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Influence of traditional and alternative additives on the physical and mechanical properties of clayey soil

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Research Paper

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Influence of traditional and alternative additives on the physical and mechanical properties of clayey soil

This study considered the effects of different types of additives on the physical and mechanical characteristics of clayey soil using a chemical stabilisation technique. Under laboratory conditions, samples of the clayey soil mixture with selected additives at percentages of 3 %, 5 %, and 7 % were prepared and tested at time intervals of 3, 7, and 28 d after the treatment. For the prepared samples, the influence of each additive on the change in the uniaxial compressive strength, Atterberg limits, and pH values was analysed. Based on the obtained results, the optimal amount of each additive for the treated soil was determined. Using the optimal additive contents, an additional series of tests to investigate the changes in the modulus of compressibility and void ratio of the treated soil were performed after 3, 7, and 28 d, as well as changes in the California bearing ratio and swelling value after 7 and 28 d. The obtained results reveal that, depending on the amounts of additives in the mixture and the time interval of the test, the physical and mechanical properties of the treated clayey soil could be considerably improved.

Key words:
clayey soil, chemical stabilization, additives, physical and mechanical properties, pH value

Prethodno priopćenje

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Utjecaj tradicionalnih i alternativnih dodataka na fizičko-mehaničke karakteristike glinovitog tla

U radu su razmatrani utjecaji različitih dodataka na promjene fizičko - mehaničkih karakteristika glinovitog tla primjenom tehnike kemijske stabilizacije. U laboratorijskim uvjetima su pripremljeni uzorci mješavine glinovitog tla s izabranim dodacima s postotkom udjela od 3 %, 5 % i 7 %, koji su potom ispitani u različitim vremenskim intervalima, 3, 7 i 28 dana nakon tretmana. Za tako pripremljene uzorke provedena je analiza utjecaja svakog od razmatranih dodataka na promjenu jednoosne tlačne čvrstoće, Atterbergovih granica i pH-vrijednosti. Na osnovi dobivenih rezultata određena je optimalna količina svakog dodatka za tretirano tlo. S optimalnim udjelom dodatka urađene su dodatne serije ispitivanja promjene modula stišljivosti i koeficijenta pora tretiranog tla nakon 3, 7 i 28 dana, odnosno promjene kalifornijskog indeksa nosivosti i vrijednosti bubrenja nakon 7 i 28 dana. Dobiveni rezultati pokazuju da se u zavisnosti od količine dodatka u mješavini i vremenskog intervala ispitivanja fizička i mehanička svojstva tretiranog glinovitog tla mogu poboljšati u znatnoj mjeri.

Ključne riječi:
glinovito tlo, kemijska stabilizacija, dodaci, fizičko-mehanička svojstva, pH-vrijednost

1. Introduction

In civil engineering, various methods for improving the geotechnical properties of soils have been successfully applied to construction. This mostly refers to soil materials whose characteristics do not meet the predefined criteria in terms of load-bearing capacity and stability. Soil stabilisation techniques for improving soil characteristics have developed , and the invention of new materials has contributed to increasing the efficiency of these methods. Many engineers have indicated that chemical stabilisation techniques are not only the best method of soil stabilisation in terms of cost-effectiveness and efficiency, but also from an ecological perspective [1].

During chemical stabilisation, soil properties are improved through two essential processes: cation exchange and pozzolanic reactions. Previous studies have extensively investigated the basic mechanisms of chemical stabilisation [2, 3]; however, the potential of each soil type must be examined separately. In clayey soil, the mineralogical composition of clay significantly influences the physical and mechanical properties of the soil [4]. Lime and cement are traditional chemical additives [5, 6]. At the end of the 20th century, fly ash was widely used as an additive [7] because it was considered a useful waste product [8, 9]. In practice, one of the three abovementioned stabilisers is used in almost 80 % of all cases [10]. However, although the use of cement improves the engineering properties of soil, its application is becoming less prevalent because of its increasing price and environmental concerns associated with its production [11-13]. Therefore, many researchers are investigating alternative materials that are suitable for both economic and ecological applications [14]. Common problems associated with the use of commercial additives include the curing time and brittleness of soil treated with pozzolans, which can cause cracks when the soil is subjected to dynamic loading [15]. Because alternative reagents have been successfully applied in other branches of civil engineering [16], there is an obvious need for their use in the field of geotechnics [17-25].

This study aims to examine the effects of different chemical stabilisers on the physical and mechanical properties of clayey soil using a chemical stabilisation technique. Lime ($Ca(OH)_2$), a traditional additive, as well as alternative additives, such as magnesium carbonate ($MgCO_3$), sodium silicate (Na_2SiO_3), and potassium hydroxide (KOH), were considered. For the laboratory tests, in accordance with national standards considering European norms (EN Standards), the soil samples were treated with different percentages of additives in the mixture with clay to determine their optimal content. In previous studies, it was concluded that the addition of lime at percentages of 1 % to 3 % would be sufficient to reduce the plasticity of clayey soil [5], and a lime addition of 2 % to 8 % could be used to achieve permanent stabilisation and cementation [26]. Soil modification was assessed by monitoring changes in the Atterberg limits and uniaxial compressive strength (UCS) of the samples. In addition to changes in the physical and mechanical characteristics, chemical modifications were also monitored for all treated soil samples. The pH of the soil treated with each additive was measured. When an additive with a sufficient amount of water is added, the pH value of the soil should increase, thus contributing to pozzolanic reactions and permanent changes in the soil composition [27]. Based on the aforementioned examinations, the optimal content was determined for each stabiliser, and additional tests were performed. Changes in the modulus of compressibility (Mv) and void ratio (e), as well as in the CBR and swelling values, were monitored over time.

2. Materials and methods

2.1. Properties of soil

Clayey soil along the route of the E-80 Niš-Dimitrovgrad Highway (near Crvena Reka) in the southeastern part of the Republic of Serbia was used in this study. A landslide was triggered during the highway construction at this location. Soil samples were collected from the depth where the sliding surface was registered, and the improvement of the geomechanical properties of this soil after mixing with additives was investigated. The tests were conducted according to national standards at the Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of the University of Niš.

