 days. Lime was added in the percentages of 4, 6 and 9 of the dry soil size in the scope of soil stabilization. The positive impacts on unconfined compressive strength and initial elastic modulus of lime modified sample with finer soils was observed when compared to coarse-grained soils.
Consoli et al. [17] aimed to quantify the effect of curing time, lime content, dry unit weight, and compaction water content on the strength of a lime treated sandy clay, as well as to evaluate the use of the porosity/lime ratio to assess its unconfined compressive strength. The results showed that compressive strength increased with increasing lime content, decreasing porosity, and increasing curing time.
Garzon et al. [18], presented a new advance in the study of engineering properties and material applications of phyllite. They investigated the stabilization and improvement in engineering properties of a Spanish phyllite clay achieved by the addition of 3, 5 and 7 w% of lime.
Ciancio et al. [19] presented experimental results illustrating the existence of an optimum lime content that maximizes the unconfined compressive strength and stiffness of an engineered lime-stabilized rammed earth and the experimental procedures employed to determine it.
Khemissa et al. [20] showed that the geotechnical parameters values were concordant and confirmed the bearing capacity improvement of natural clay, which was translated by a significant increase in soil strength and durability. However, the best performance was obtained for a mixed treatment corresponding to 8% cement and 4% lime content.

3. Laboratory plan

3.1. Research methodology

This research was made to evaluate the impact of lime powder on the behaviour and resistance parameters of clay soils, a type of kaolinite clay with various percentages of lime. The first challenge in this mixture was the accurate mixing and uniform distribution of these additives in soil. The lack of uniform distribution of these additives resulted from with accumulation and ineffectiveness. According to the conducted studies, the ball mill method has been used to spread lime in soil. This mill is usually in the form of a cylinder in which a certain volume of steel or ceramic balls of specified size are placed. In this regard, the soil mixture with different percentages of lime is placed in dry form inside the ball mill machine for half an hour. In this container, 65 ceramic balls with 1.5 cm average diameter are used as grinding materials. Since the reaction of lime with soil and its setting is a time-dependent phenomenon, the samples were subjected to strength testing at various test duration intervals.

3.2. Materials used

3.2.1. Clay soils

The clay used in this research is made of kaolinite which is produced commercially. This clay was placed for 24 hours in an oven at 100° C until it became completely dry. To eliminate lumps created by exposure to moisture, the clay was spread over a smooth table and then the lumps were crushed by rolling a heavy steel drum over the clay material. The obtained clay was passed through a standard sieve No. 200. Chemical and physical properties of the clay soil used in this research are shown in Table 1a and 1b..

Table 1a. Physicochemical characteristics of kaolinite used in the research (Chemical composition)

Kaolinite	
Chemical compounds	
SiO_2	**47 %**
Al_2O_3	**38.3 %**
Alkali ($K_2O.Na_2O$)	**0.8 %**
Fe_2O_3	**0.5 %**
TiO_2	**-**
CaO	**-**
MgO	**-**
Volatile substances	**13.4 %**
pH	**5.1**
Ion transmission capacity Hydrogen equivalent mg per 100 g dry soil	**2-16**

Table 1b. Physicochemical characteristics of kaolinite used in the research (Physical composition)

Physical composition	
0.002-0.06 mm (particle size)	**6 %**
< 0.002 mm (particle size)	**94 %**
G_s	**2.57**
Liquid Limit	**75**
Plastic Limit	**42**
Plasticity index	**33**
Activity	**0.35**
Unconfined compressive strength [kPa], optimum water content	**350**
Modulus of elasticity [kg/cm^2]	**35**
Optimum water content [%]	**29.5**
Maximum dry unit weight [g/cm^3]	**1.40**
CBR	**1**

3.2.2. Lime powder

Lime is not appropriate for the stabilisation of soils which contain more than two percent of organic materials and also more than a half percent of sulphate soluble in water. The lime used in this research has a unit weight of 2.2 grams per cubic centimetre. The lime grain size varies between 0.002 and 0.2 mm, and its melting temperature is 2650 ° C. The chemical analysis of hydrated lime powder is shown in Figure 1 and Table 2.

