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Chemical Stabilisation of Clayey Soil—Comparison of a Variety of Additives with Respect to Their Effects on the Soil Compressive Strength and Shear Strength

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Abstract: The unconfined compressive strength and shear strength represent the basic mechanical properties of clayey soil. If the soil in its natural state does not have sufficiently good mechanical properties, in engineering practice, it can be improved by chemical stabilisation of the soil. The stabilisation procedure involves adding reagent(s) to the soil with the aim of permanent improvement in the mechanical properties of the soil. In this study, the individual effects of seven different chemical stabilisers (traditional and alternative) on the mechanical properties of clayey soil were analysed. In the first stage of the research, comprehensive analyses were conducted on the effect of each of the selected stabilisers on the compressive strength of the soil. Each of the selected stabilisers was considered with three different content percentages in the soil mixture, with the aim of determining the optimal stabiliser content. Unconfined compressive tests were conducted to determine the unconfined compressive strength (UCS) of the soil. In the second stage of the research, extensive analyses of the effects of each of the selected stabilisers alone on the improvement in soil shear strength parameters (cohesion and internal friction angle), were carried out with the optimal content of each of the stabilisers. The shear strength parameters were determined by direct shear tests. Both stages of the research were conducted at three different time intervals after the chemical stabilisation (3, 14, and 28 days) in order to determine the long-term efficiency of the chemical treatment of clayey soil. Based on detailed comparative analyses, it was determined that all the selected stabilisers contributed to a lesser or greater extent to a significant improvement in the analysed mechanical properties of clayey soil. A statistical analysis of the obtained results was also conducted using the method of analysis of variance (ANOVA), on the basis of which the individual effect of each selected stabiliser on improving the mechanical properties of clayey soil was validated and quantified.

Keywords: clayey soil; chemical stabilisation; traditional stabilisers; alternative materials; unconfined compressive strength; shear strength; analysis of variance (ANOVA)

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1. Introduction

Clayey soils often represent a serious challenge for application in engineering practice due to their lower values of mechanical strengths, high plasticity, and tendency to swell and

shrink. The improvement in these properties is essential for the stability and longevity of infrastructure facilities, primarily in road construction. In geotechnical practice, numerous techniques have been developed in order to improve clayey soil properties, among which is the chemical stabilisation technique, which is widely used. This method implies the addition of certain additive(s) to a natural soil of weak characteristics by simple mixing. The stabilisation mechanism itself is based on the reaction of the additives with the existing mineral components of the clayey soil, thus forming new compounds that contribute to increasing the mechanical strength and reducing the deformability of the soil [1–4].

Chemical stabilisers include a wide range of materials such as cement, lime, industrial waste products (e.g., fly ash, rock flour, slag, etc.), polymers, fibers, chemical reagents, waste/recycled materials (e.g., shredded rubber, crushed glass, etc.), and asphalt emulsions of tar and bitumen [5–10]. In addition to the individual effect of additives, some studies have also examined the effects of some of their combinations [11–13].

Among these, lime is the most commonly used. Previous studies have shown that the addition of a stabiliser such as lime can significantly improve the mechanical strength of fine-grained soil [14–18]. Although research shows that lime can significantly improve soil properties by reducing its plasticity and tendency to swell, it can have negative effects in the presence of sulfate ions in clay, leading to the formation of minerals that cause soil swelling [19]. Ferris et al. [20] were among the first to highlight the formation of these minerals as a problem in soil stabilisation using lime. Furthermore, the use of lime is often criticised in recent times, primarily due to its impact on the environment (due to CO_2 emission), energy consumption, and cost. During the production of lime, on the one hand, large amounts of natural raw materials are consumed. Namely, during the decarbonisation of limestone ($CaCO_3$), a large amount of CO_2 is released into the atmosphere. On the other hand, when stabilising 1000 kg of soil, the minimum amount of stabiliser is 20 kg (2%) [15]. In order to produce this amount of stabiliser, a minimum of 30 kg of natural raw material is required, and 96 MJ of fossil fuels are consumed. During the standard production process, about 18 kg of CO_2 is emitted into the atmosphere [21]. Therefore, any reduction in the consumption of this stabiliser would have a positive effect on the reduction in the consumption of natural raw materials, as well as on the reduction in CO_2 emissions.