Figure 1 shows the mineralogical composition of the natural clayey soil used in this study, which was determined by X-ray diffraction (XRD). As shown by the XRD spectrum, the investigated soil in its natural state consisted of various minerals, among which calcite and quartz were dominant. In addition, clay minerals such as illite, montmorillonite, and clinochlore, were also present. Kaolinite was not identified in the clayey soil.

The geomechanical properties of the natural clayey soil used in the experiment were determined by corresponding laboratory tests and are shown in Table 1.

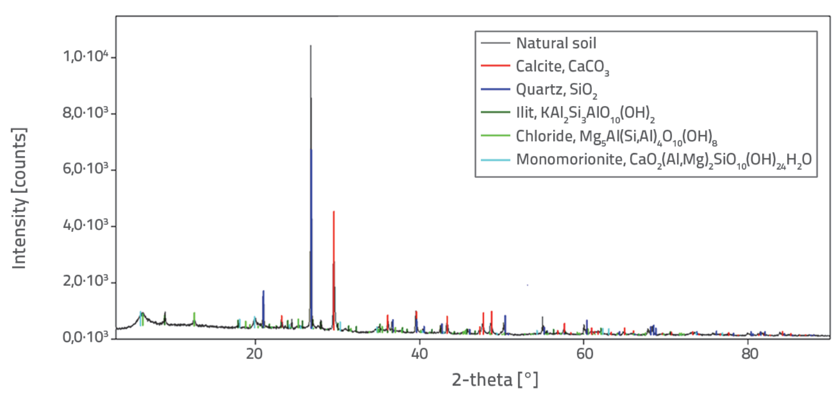

Figure 1. Mineralogical composition of the natural clayey soil obtained by XRD analysis

Table 1. Properties of the clayey soil used in the experiments

Property of soil	**Symbol** [unit]	**Value**
Particle density	Gs [–]	2.705
Grain size distribution	Gravel [%]	1.2
	Sand [%]	4.9
	Silt [%]	40.6
	Clay [%]	53.3
Coefficient of uniformity	Cu [–]	8.0
Coefficient of curvature	Cc [–]	2.0
USCS soil classification	Symbol [–]	CL
Maximum dry density	MDD [g/cm^3]	1.903
Optimum moisture content	OMC [%]	18.5
Uniaxial compressive strength	UCS [kPa]	205
Liquid limit	LL [%]	49
Plastic limit	PL [%]	23
Plasticity index	PI [%]	26
pH value	pH (–)	9.5
Modulus of compressibility	Mv [MPa]	12.945
Void ratio	e [–]	0.554
California bearing ratio	CBR [%]	2.71
Swelling	s [%]	2.91

Table 2. Properties of additives considered in this study.

Property [unit]		**Additive**			
		Lime $Ca(OH)_2$	**Magnesium carbonate** $MgCO_3$	**Sodium silicate** Na_2SiO_3	**Potassium hydroxide** KOH
Compound [%]	CaO	71.01	–	–	–
	MgO	–	47.0	–	–
	SiO_2	–	–	28.00	–
	Na_2O	–	–	8.00–9.00	–
	K_2O	–	–	–	84.00
Specific mass [g/cm^3]		2.21	2.96	1.37	2.04
pH value [–]		12.60	10.00	10.80	13.50

2.2. Additives

Lime ($Ca(OH)_2$) is a versatile and economical solution for chemical soil stabilisation, primarily because of its ability to neutralise soil acidity by increasing the soil pH and improving its engineering properties. Lime has been successfully applied for the stabilisation of most soil types. Soils with a PI > 15 % are considered particularly suitable for lime stabilisation [5]. The addition of an optimal amount of lime significantly increases the soil strength and improves the stability and bearing capacity of the soil, whereas it reduces the soil plasticity, permeability, and swelling potential [28-30]. Commercial hydrated lime CL-90-S was used in this study for testing purposes. In addition to their numerous advantages, traditional additives also have certain disadvantages; therefore, numerous researchers have proposed compounds based on magnesium [31-33], sodium silicate [34, 35], and potassium [36] as alternative additives. Alternative additives have been shown to significantly improve the characteristics of expansive and sandy clays [37-39]. Therefore, in this study, we examined the effects of traditional and alternative additives on clayey soils collected from a landslide area. The basic characteristics of the additives that were used, along with the main compounds of each additive, are presented in Table 2.

2.3. Experimental research methods

To evaluate the effects of the chemical stabilisation of clayey soil when considering a variety of additives, changes in the UCS, Atterberg limits (Liquid Limit (LL) and Plastic Limit (PL)), and the associated plasticity index (PI) were considered. Each additive was added to the natural soil at percentages of 3 %, 5 %, and 7 % of the dry weight of the soil sample. Samples for the UCS test were prepared under laboratory conditions in accordance with the corresponding national standard [40] with optimal water content and compacted using the standard Proctor test at an energy of 600 kNm/m^3. The Atterberg limits were determined based on national standards [41]. To determine the durability of the effects of chemical stabilisation on the treated clayey soil, the samples were kept in plastic foil until testing at 3, 7, and 28 d after the chemical treatment.

Based on the obtained results of the above-mentioned tests, the optimal content for each of the considered additives in the mixture with clay was determined. Therefore, additional tests were conducted on samples with the optimal additive contents considering the variations in the modulus of compressibility, void ratio, California bearing ratio (CBR), and swelling potential of the treated soil. Using an oedometer, the changes in the modulus of compressibility and void ratio [42] were tested on samples with a height of 20 mm and diameter of 70 mm, where the maximum load was 400 kPa. All the samples were saturated for 24 h before the test. Furthermore, the change in the CBR value [43] was examined. The samples were compacted at the optimum moisture level obtained from the Proctor tests. Prior to the test, the samples were treated in water for 96 h, and the swelling value of the soil was measured using a comparator. Additional tests in the oedometer were performed after 3, 7, and 28 d, whereas the CBR test was performed 7 and 28 d after adding the additive. Results after 3 d (72 h) after the treatment could not be obtained because, as previously explained, the standard test procedure included curing the samples in water for 4 d (96 h)).