Figure 1. Hydrated lime powder

Table 2. Chemical analysis of hydrated lime powder

Chemical analysis	Hydrated lime powde [%]
Calcium oxide	74.80
Magnesium Oxide	0.45
Boric oxide	0.55
Silicon dioxide	0.30
Sulphur trioxide	0.25
Ignition loss	23.4

3.3. Conducted experiments

3.3.1. Power Hydrogen (pH)

pH is a term that indicates an acidic or alkaline condition. It answers to this question: Is the soil acidic, or alkaline, or neutral? The soil pH is one of very significant physiological characteristics of the soil solution and has a significant impact on its physical, chemical, and biological properties. pH is variable and may range between 0 and 14. Thus a pH equal to 7 is neutral, while a higher pH is considered as alkaline, and a lower pH as acidic. To measure the pH value of soil, the following steps must be taken:

- weigh 20 grams of soil sample in a 100 ml beaker
- add 50 ml of distilled water to it
- mix this mixture slowly and alternately for 30 minutes (in 10 minute intervals)
- use a pH meter to measure the pH value of soil.

3.3.2. Atterberg limits

This test as per ASTM D4318 is conducted on kaolinite clay soil samples and samples modified by adding various percentages of lime. The liquid limit and plastic limit tests are conducted for clay with high liquid limit (CH) with and without lime. To produce testing samples, dried clay (dried in oven for 24 hours) is first mixed with a certain percentage of lime (2, 4, 8, 16 percent of lime powder) using a spatula. The obtained mixture is placed in a ball mill. According to the percent of lime, the mixing time lasts between a half an hour and an hour. Some distilled water is added to the mixture according to ASTM D4318 to the mixture to obtain the liquid limit and plastic limit. According to time for lime reaction with soil, the samples to be tested at 3, 7, 28 and 90 days were placed in a sealed plastics container, and were kept in a humid room at a temperature of 23-25 ° C.

3.3.3. Compaction test

Compaction means to reduce the volume of soil in contact by withdrawing the air by force. In this case, the friction between particles and their weight increase and this weight, in fact, is considered as the soil compaction measure. In this research, compaction was tested according to ASTM D 698-78 in order to determine an optimum water content and maximum dry unit weight of soil modified using different percentages of the limeSample preparation for compaction teste was conducted with larger dimensions than for instance for test such as Atterberg Limits.

3.3.4. Unconfined Compressive Strength (UCS) test

The purpose of the unconfined compression test is to quickly obtain an approximate compressive undrained strength of cohesive soils that possess sufficient cohesion to permit testing in an unconfined state. The UCS is the load per unit area at which the cylindrical specimen of cohesive soil fails in compression. Shear strength is a half of the value of the unconfined compressive strength. This test can be called a triaxial test with confining pressures equal to zero, which is performed according to the ASTM D2166.

In fact, the shear strength of cohesive soils is caused by two types of resistance: frictional resistance and cohesion resistance. In this research, the controlled strain test was used as it is simpler than the controlled stress test. The strain in this test was between 0.5 to 2 percent per minute. The samples used in this test were prepared of natural clay and clay modified with lime. To achieve the maximum strength, the samples were prepared taking into account the calculated optimum water content from compaction tests. So, the calculations were based on the axial strain and stress, while the ultimate stress value was obtained from the stress - strain curve.

3.3.5. CBR

This test is the most common method for determining relative resistance of soils for road construction purposes. By using the results of this experiment, the bearing capacity of the soil and all pavement layers, such as the foundation and base course layers, can be determined, and the thickness of these layers can be achieved based on these results. This test as per ASTM D1883-87 was conducted for clay soil modified with lime. In this research, samples were treated as follows:

- clay soil and lime were oven-dried for 24 hours
- clay soil and dried lime were combined in various percentages
- distilled water was added to the mixture
- to determine long time impact of lime on the soil, samples were stored in sealed plastic containers at ambient temperature
- compaction test aimed at determining an optimum water content was conducted at specified intervals
- appropriate compositions of soil and lime were mixed with water and, at that, an optimum water content for compaction test was specified in line with the CBR test.