For the reasons mentioned, growing attention has recently been paid to new materials as potential stabilisers. In addition to new commercial products such as magnesium carbonate, sodium silicate, and chloride-based compounds, which are being considered due to their specific chemical composition [22–25], the trend of reuse of industrial waste, such as fly ash, for the purpose of improving soil properties is also gaining importance [26].

A detailed overview of the hitherto performed studies reveals that in the focus of the specific research, a single reagent or combination of two reagents of different types was considered. This finding points to the fact that there is a lack of an extensive comparative study involving a broad range of reagents of different kinds. What is also particularly important is the evident scarcity of research regarding the effects of new materials as stabilisers on crucial geotechnical soil characteristics, such as shear strength parameters—soil cohesion and angle of internal friction.

In accordance with all aforementioned, this study deals with an extensive comparative study on individual effects of a broad range of materials as stabilisers, classified as traditional stabilisers with a wide application in geotechnics (lime and fly ash) and nontraditional—alternative materials (magnesium carbonate, sodium silicate, and chloride-based compounds), on the crucial geotechnical properties of clayey soil. In the first part of the study, for each of the selected stabilisers, soil samples were treated with three different stabiliser contents with respect to the dry weight of the soil sample. On the basis of the investigation into the soil unconfined compressive strength (UCS), monitored at three

different time intervals after the soil treatment (3, 14, and 28 days), the optimal content for each of the stabilisers in the mixture with clayey soil was determined. In the second stage of the study, the given soil samples were prepared with the optimal stabiliser content for each of the considered stabilisers, and additional tests were carried out with regard to the individual effect of each stabiliser on the shear strength parameters of the clayey soil, which were monitored over time after the chemical stabilisation (3, 14, and 28 days), in order to assess both the short-term effects and the long-term effects of stabilisation.

Considering the soil UCS, a significant number of studies have addressed the improvement in this soil property by adding lime or fly ash (as traditional additives), and examining the effects of these additives on a wide range of soil types. However, the effects of the addition of alternative reagents have been investigated from the aspect of this soil property only for the cases of a specific additive on a specific soil type (e.g., the effect of magnesium carbonate on a sandy/silty soil [27], sodium silicate on a tropical laterite soil [28], chloride-based salts on a silty clay soil [29]). This ultimately precluded the comparability of results in terms of stabiliser effects. It is precisely in this aspect that one of the innovations of this research is reflected because the individual effects of different types of stabilisers are examined on the same soil, which enables their mutual comparison and, ultimately, the selection of the most effective stabiliser.

In terms of the soil shear strength and its relevant parameters, there is a rather limited base of previous research, in particular from the aspect of the effects of alternative additives that are considered in the present research. With regard to traditional additives, it was practiced in previous studies to examine the effects of a single additive on a specific type of soil [30] or what was much more common to investigate the combined effects of two or more traditional additives [31,32]. When it comes to alternative materials, the effects of a mixture of traditional additive(s) with alternative material(s) were mostly considered in previous research [33,34]. Therefore, there is a lack of studies on the effects of different types of additives (both traditional and alternative) on the same type of soil and a mutual comparison of the individual effects of the considered additives on the shear strength parameters of the soil. This finding represents another innovative aspect of the present research, given that the individual effects of a variety of stabilisers on the shear strength parameters are observed on the same soil, thus enabling their mutual comparison with the aim of identifying the most effective stabiliser.

2. Materials and Methods

2.1. Materials Considered in the Study

2.1.1. Clayey Soil

The clayey soil used in this research originates from a site in Crvena Reka in the southeastern part of the Republic of Serbia and was available during the construction of the E-80 Highway (Figure 1).

The mineralogical composition of the natural clayey soil used in the research was determined by X-ray Diffraction (XRD) analysis, which is most commonly used to determine the qualitative and quantitative content of minerals. As can be seen from the XRD spectrum given in Figure 2, its mineralogical composition consists of clay minerals (montmorillonite ($CaO_2(Al,Mg)_2SiO_{10}(OH)_{24}H_2O$)—15%, illite ($KAl_2Si_3AlO_{10}(OH)_2$—11%, and clinochlore ($Mg_5Al(Si,Al)_4O_{10}(OH)_8$)—10%) along with other minerals (calcite ($CaCO_3$)—39% and quartz (SiO_2)—25%). The results of this research should indicate the potential of reusing the clayey soil material after mixing with a certain chemical stabiliser.