Special attention should also be paid to the chemical changes that occur in the soil during stabilisation with additives. Therefore, in addition to changes in the physical and mechanical characteristics of the soil, changes in the chemical properties of the soil were also monitored via variations in the pH. A review of the literature revealed that changes in the pH can be observed immediately after mixing the soil and additives and that it does not change significantly over time [44]. Based on the conclusions of the aforementioned research, to determine the change in pH of the treated soil, three representative testing periods were selected: 1, 3, and 28 d after treatment. The soil properties were examined in a water solution (soil: water = 1 : 2.5). For this test, 10 g of dry soil was added to 25 mL of distilled water and mixed for 10 min. After approximately 30 min, when the solution was clear, the electrodes were immersed in the solution, and the pH value was determined.

3. Results and analysis

3.1. Uniaxial compressive strength

Figure 2 shows the UCS of the soil. The results represent the mean UCS values of three treated soil samples. Each of the applied additives contributed to an increase in the UCS, with lime and magnesium carbonate proving to be the most effective. The addition of lime resulted in the highest UCS values after chemical treatment. Regardless of the amount of additive, a significant improvement in the soil properties was observed over time. Therefore, with the addition of 3 % lime, the UCS value doubled 3 d after soil treatment from 205 kPa in the original soil to 435 kPa. After 7 d, the UCS value increased to 533 kPa, and after 28 d, it increased by up to four-times the initial value (896 kPa). A similar trend of increasing UCS values with time was observed for the samples with 5 % and 7 % lime. Furthermore, a particularly significant improvement in this soil property was observed when the lime content in the clay

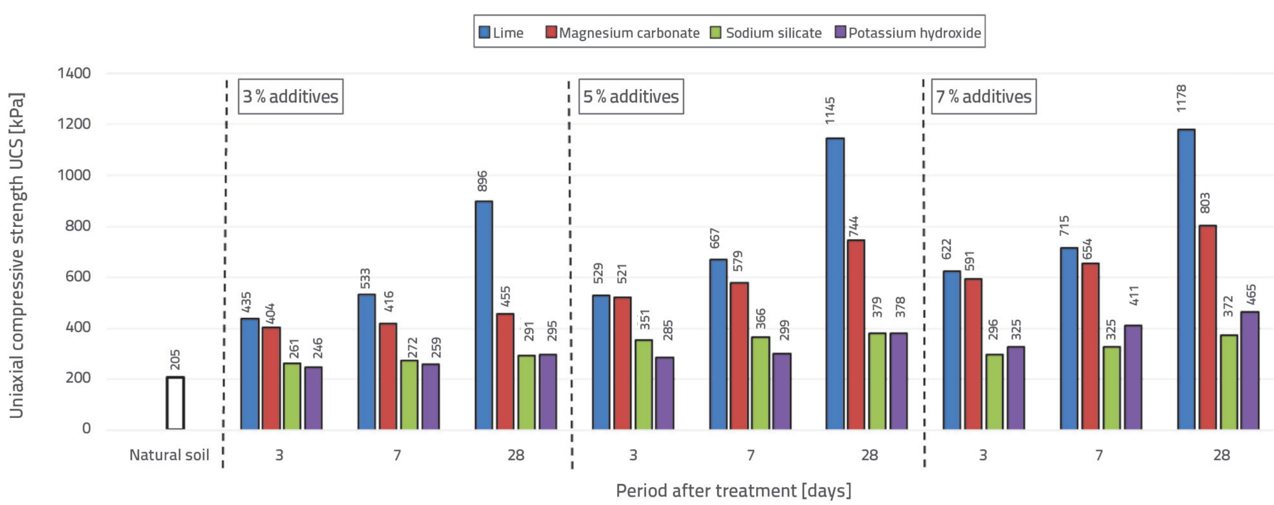

Figure 2. Changes in the soil UCS values for additives with increasing additive content over time

mixture was increased from 3 % to 5 %, whereas an increase of 7 % did not contribute to a more significant difference compared with the results for the case of 5 % lime addition. For example, after 28 d, the UCS value with the addition of 3 % lime increased by approximately four times (896 kPa); with the addition of 5 % lime, the increase was approximately 5.5 times (1145 kPa), whereas the UCS value with the addition of 7 % lime was 5.75 times higher than the initial value for the natural soil (1178 kPa). This indicated that the optimal lime content was 5 %.

At 3 d after treatment with magnesium carbonate, UCS values similar to those observed upon the addition of lime were observed for all additive contents of 3 %, 5 %, and 7 %. However, the improvement in soil properties over time was not as pronounced as that in the case of lime addition. Therefore, with the addition of 3 % magnesium carbonate, the UCS increased to 404 kPa at 3 d after treatment. After 7 d, the UCS value increased to 416 kPa, and after 28 d, it was 455 kPa (approximately 50 % lower than that of lime). For samples with 5 % and 7 % magnesium carbonate, a slightly higher trend of increasing UCS values over time was noticeable (35 % and 30 % lower UCS values compared to lime, respectively). In addition, similar to the samples with added lime, a greater increase in the UCS value was observed when the magnesium carbonate content increased from 3 % to 5 % than when it increased from 5 % to 7 %. For example, after 28 d, the UCS value with the addition of 3 % magnesium carbonate increased by approximately two-times (455 kPa); with the addition of 5 % magnesium carbonate, the increase was approximately 3.5-times (744 kPa), whereas the UCS value with the addition of 7 % magnesium carbonate was four-times higher than the initial value for the natural soil (803 kPa). Therefore, the optimal content of magnesium carbonate from the perspective of soil properties was 5 %.

The measured UCS values with the addition of sodium silicate or potassium hydroxide were significantly lower than those obtained with the addition of lime and magnesium carbonate; however, their application resulted in an increase in soil strength. The maximum UCS value for sodium silicate was obtained with the addition of 5 % sodium silicate after 28 d (379 kPa). The results also showed that slightly higher UCS values were obtained with the addition of 5% sodium silicate than with the addition of 7 % silicate at the corresponding time intervals. This indicates that the optimal content of this additive from this perspective is 5 %.