4. Results and discussion

4.1. PH test

The pH value of soil increased with the addition of lime. This alkaline environment enhances the solubility of silica and alumina components and in response to available calcium, calcium silicate hydrate and calcium aluminate hydrate are formed. These sustainable compounds are very similar to the compounds observed in Portland cement concrete.

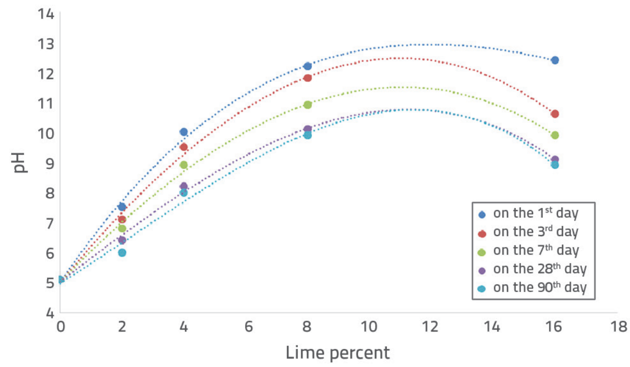

Figure 2. Changes in pH of clay modified with various percentages of lime powder during curing time

According to Figure 2, the addition of lime rapidly increased the PH value of soil. These changes have increased the maximum to 12.4. After a few days, the PH value of soil with fewer changes improved, which is due to the creation of stable compounds after the reaction of lime in soil subsided.

4.2. Atterberg limit tests

The impact of soil stabilization with lime is greatly dependent on the plasticity Index and soil reactivity. The Atterberg Limit gave us the necessary information on limits linked with the content of water (moisture) in clay and silts. In this research, the effects of various percentages of lime were investigated based on liquid limit and plastic limit of kaolinite clay soil. Changes in Atterberg Limits are presented in Figure 3.

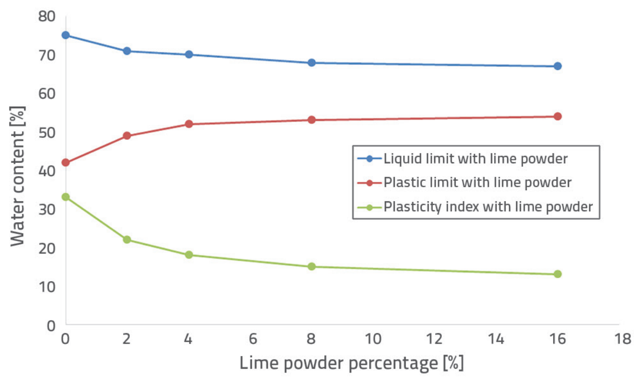

Figure 3. Modified clay Atterberg limits with various percentages of lime at the first day

The liquid limit decreased after addition of lime to soil. But regardless of such increase or decrease in liquid limit, the severe decline in plasticity index (PI) was registered. The addition of lime to soil caused sudden reduction of the soil plasticity index. By adding lime to the soil, the plastic limit (PL) increased with the increase of the amount of lime added. This pattern continues until the added lime allowed limit. After that, the addition of more lime will not have a remarkable effect on the increase in plastic limit and, also, it is not economical. This limit amount is the lime fixation point (LFP).

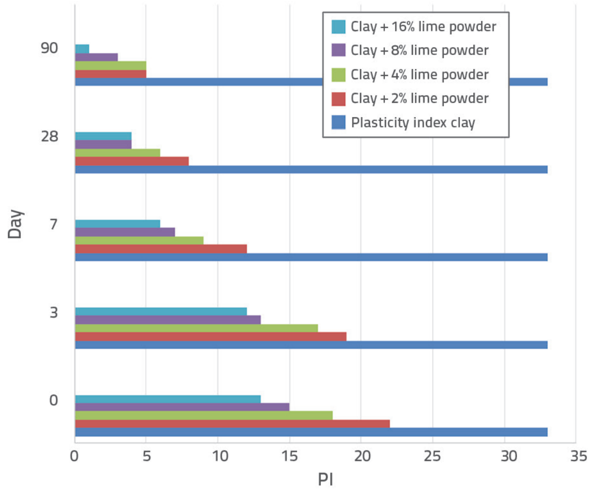

Figure 4. Modified clay plastic sign with various percentages of lime powder during curing time