The physico–mechanical properties of the natural clayey soil were determined by laboratory tests and are presented in Table 1.



Figure 1. Field sampling of the clayey soil.

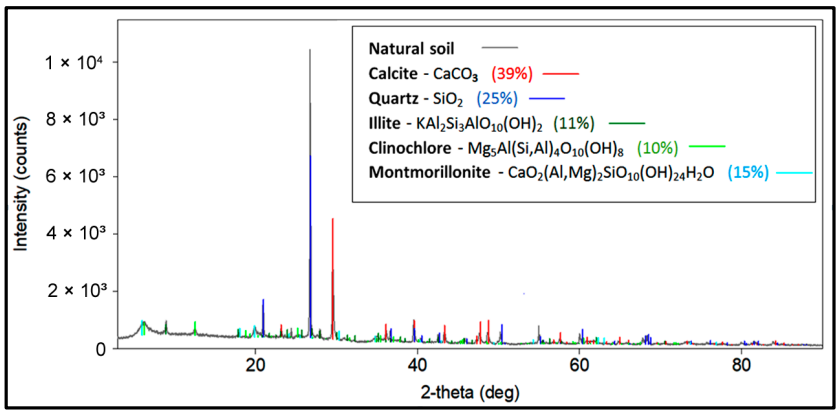


Figure 2. XRD spectrum of the mineralogical composition of the natural clayey soil.

Table 1. Properties of the clayey soil used in the present research.

Property of Soil	Symbol (Unit)	Value
Particle Density	Gs (−)	2.705
Grain Size Distribution	Gravel (%) Sand (%) Silt (%) Clay (%)	1.2 4.9 40.6 53.3
Coefficient of Uniformity Coefficient of Curvature	Cu (−) Cc (−)	8.0 2.0
USCS Soil Classification Maximum Dry Density Optimal Moisture Content	Symbol (−) MDD (g/cm^3) OMC (%)	CL 1.903 18.5
Liquid Limit Plastic Limit Plasticity Index	LL (%) PL (%) PI (%)	49 23 26
pH Value	pH (−)	9.5
Modulus of Compressibility California Bearing Ratio Swelling	Mv (MPa) CBR (%) s (%)	12.945 2.71 2.91
Unconfined Compressive Strength	UCS (kPa)	205
Cohesion Internal Friction Angle	c (kPa) φ (°)	16.9 16.5

2.1.2. Additives

All additives (stabilisers) considered in this study were classified into two categories—traditional stabilisers and alternative materials. The usual criterion for this classification is the widespread use of certain materials for the purpose of soil stabilisation, so traditional stabilisers are characterised by a wider application for these purposes, while on the contrary, alternative (non-traditional) materials are those that are not normally used for these purposes. On the other hand, the official classification into traditional and alternative materials is actually based on the presence of calcium compounds in the chemical composition of stabilisers, so traditional stabilisers are those based on the presence of a large amount of calcium compounds, whereas alternative materials are those that do not contain calcium-based compounds in large quantities.

Traditional (calcium-based) stabilisers, such as lime, enable the modification of clayey soil properties through five distinctive processes: (1) hydration, (2) cation exchange, (3) flocculation and agglomeration, and (4) pozzolanic reaction [31,35,36]. The cation exchange process due to the mixing of the stabiliser with the soil causes the flocculation and agglomeration of particles, which result in the creation of larger particles in the soil that is then characterised by a lower water permeability and lower plasticity. This process begins immediately after mixing the stabiliser and the soil and lasts only a few hours. The hydration process takes longer, sometimes up to 28 days. In addition, the presence of OH^- ions increases the pH value of the soil, which allows the pozzolanic reaction to develop. As a result of this reaction, the added Ca^{2+} components from the stabiliser (reagent) react with the silicates (SiO_2) and aluminates (Al_2O_3) from the clay minerals and produce compounds such as calcium silicate hydrates (CSH), calcium aluminate hydrates (CAH), and calcium alumino-silicate hydrates (CASH), which act as gel-like materials with highly binding properties. In addition to lime, fly ash is also included in traditional stabilisers, which began to be successfully used for soil improvement at the end of the 20th century [37]. Fly ash can be used alone and can contribute to an improvement in certain geomechanical soil properties [30,38], but it is often used in combination with lime or cement [32,39].