The samples treated with potassium hydroxide provided a maximum UCS value at 7 % after 28 d (465 kPa). In contrast to the three previously mentioned additives, for all the considered time intervals, an almost constant increase in the UCS value with increasing potassium hydroxide content was observed. Therefore, the optimal content of this additive in this study was determined to be 7 %; however, given the approximately constant increase in UCS values with increasing potassium hydroxide content, further research using higher percentages of this binder in the mixture should be conducted to determine its optimal additive content in the clay mixture.

3.2. Atterberg limits

During the Atterberg limit tests, changes in the LL and PL values were registered, based on which the corresponding PI was calculated (PI = LL - PL). The results are shown in Figs. 3 and 4.

Figure 3 shows the changes in the soil LL and PL values for the considered additives with increasing additive content over time. In this figure, the lower part of the columns (solid colour) shows the measured LL values, whereas the upper part of the columns (dotted colour) represents the measured PL values. There were no large oscillations in the change in LL, regardless of the type of applied additive or the time interval of soil testing after treatment. The maximum increase in LL was recorded with the addition of 7 % magnesium carbonate after 28 d (LL = 54 %). However, a change in the PL value was evident in all tested samples. Considering that the LL values remained unchanged, the trend of increasing PL values had a positive effect on the soil, as the soil maintained a semi-solid state of consistency even with increased water content. It was also observed that

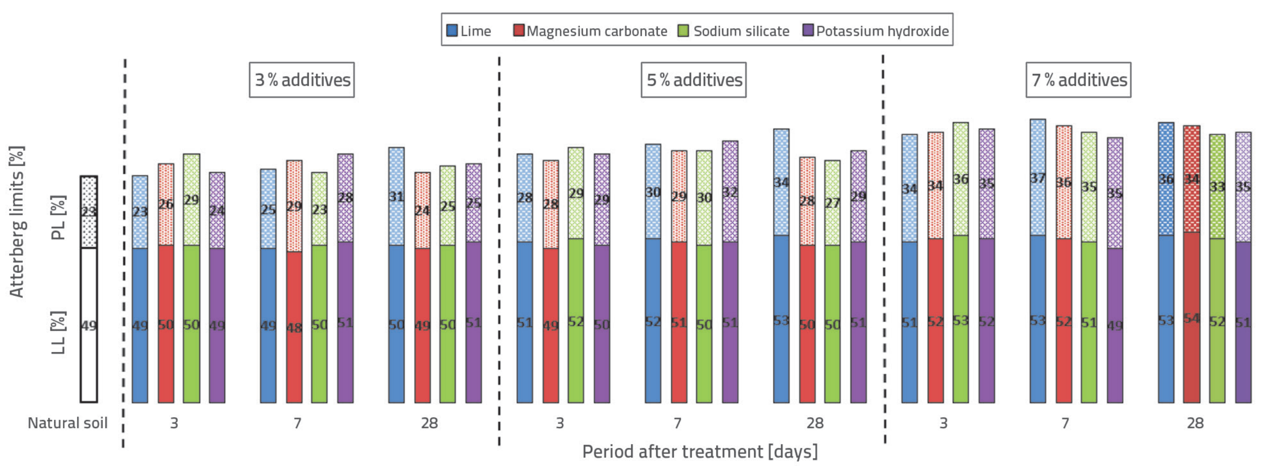

Figure 3. Change in the soil LL and PL values for the considered additives with increasing additive content over time

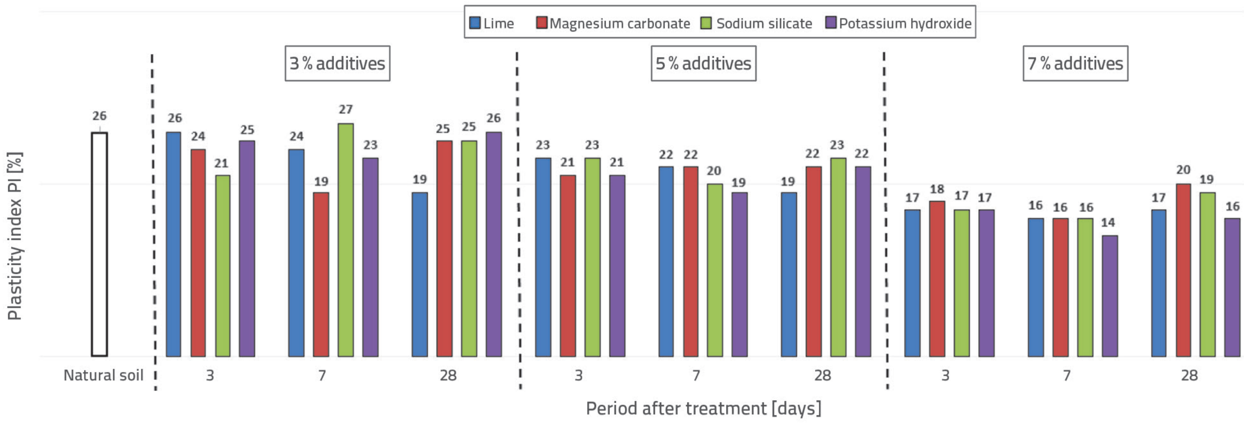

Figure 4. Change in the soil PI value for the considered additives with increasing additive content over time

for each of the considered additives, the greatest increase in the PL value was achieved with an addition of 7 % additive.

Figure 4 shows that with the addition of 7 % additive, the PI values were more affected by the percentage share of the additive than by the time elapsed after the treatment. However, with a smaller percentage of additive in the mixture (3 %), the oscillations in the results over time were much more pronounced. Given that the PI value is a computational value that depends on two parameters (LL and PL), the results obtained for PI values involve the modification of both quantities that change independently of each other. Such an oscillatory trend in the change in the value of PI indicates that an unequivocal conclusion about the influence of stabiliser addition on clay consistency cannot be made solely based on this parameter. Nevertheless, this parameter demonstrates the effect of each additive on the decrease in the PI value of clayey soil for all selected time intervals as the amount of additives in the soil increased.