Plasticity index (PI) changes observed during curing time are shown in Figure 4. After the lime reaction with clay soil subsided and after soil stabilization, the plasticity index declined.

4.3. Compaction test

Compaction parameters are modified by lime stabilization. For a specified water content, the dry unit weight of lime-modified soil is less than that of natural soil. According to Table 3, at the same time, the maximum dry unit weight of lime-modified soil requires greater water content for compaction. In this research, the compaction test was performed on all modified samples. The fact that lime is added to soil has not changed the standard form of the fine-grained soil compaction curve. In fact, the optimum water content of lime-stabilized soil is always greater than that of the initial soil. By changing the particle size of clay to obtain more resistant larger particles, the maximum dry unit weight of modified soil increases a few days after the lime and soil curing time.

Table 3. Compaction test results for clay soil with different percentages of lime powder

Day	Sample introduction	Naming	ω_{opt}	γ_d [g/cm^3]
0	Kaolinite clay	K0	29.5	1.40
	Clay + 2% Lime powder	KP02	32.4	1.30
	Clay + 4% Lime powder	KP04	32.8	1.27
	Clay + 8% Lime powder	KP08	33	1.23
	Clay + 16% Lime powder	KP016	33.7	1.17
3	Kaolinite clay	K3	29.5	1.40
	Clay + 2% Lime powder	KP32	27.4	1.51
	Clay + 4% Lime powder	KP34	27.3	1.53
	Clay + 8% Lime powder	KP38	26.9	1.56
	Clay + 16% Lime powder	KP316	26.5	1.60
7	Kaolinite clay	K7	29.5	1.40
	Clay + 2% Lime powder	KP72	27.1	1.55
	Clay + 4% Lime powder	KP74	27	1.56
	Clay + 8% Lime powder	KP78	26.9	1.60
	Clay + 16% Lime powder	KP716	26.5	1.62
28	Kaolinite clay	K28	29.5	1.40
	Clay + 2% Lime powder	KP282	26.9	1.60
	Clay + 4% Lime powder	KP284	26.9	1.63
	Clay + 8% Lime powder	KP288	26.7	1.65
	Clay + 16% Lime powder	KP2816	26.3	1.67
90	Kaolinite clay	K90	29.5	1.40
	Clay + 2% Lime powder	KP902	26.4	1.65
	Clay + 4% Lime powder	KP904	26.2	1.66
	Clay + 8% Lime powder	KP908	26	1.68
	Clay + 16% Lime powder	KP9016	25.9	1.68

4.4. Unconfined Compressive strength (UCS) test:

The stabilization with lime is widely employed to improve physical and mechanical properties of various types of soils but, in particular, it is applied to improve properties of fine-grained soils. The shear strength and stiffness improvement was registered several weeks after addition of lime and so the time is considered an important parameter in the analysis of soil stabilized with lime. For LFP (Plastic limit charts), unconfined compressive strength tests are preformed on clay soil samples, and the corresponding results are presented in Figures 5-9. By adding lime, the maximum unconfined compressive strength of modified soil was increased, and this trend continued at a higher rate with an increase in curing time.