In this study, the following traditional stabilisers were used: commercial lime CL 90 S (with the chemical composition CaO—71.01%, MgO—3.05%, and SiO_2—2.14%) and fly ash from the thermal power plant Kostolac (with the chemical composition SiO_2—56.38%, Al_2O_3—17.57%, Fe_2O_3—10.39%, CaO—7.46%, and MgO—2.13%).

Previous studies have shown that the content of lime in the mixture with soil when improving clayey soil properties is usually in the range of 2 to 8% [15,40] and in the case of the application of fly ash, 10–30% [30,38]. Accordingly, for the purpose of determining the optimal stabiliser content, samples of clayey soil with the addition of 3%, 5%, and 7% lime, as well as the addition of 10%, 15%, and 20% fly ash, were investigated in this study.

Alternative (non-calcium-based) additives are materials that do not contain calcium-based compounds in large amounts. For the purpose of this study, compounds based on magnesium (magnesium carbonate ($MgCO_3$) were used, then compounds based on chloride (ferric chloride ($FeCl_3$), calcium chloride ($CaCl_2$), and potassium chloride (KCl)), as well as sodium silicate (Na_2SiO_3). The selection of the mentioned alternative stabilisers was made in accordance with the results of previous research, in which it was established that the addition of these materials could improve certain properties of the soil. Thus, for example, an increase in soil bearing capacity was achieved by adding magnesium-based materials [41,42], or sodium silicate [43]. Studies have shown that chloride-based electrolytes can be effectively used instead of lime in soil stabilisation owing to their better solubility, easier mixing with the soil, and provision of the necessary cations for the cation exchange process [29]. Therefore, it is about reagents in the liquid state, which are more economical to transport than traditional ones and can be diluted with water on site.

In the available literature, the content percentage of magnesium-based additives and sodium silicate does not exceed 10% [27,28,41–43], whereas the content of these additives in combination with other stabilisers is often lower than 3% [33,34,44]. Therefore, for the purposes of this research, as was the case with the samples with added lime, mixtures with the addition of 3%, 5%, and 7% of magnesium carbonate were tested, and the same percentages were chosen for the mixtures with sodium silicate.

Regarding the optimal content of chloride-based reagents, it can be found in the literature that sometimes even less than 1% of chloride is the optimal content percentage required for the stabilisation of mostly expansive soils [45–47]. For the purpose of determining the optimal content for each of the considered chlorides, soil samples with the addition of 1%, 2%, and 3% reagent were tested in this study.

Table 2 summarises the selected stabilisers and the considered content percentages of stabilisers, along with the corresponding labels of the examined mixtures.

Table 2. Overview of the tested mixtures (specimens) with the selected contents of examined traditional stabilisers (in total 2) and alternative stabilisers (in total 5).

Stabiliser	Content of a Stabiliser	Label of a Mixture
Traditional stabilisers		
Lime	3%	L3
	5%	L5
	7%	L7
Fly Ash	10%	FA10
	15%	FA15
	20%	FA20
Alternative materials		
Magnesium Carbonate	3%	MC3
	5%	MC5
	7%	MC7
Sodium Silicate	3%	SS3
	5%	SS5
	7%	SS7
Ferric Chloride	1%	FC1
	2%	FC2
	3%	FC3
Calcium Chloride	1%	CC1
	2%	CC2
	3%	CC3
Potassium Chloride	1%	PC1
	2%	PC2
	3%	PC3

Overall, the primary goal of this study was to investigate the potential of each of the selected additives alone (without combining them mutually) in terms of improving the unconfined compressive strength and the shear strength parameters (cohesion and internal friction angle), which are of paramount importance in geotechnical and civil engineering.

2.2. Methods of Experimental Research

The experimental research and accompanying tests were carried out at the Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of the University of Niš. All tests were carried out according to the current national standards, which are harmonised with the actual European norms (EN).

The soil material from the aforementioned location was brought to the laboratory, where it was first dried in an oven at a temperature of 105 °C for 24 h. After that, the material was crushed, and then sifted on a 4 mm sieve, with the aim of eliminating sporadic coarse-grained fractions. Additives of interest were added individually to the clay material prepared in this way, with the considered content percentages in the mixture with the soil in relation to the dry weight of the soil.