As mentioned above, the success of the application of a specific additive is primarily reflected in the increase in the UCS and decrease in PI of the soil. Based on the obtained results, as well as the pH values observed before and after the chemical treatment of the soil, the optimal values of each of the considered additives were determined for further tests.

3.3. pH value

High soil pH values enable pozzolanic reactions between additives and soil, which form new compounds that contribute to soil binding and stabilisation. For example, when lime is added to clayey soil, calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH) form gel-like materials with high binding properties.

The change in the pH of the tested clayey soil with increasing additive content over time is shown in Table 3. The results indicate that all the additives used in this study contributed to

Table 3. Change of the soil pH value for the considered additives with increasing additive content and over time

Soil			pH value		
			After 1 d	After 3 d	After 28 d
Natural soil			9.5	9.5	9.5
Soil treated by the chemical stabilization technique	Lime ($Ca(OH)_2$)	3 %	12.1	12.0	12.0
		5 %	12.5	12.5	12.4
		7 %	12.8	12.8	12.7
	Magnesium carbonate ($MgCO_3$)	3 %	10.9	10.7	10.7
		5 %	12.1	12.1	12.0
		7 %	12.7	12.7	12.6
	Sodium silicate (Na_2SiO_3)	3 %	11.7	11.7	11.7
		5 %	12.0	12.0	12.0
		7 %	12.1	12.1	12.0
	Potassium hydroxide (KOH)	3 %	12.0	11.8	11.8
		5 %	12.2	12.2	12.1
		7 %	12.5	12.4	12.3

an increase in the pH of the clayey soil. An increase in the pH value was noted in the initial period (24 h) after mixing with the additive, after which the pH values remained constant or decreased slightly, confirming the previously mentioned conclusions of relevant studies [44]. The results of the treated soil clearly demonstrate the potential of alternative additives for permanent changes in the chemical properties of the soil.

The optimal additive content is the percentage share of the additive in the mixture with the soil that provides the greatest improvement and stabilisation of the soil. The best effect of the additive was achieved at a soil pH of 12.4, whereas for pH values above 12.4, the stability of the clay crystal lattice was disturbed [45-47].

Accordingly, considering both the soil UCS values (Figure 2) and pH values (Table 3), it was concluded that the optimal potassium hydroxide content as an additive was 7 %, whereas for the other additives, it was 5 %. The determined optimal additive contents were used to conduct additional tests, and the results are presented in the following subsections.

3.4. Modulus of compressibility and void ratio

The modulus of compressibility (Mv) was determined using an edometric test for four load levels (0-50, 50-100, 100-200, and 200-400 kPa). The recorded Mv values at the maximum load (200-400 kPa) are shown in Figure 5. The clayey soil samples were tested at time intervals of 3, 7, and 28 d after treatment with the optimal additive content for each of the four considered additives. According to the obtained results, it can be concluded that each of the additives contributed to an increase in the value of Mv, whereby the maximum values were reached seven days after treatment. Given this time interval, the highest increase in the value of Mv was achieved by adding a traditional additive, namely lime (38.392 kPa), as this value was increased by approximately three times compared to the natural soil. Considering the alternative additives, the highest values were obtained with the addition of magnesium carbonate (2.5-times higher Mv than that of natural soil), whereas with the addition of sodium silicate or potassium hydroxide, the Mv were approximately doubled. After 28 d, for each of the considered additives, the measured values of Mv were lower by 3-9 % compared to the values achieved after 7 d. Therefore, in the case of each of the selected additives, the trend of increasing the value of the compressibility modulus was most pronounced in the period up to 7 d after the treatment, and a slight decrease in this value was noticeable until 28 d, which should stabilize over time. This trend of a slight decrease in Mv is not unusual, and it has been confirmed in other studies [8]. Overall, each of the considered additives resulted in a significant increase in Mv compared to its initial value, which effect is permanent (i.e., long-term stabilisation was confirmed).

Based on the results of the oedometer test, the values of the void ratio (e) were calculated and are shown in Figure 6. For each of the considered additives, the values of the void ratio in the first 7 d increased slightly compared to the natural soil state, and at 28 d, the void ratio decreased significantly. This result is unsurprising because the compounds that are formed via the reaction of the soil and additive have a smaller volume than the soil particles in their natural state. The formed compounds, in addition to being characterised by very high strength, are porous materials that contribute to the increase in total porosity during the initial days of the chemical stabilisation process. This phenomenon was indicated in a study by Eyo et al. [48], wherein after 7 d of curing, physically visible changes in the porosity of the stabilised samples were present, accompanied by the development of pores with a relatively large diameter ranging between 4 and 40 μm.

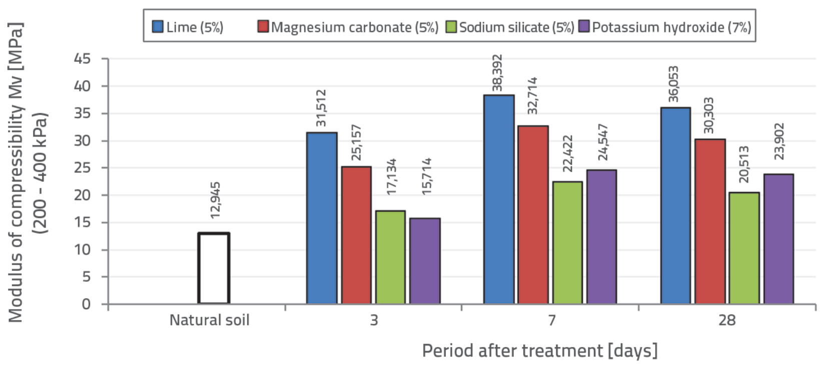

Figure 5. Change in soil Mv values over time, given the optimal content of the considered additives