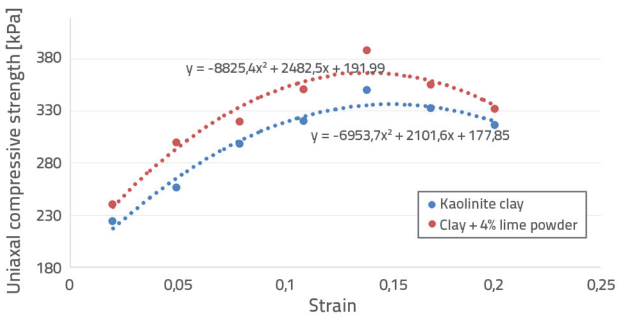

Figure 5. Stress-strain curve for modified soil with LFP in the first day

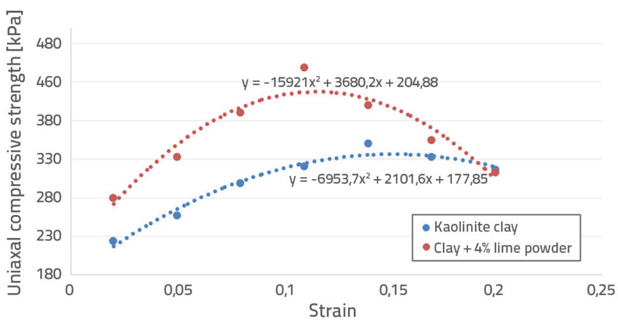

Figure 6. Stress-strain curve for modified soil with LFP in the third day

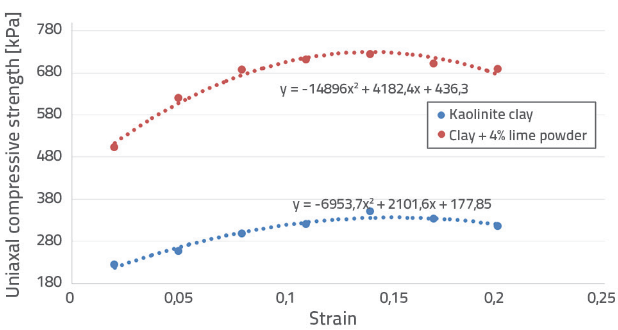

Figure 7. Stress-strain curve for modified soil with LFP in the seventh day

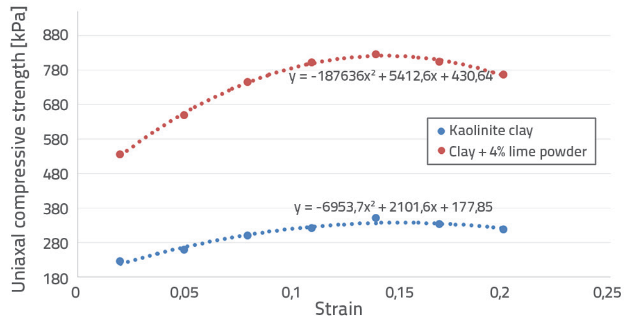

Figure 8. Stress-strain curve for modified soil with LFP in the twenty-eighth day

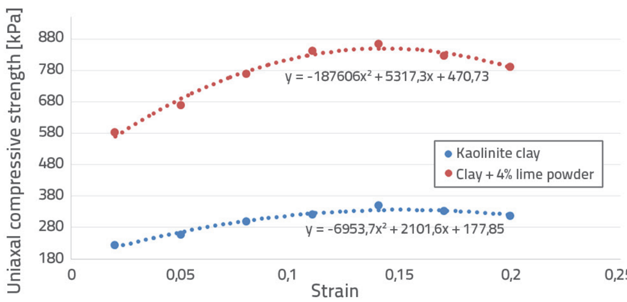

Figure 9. Stress-strain curve for modified soil with LFP in the ninetieth day

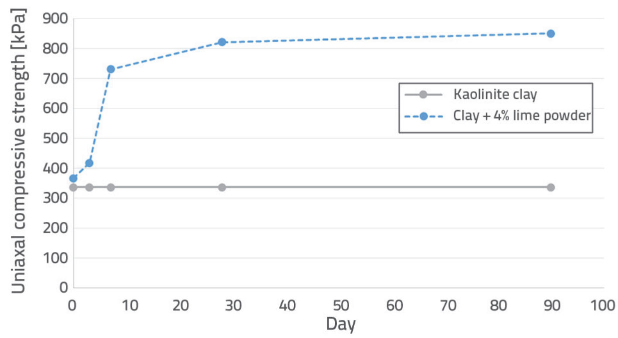

Figure 10. Maximum unconfined compressive stress (q_u) changes during curing time for lime-modified soil