In accordance with the valid national standard (SRPS EN 13286-41:2022 [48]), samples for the test of unconfined compressive strength (UCS) were prepared in laboratory conditions, with the optimum moisture content (OMC), which was chosen to be the same as the optimum moisture content of the natural clayey soil according to the Proctor test (OMC = 18.5%, Table 1), for the sake of comparability of the results for the natural and treated clayey soils. The samples were compacted during the standard Proctor test with a compaction energy of 600 kNm/m^3. The cylindrical sample was 15 cm in height and 10 cm in diameter. The treated samples were wrapped in a plastic foil and stored in a closed plastic box until the appropriate time for conducting the test, in order to maintain the same moisture content of the sample over time. UCS tests were conducted in a press manufactured by UTEST, which can record relatively small pressure values (Figure 3a).

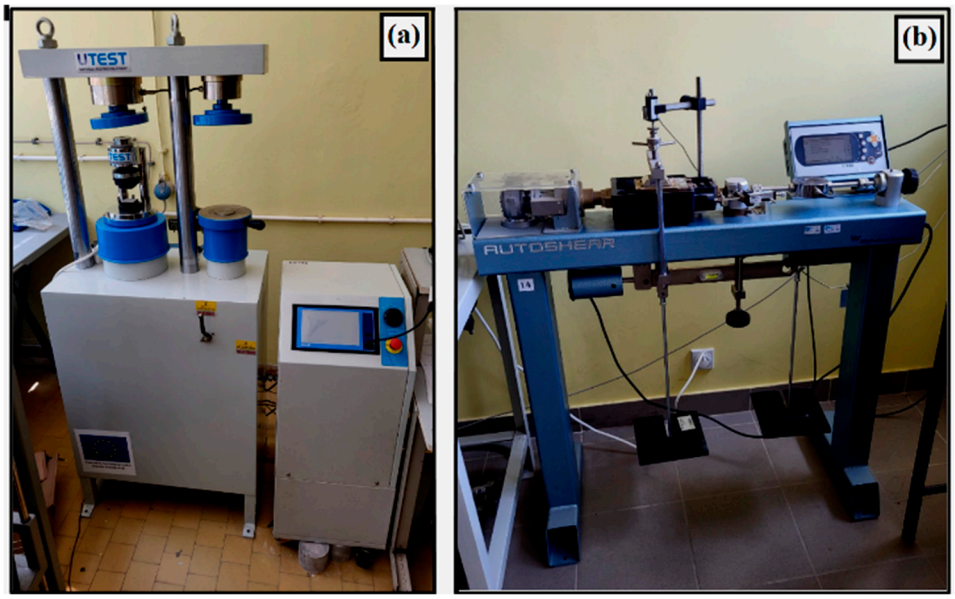


Figure 3. Equipment used in the research: (**a**) equipment for the UCS test (press); (**b**) equipment for the direct shear test (shear box apparatus).

The direct shear test was also performed according to the corresponding national standard (SRPS EN ISO 17892-10:2019 [49]), on a shear box apparatus manufactured by CONTROLS (Figure 3b). The samples were of the square shape at the base, with dimensions 6.0 cm × 6.0 cm, and with a height of 2.0 cm. During testing, the samples were loaded with normal stresses of 50 kPa, 100 kPa, and 200 kPa. The shear rate was 0.0083 mm/min. The samples for this test were also prepared with a moisture content equal to the optimum moisture content of natural soil according to Proctor (18.5%), for the sake of comparability of the results of natural and treated clayey soil.

3. Results of the Study, Analysis, and Discussion

3.1. Soil Unconfined Compressive Strength (UCS)

When examining the unconfined compressive strength (UCS), three different content percentages in the mixture for each of the selected stabilisers were considered, as already

indicated in Table 2. The measured UCS value of the natural clayey soil was 205 kPa. A total of 189 samples were tested in the corresponding time intervals—3, 14, and 28 days after the chemical treatment, for each of the selected stabilisers with three different percentages. The test results are shown in Table 3, along with the measured UCS values for the three tested samples, their average value, and standard deviation. It can be seen that the standard deviation, which represents the average deviation of all measurements from their mean value, is sufficiently small in all the considered cases, thus implying that the procedure and results are repetitive.

Table 3. UCS value for the corresponding content percentage of the selected stabilisers in the mixture with clayey soil and time interval after the chemical treatment.