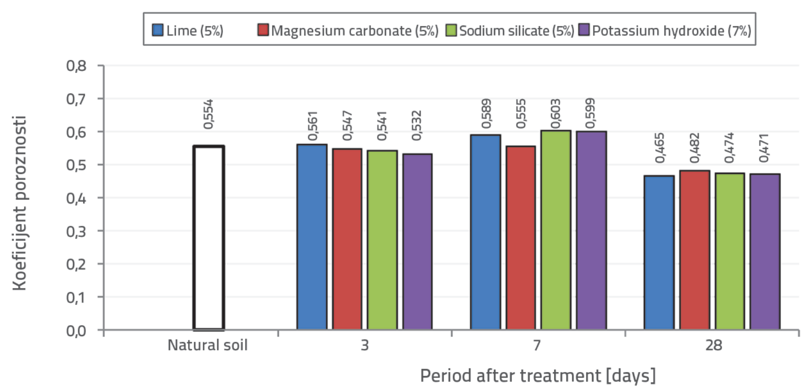

Figure 6. Change in soil void ratio over time given the optimal content of the considered additives

This trend was subsequently reduced probably owing to the formation of bonds between soil particles in the pozzolanic reactions.

3.5. California bearing ratio and swelling

Clayey soils are characterised by a low CBR; therefore, a low CBR value is one of the common criteria for replacing soil materials or improving natural soil conditions for construction purposes. The results of this study show that each of the considered additives, both traditional and alternative, contributed to an improvement in the CBR over time. The CBR values with the addition of the optimal amounts of each of the considered additives are shown in Figure 7. Compared to the soil properties in their natural state, the greatest improvement was observed with the addition of lime (increasing the CBR value by up to seven times), and a significant improvement was achieved with the addition of magnesium carbonate (with a CBR value increase of three times). The slightest improvement was achieved with the addition of silica silicate after 7 d (increase in the CBR value of 1.5 times), as well as potassium hydroxide after 28 d (increase in CBR value by up to two times). In engineering practice, a CBR value of greater than 5 % is the most frequently required condition for clayey soils, and the obtained results indicate that each of the considered additives can be applied to stabilise clayey soils according to this criterion.
Considering the standards for evaluating the swelling (s) of soil, the soil samples were immersed in water for 96 h before testing

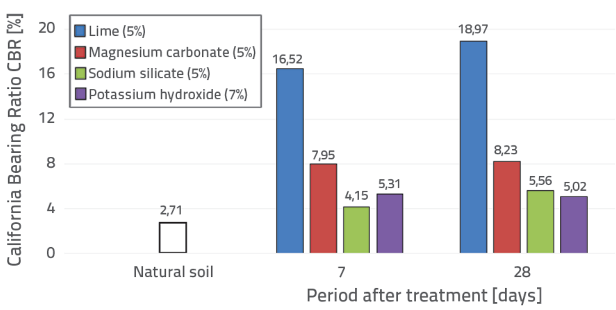

Figure 7. Change in soil CBR over time at the optimal additive contents

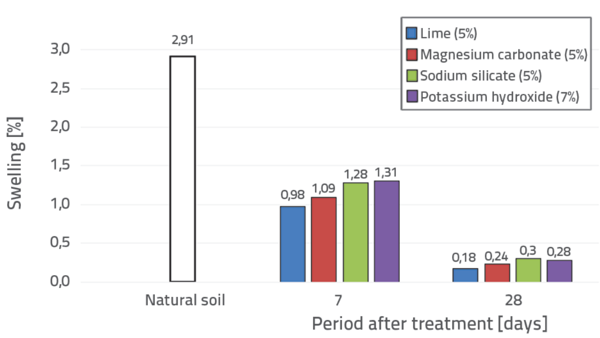

Figure 8. Change in soil swelling over time at the optimal additive contents

under laboratory conditions, after which the swelling of the soil was recorded. Each additive significantly reduced soil swelling (Figure 8). A particularly noticeable reduction in swelling for each of the considered additives was observed 28 d after soil treatment by up to ten times.

4. Conclusions

In this study, the effects of various additives on the physical and mechanical properties of clayey soil were investigated using a chemical stabilisation technique. Four different additives were considered in this study: lime as a traditional additive, and magnesium carbonate, sodium silicate, and potassium hydroxide as alternative additives. Samples of the clayey soil mixture were prepared with each of the selected additives at three different percentages to determine the optimal additive contents in the soil mixture. Changes in the properties of the tested samples were monitored at different time intervals after soil treatment to determine the durability of the effects of the implemented chemical soil stabilisation technique. The most significant findings of this research are as follows:

- With respect to increasing the UCS of soil, the most effective additives were lime and magnesium carbonate, whereas sodium silicate and potassium hydroxide had a smaller effect on the properties of natural clay.
- None of the selected additives contributed to a significant increase in the LL value, regardless of the additive content in the mixture or the time elapsed following soil treatment. However, each additive increased the PL value. This ultimately led to a decrease in the value of PI, especially over time, thus enabling the treated clayey soil to remain in a semi-solid state of consistency even with a high water content. This is favourable for the use of this soil in practical construction applications.
- Each of the selected additives contributed to an increase in the pH of the soil in the initial period after treatment, thus reducing soil acidity and initiating pozzolanic reactions. Based on the results of the soil UCS and pH, it was concluded that the optimal amount of additive for the treated soil is 5 % for lime, magnesium carbonate, and silicium silicate, while 7 % is optimal for potassium hydroxide.
- Similar to the effect on the UCS of soil, the best results in terms of increasing the modulus of compressibility were achieved with the addition of lime and magnesium carbonate, although other additives also contributed by a lesser extent to the reduced compressibility of the treated soil compared to the natural soil.
- For all selected additives, the porosity of the treated soil remained unchanged or increased slightly in the initial period after treatment, which can be explained by the formation of inherently porous compounds. However, the soil porosity decreased over time regardless of the type of additive that was used.

- Each of the considered additives contributed to an increase in the CBR by at least 5 %, which is one of the most common requirements of soil for use in construction applications. The greatest improvement was achieved via lime stabilisation, and a significant improvement was achieved by adding magnesium carbonate. In contrast, the application of sodium silicate or potassium hydroxide resulted in the lowest CBR values.
- Each additive significantly contributed to the reduction in clayey soil swelling by approximately ten times.