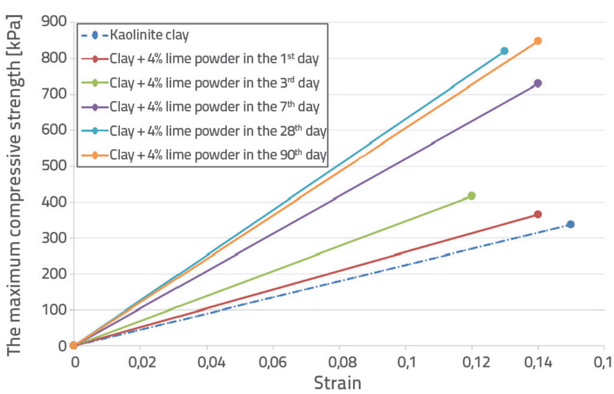

Figure 11. Maximum change of modulus for lime-modified soil at maximum unconfined compressive strength point during curing time

As shown in Figures 10 and 11, the maximum unconfined compressive stress (q_u) changes over the curing time. The change of the maximum modulus for lime modified soil at corresponding points is analysed by the maximum unconfined compressive strength testing. At the same time, the modulus of sample increases with an increase in curing time, and this trend continues until 28 days of cure, after which the trend does not change significantly. The strength of modified samples increases with an increase in the reaction of lime in the soil.

4.5. CBR tests

The change in bearing capacityof the lime-modified soil during the curing time was analysed. The addition of lime caused a substantial increase in the CBR value of soil. According to test results, after 28 days, the CBR value of soil amounted to more that 14 %, and this value continued to increase until 90 days but at a lower rate, as shown in Figure 12.

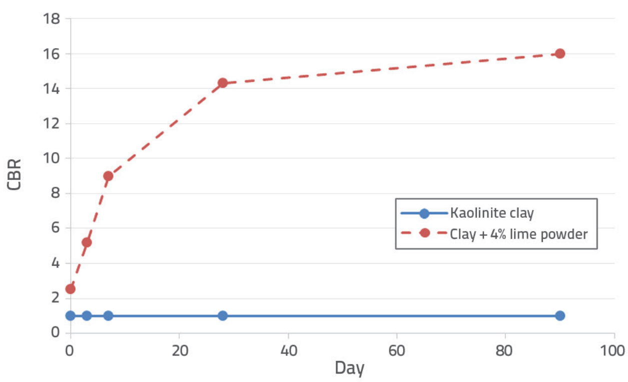

Figure 12. Change of CBR value for modified soil samples, with optimum percentage of lime during curing time

5. Conclusions

Low bearing lay soils can be stabilised by addition of various additives. Due to its low cost, availability, and positive impact on bearing capacity lime has been traditionally applied as a mean to stabilise poor soil. The addition of 2.4 and 8 percentages of lime to kaolinite clay soil over the curing time from the first day until the ninetieth day was investigated in this research. The following laboratory analyses were conducted: pH, Atterberg limits, dry weight, unconfined compressive strength tests (UCS), and CBR tests. According to the results, the pH value of modified soil decreased over the curing time. It is a physiological characteristic of the soil solution. A lower pH value would be a sign of structured soil. According to the Atterberg limits test, the plasticity index of the lime powder stabilized soil decreased and an optimum percentage of lime, pointing to economical use, was achieved as the lime fixation point. In the compaction test, the optimum water content of lime-stabilized soil is in the beginning greater than that of the initial soil. Over the curing time, the particle size of clay changed to larger particles and the maximum dry unit weight of the modified soil increased. Lime-modified soil exhibited an increase in the maximum unconfined compressive strength, and this trend continued with the curing time but at a higher rate. Indeed, the Young's modulus of lime-powder modified samples increased. Also, CBR test showed an Increase amounting to more than 14 %

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