Stabiliser	Mixture Label	Unconfined Compressive Strength UCS (kPa) *								
		After 3 Days			After 14 Days			After 28 Days		
		Measured Values	Average Value	Standard Deviation	Measured Values	Average Value	Standard Deviation	Measured Values	Average Value	Standard Deviation
Traditional stabilisers										
Lime	L3	431; 438; 435	435	3.512	691; 676; 685	684	7.550	898; 901; 889	896	6.245
	L5	525; 536; 526	529	6.083	782; 784; 791	786	4.726	1140; 1144; 1151	1145	5.568
	L7	621; 618; 628	622	5.132	826; 831; 821	826	5.000	1186; 1172; 1175	1178	7.371
Fly Ash	FA10	292; 280; 279	284	7.234	298; 307; 288	298	9.504	309; 302; 310	307	4.359
	FA15	352; 344; 345	347	4.359	357; 371; 367	365	7.211	378; 361; 374	371	8.888
	FA20	306; 305; 301	304	2.646	332; 318; 327	326	7.095	345; 349; 331	342	9.452
Alternative materials										
Magnesium Carbonate	MC3	407; 406; 399	404	4.359	413; 421; 431	422	9.018	459; 462; 445	455	9.074
	MC5	525; 527; 520	521	3.606	669; 657; 657	661	6.928	751; 739; 741	744	6.429
	MC7	596; 585; 592	591	5.568	725; 730; 738	731	6.557	805; 807; 796	803	5.859
Sodium Silicate	SS3	259; 265; 259	261	3.464	280; 278; 274	277	3.055	295; 297; 282	291	8.145
	SS5	365; 351; 357	351	7.024	367; 372; 375	371	4.041	371, 382; 385	379	7.371
	SS7	292; 301; 294	296	4.726	326; 334; 328	330	4.726	379; 370; 368	372	5.859
Ferric Chloride	FC1	268; 279; 270	272	5.859	289; 299; 297	295	5.292	289; 274; 279	281	7.638
	FC2	281; 284; 295	287	7.371	351; 339; 346	345	6.028	369; 364; 374	369	5.000
	FC3	279; 294; 285	286	7.550	326; 334; 328	329	4.163	341; 348; 351	347	5.132
Calcium Chloride	CC1	295; 297; 302	298	3.606	319; 325; 317	320	4.163	379; 368; 367	371	6.658
	CC2	316; 301; 309	309	7.506	369; 360; 372	367	6.245	394; 390; 389	391	2.646
	CC3	297; 308; 313	306	8.185	349; 358; 350	352	4.933	362; 374; 363	366	6.658
Potassium Chloride	PC1	257; 252; 241	250	8.185	329; 318; 325	324	5.568	335; 331; 344	337	6.658
	PC2	270; 258; 264	264	6.000	302; 315; 318	312	8.505	349; 338; 339	342	6.083
	PC3	238; 249; 235	241	7.371	305; 309; 314	309	4.509	316; 309; 313	313	3.512

* The measured UCS value of the natural clayey soil was 205 kPa.

With the addition of 3% lime (L3), the value of UCS increased more than twice 3 days after the chemical treatment (435 kPa), whereas for the addition of 7% lime (L7), after the same time interval, the UCS value tripled (622 kPa). With the addition of 20% fly ash (FA20), a lower UCS value was achieved (304 kPa) than with the addition of 15% of this stabiliser (FA15) 3 days after the chemical treatment (347 kPa).

Of the alternative reagents, 3 days after the chemical treatment, the addition of 7% magnesium carbonate (MC7) contributed to the greatest increase in the UCS value (591 kPa). A significant improvement was also achieved by adding only 5% sodium silicate (SS5, 351 kPa). Of the other alternative stabilisers, the best results were achieved with the addition of 2% for each of the considered chlorides: ferric chloride (FC2, 287 kPa), calcium chloride (CC2, 309 kPa), potassium chloride (PC2, 264 kPa). It should be noted that the UCS values were very close to each other with the addition of different percentages of each of the selected chlorides.

UCS testing at different intervals after the chemical stabilisation aimed to verify the durability of the soil stabilisation effect. For all the selected stabilisers, regardless of content percentage in the mixture, the maximum UCS values were obtained 28 days after the treatment, which is graphically interpreted and compared in Figure 4.