The obtained results confirmed that the improvement of soil properties can be successfully achieved by using traditional additives (lime) as well as alternative additives, in particular magnesium carbonate. Applying additives to natural clayey soils enable their use in various construction applications.

It should be noted that the results presented in this study refer to locally obtained clayey soil. However, to improve the reliability of the conclusions, more comprehensive research is required considering a larger number of tests on a greater variety of clayey soils obtained from a wider area.

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REFERENCES

[1] Saeid, A., Amin, C., Hamid N.: A review on the lime and fly ash application in soil stabilization, International Journal of Biological, Ecological and Environmental Sciences (IJBEES), 1 (2012) 3, pp. 124-126.

[2] Diamond, S., Kinter, E.B.: Mechanisms of soil-lime stabilization, Highway research record, 92 (1965) 303, pp. 83-102.

[3] Leroueil, S., Vaughan, P.R.: The general and congruent effects of structure in natural soils and weak rocks, Géotechnique, 40 (1990) 3, pp. 467-488.

[4] Karakan, E.: Influence of clay mineralogy on undrained shear strength using Fall cone test, Građevinar, 75 (2023) 7, pp. 642-652, https://doi.org/10.14256/JCE.3558.2022

[5] Bell, F.: Lime stabilization of clay minerals and soils, Engineering Geol., 42 (1996) 4, pp. 223-237.

[6] Sherwood, P.: Soil stabilization with cement and lime, State of the Art Review, Transport Research Laboratory, London, HMSO, 1993, http://worldcat.org/isbn/9780115511714

[7] Ferguson, G.: Use of self-cementing fly ashes as a soil stabilization agent, ASCE Geotechnical Special Publication, 36, pp. 1-14, 1993.

[8] Vukićević, M., Pujević, V., Marjanović, M., Jocković, S., Maroš-Dragojević., S.: Stabilizacija sitnozrnatog tla letećim pepelom, Građevinar, 67 (2015) 8, pp. 761-770, https://doi.org/10.14256/JCE.1281.2014

[9] Zafirovski, Z., Markovski, M., Ognjenovic, S., Gacevski, V., Nedevska, I., Ristov, R.: Subbase stabilization with fly ash. Facta Universitatis, Series: Architecture and Civil Engineering, (2023), online first, https://doi.org/10.2298/FUACE230630033Z

[10] Onyelowe, K.C., Okafor, F.O.: Acomparative review of soil modification methods, ARPN Journal of Earth Sciences, 1 (2012) 2, pp. 36-42.

[11] Al-Swaidani, A., Hammoud, I., Meziab, A.: Eect of Adding Natural Pozzolana on Geotechnical Properties of Lime-Stabilized Clayey Soil, Journal of Rock Mechanics and Geotechnical Engineering, 8 (2016) 5, pp. 14-25, https://doi.org/10.1016/j.jrmge.2016.04.002

[12] Thomas, A., Tripathi, R.K., Yadu, L.K.: A laboratory investigation of soil stabilization using enzyme and alkali-activated ground granulated blast-furnace slag, Arabian Journal Sciences Engineering, 43 (2018) 10, pp. 5193-5202, https://doi.org/10.1007/s13369-017-3033-x.

[13] Lebo, Ž., Bačić, M., Jurić Kaćunić, D., Kovačević, M.S.: Zagreb clay improved with various binders, Građevinar, 73 (2021) 9, pp.871-880, https://doi.org/10.14256/JCE.3300.2021

[14] Afrasiabian, A., Salimi, M. Movahedrad, M., Vakili, A.H.: Assessing the impact of GBFS on mechanical behaviour and microstructure of soft clay, International Journal of Geotechnical Engineering, 15 (2019) 3, pp 327-337, https://doi.org/10.1080/19386362.2019.1565393.

[15] Zahri, A.M., Zainorabidin, A.: An overview of traditional and non traditional stabilizer for soft soil, IOP Conf. Series: Materials Science and Engineering, 527 (2019) 012015.

[16] Liska, M., Al-Tabbaa, A.: Ultra-green construction: reactive magnesia masonry products, Proceedings of the Institution of Civil Engineers - Waste and Resource Management, 162 (2009) 4, pp.185-196, https://doi.org/10.1680/warm.2009.162.4.185.

[17] Pourakbar, S., Huat, B.K.: A review of alternatives traditional cementitious binders for engineering improvement of soils, International Journal of Geotechnical Engineering, 11 (2016) 2, pp.206-216, https://doi:10.1080/19386362.2016.1207042

[18] Santoni, R., Tingle, J., Webster, S.: Stabilization of Silty Sand with Nontraditional Additives, Transportation Research Record: Journal of the Transportation Research Board, 1787 (2002) 1, pp. 61-70, https://doi:10.3141/1787-07

[19] Shon, C.S., Saylak, D., Mishra, S.K.: Combined Use of Calcium Chloride and Fly Ash in Road Base Stabilization, Transportation Research Record: Journal of the Transportation Research Board, 2186 (2010) 1, pp. 120-129, https://doi:10.3141/2186-13

[20] Marto, A., Latifi, N., Eisazadeh, A.: Effect of non-traditional additives on engineering and microstructural characteristics of laterite soil, Arabian Journal Sciences Engineering, 39 (2014) 10, pp. 6949-6958, https://doi.org/10.1007/s13369-014-1286-1

[21] Moayedi, H., Huat, B.B., Kazemian, S., Daneshmand, S.: Stabilization of organic soil using sodium silicate system grout, International Journal of Physical Sciences, 7 (2012) 9, pp. 1395-1402, https://doi:10.5897/ijps11.1509

[22] James, J., Kasinatha, P.: Effect of phosphogypsum on strength of lime stabilized expansive soil, Građevinar, 66 (2015) 12, pp. 1109-1116, https://doi.org/10.14256/JCE.1097.2014

[23] Latifi, N., Marto, A., Eisazadeh, A.: Physicochemical behavior of tropical laterite soil stabilized with non-traditional additive, Acta Geotechnica, 11 (2016) 2, pp. 433-443, https://doi.org/10.1007/s11440-015-0370-3

[24] Mousavi, S.E., Karamvand, A.: Assessment of strength development in stabilized soil with CBR PLUS and silica sand, Journal of Traffic and Transportation Engineering, 4 (2017) 4, pp. 412-421, https://doi:10.1016/j.jtte.2017.02.002

[25] Jeremiah, J.J., Abbey, S. J.: Booth, C.A., Kashyap, A.: Geopolymers as Alternative Sustainable Binders for Stabilisation of Clays - A Review, Geotechnics, 1 (2021) 2, pp. 439-459. https://doi.org/10.3390/geotechnics1020021

[26] Basma, A., Tuncer, E.R.: Effect of lime on volume change and compressibility of expansive clays. Transportation Research Record, 1295 (1991), pp.52-61.

[27] Kavak, A., Akyarli, A: A field application for lime stabilization, Environmental Geology, 51 (2007) 6, pp. 987-997, https://doi.org/10.1007/s00254-006-0368-0.

[28] Babu, N., Poulose, E.: Effect of lime on soil properties: A review, International Research Journal of Engineering and Technology, 5 (2018) 5, pp. 606-610.

[29] Das, B.M.: Principles of foundation engineering, Cengage learning, Boston, USA, 2015.

[30] Han, J.: Principles and practice of ground improvement, John Wiley & Sons, Hoboken, New Jersey, USA, 2015.

[31] Taha Jawad, I., Raihan Taha, M., Hameed Majeed, Z.A., Khan, T.: Soil Stabilization Using Lime: Advantages, Disadvantages and Proposing a Potential Alternative, Research Journal of Applied Sciences, Engineering and Technology, 8 (2014) 4, pp. 510-520, https://doi:10.19026/rjaset.8.1000

[32] Seco, A., Miqueleiz, L., Prieto, E., Marcelino, S., García, B., Urmeneta, P.: Sulfate soils stabilization with magnesium-based binders, Applied Clay Science, 135 (2016), pp. 457-464, http://dx.doi.org/10.1016/j.clay.2016.10.033

[33] Gu, K., Jin, F., Al-Tabbaa, A., Shi, B., Liu, J.: Mechanical and hydration properties of ground granulated blastfurnace slag pastes activated with MgO–CaO mixtures, Construction and Building Materials, 69 (2014), pp. 101-108. https://doi:10.1016/j.conbuildmat.2014.07

[34] Hurley, C.H., Thornburn T.H.: Sodium silicate stabilization of soils: A review of the literature, Compaction and stabilization, University of Illinois, pp. 46-79, 1972, http://onlinepubs.trb.org/Onlinepubs/hrr/1972/381/381-007.pdf

[35] Maaitah, O.N.: Soil stabilization by chemical agent, Geotechnical and Geological Engineering, 30 (2012), pp. 1345-1356, https://doi.10.1007/s10706-012-9549-7

[36] Elkhebu, A.G., Zainorabidin, A., Bujang, H.B., Bakar, I.H., Abdeljouad, L.A., Dheyab, W.: Alkaline activation of clayey soil using potassium hydroxide & fly ash, International Journal of Integrated Engineering, 10 (2018) 9, pp. 84-89, https://doi.org/10.30880/ijie.2018.10.09.016

[37] Yi, Y., Liska, M., Unluer, C., Al-Tabbaa, A.: Carbonating magnesia for soil stabilization, Canadian Geotechnical Journal, 50 (2013) 8, pp. 899-905, http://doi.org/10.1139/cgj-2012-0364

[38] Vakili, M.V., Chegenizadeh, A., Nikraz, H., Keramatikerman, M.: Investigation on shear strength of stabilised clay using cement, sodium silicate and slag, Applied Clay Science, 124 (2016), pp. 243-251, https://doi.org/10.1016/j.clay.2016.02.019

[39] Pourebrahim, F., Sayyed Y.Z.: Stabilizers effects comprehensive assessment on the physical and chemical properties of soft clays, Shock and Vibration 2022 (2022), 5991132, https://doi.org/10.1155/2022/5991132

[40] ISS - Institute for Standardization of Serbia, SRPS EN 13286-41:2022 Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures, 2022.

[41] ISS - Institute for Standardization of Serbia, SRPS EN ISO 14688-2:2018 Geotechnical investigation and testing - Identification and classification of soil - Part 2: Principles for a classification, 2018.

[42] ISS - Institute for Standardization of Serbia, SRPS EN ISO 17892-5:2017 Geotechnical investigation and testing - Laboratory testing of soil - Part 5: Incremental loading oedometer test, 2017.

[43] ISS - Institute for Standardization of Serbia, SRPS EN 13286-47:2022 Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling, 2022.

[44] Tanzadeh, R., Vafaeian, M., Fard, M.Y.: The influence of lime powder on the behaviour of clay soil, Građevinar, 73 (2021) 9, pp. 907-915, https://doi.org/10.14256/JCE.1871.2016

[45] Eades, J.L., Grim, R.E.: A quick test to determine lime requirements for lime stabilization, Behavior Characteristics of Lime-soil Mixtures, Highway Research Board, pp. 61-72, 1966, http://onlinepubs.trb.org/Onlinepubs/hrr/1966/139/139-005.pdf

[46] Khattab, S.A.A., Al-Mukhtar, M., Fleureau, J.M.: Long-term stability charac-teristics of a lime-treated plastic soil, Journal of Materials in Civil Engineering, 19 (2007) 4, pp. 358-366, https://doi:10.1061/(ASCE)0899-1561(2007)19:4(358)

[47] Firoozi, A.A., Guney Olgun, C., Firoozi, A.A., Baghini, M.S.: Fundamentals of soil stabilization, International Journal of Geo-Engineering, 8 (2017) 1, pp. 1-16, https://doi:10.1186/s40703-017-0064-9

[48] Eyo, E.U., Ng'ambi, S., Abbey, S.J.: An overview of soil-water characteristic curves of stabilised soils and their influential factors. Journal of King Saud University - Engineering Sciences, 34 (2020) 1, pp. 31-45, https://doi:10.1016/j.jksues.2020.07.013