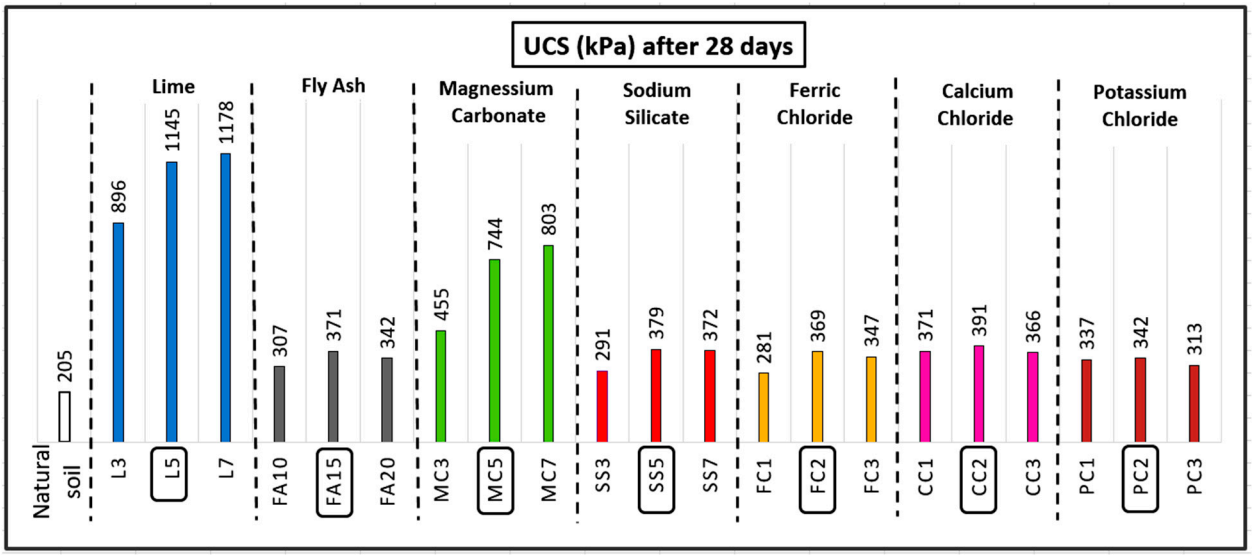


Figure 4. Comparison of the soil UCS value obtained 28 days after the chemical treatment for the corresponding content percentage of the selected stabilisers in the mixture with clayey soil.

As seen in the mentioned figure, each of the considered stabilisers contributed to an increase in the UCS value of the chemically treated clayey soil. The greatest progress was achieved with the addition of lime (increasing the UCS value up to six times). With the addition of magnesium carbonate, a significant increase in the UCS value of clayey soil was achieved (up to a fourfold increase in the UCS value). All other considered stabilisers contributed to an increase in the UCS value to a lesser extent (increasing the UCS value approximately two times).

By looking at the UCS values obtained 28 days after the treatment, based on these results and for the purposes of further testing, the optimal content of each of the selected stabilisers (which are also marked in Figure 4) was determined:

- When it comes to lime, a particularly significant improvement was observed when the lime content was increased from 3% (L3) to 5% (L5), whereas an increase to 7% lime addition (L7) did not contribute to a significant improvement in the results obtained with 5% lime. Therefore, 5% lime was found to be the optimal concentration of this stabiliser in a mixture with clayey soil;
- A similar trend in the change in the UCS value was also observed in the case of the addition of magnesium carbonate, so in accordance with this, in the case of this type of additive it was determined that the optimal content was 5% as well (MC5);
- In the case of all other considered stabilisers, the optimal content, for which the maximum increase in the UCS value was achieved, was clearly distinguished, namely: 15% in the case of fly ash (FA15), 5% in the case of sodium silicate (SS5), and 2% in the case of each of the considered chlorides (ferric chloride (FC2), calcium chloride (CC2), potassium chloride (PC2)).

The trend change in the soil UCS value over time for samples prepared with optimal content for each of the considered stabilisers is presented in Figure 5. It can be seen that in the case of each of the considered stabilisers, the effect of improving soil properties over time was achieved. By adding lime (L5) as a traditional stabiliser but also considering magnesium carbonate (MC5) as an alternative stabiliser, a significant improvement in the UCS value was achieved. All other stabilisers contributed to an improvement in the soil from this aspect, but to a lesser extent (the increase in UCS value is less than twice).

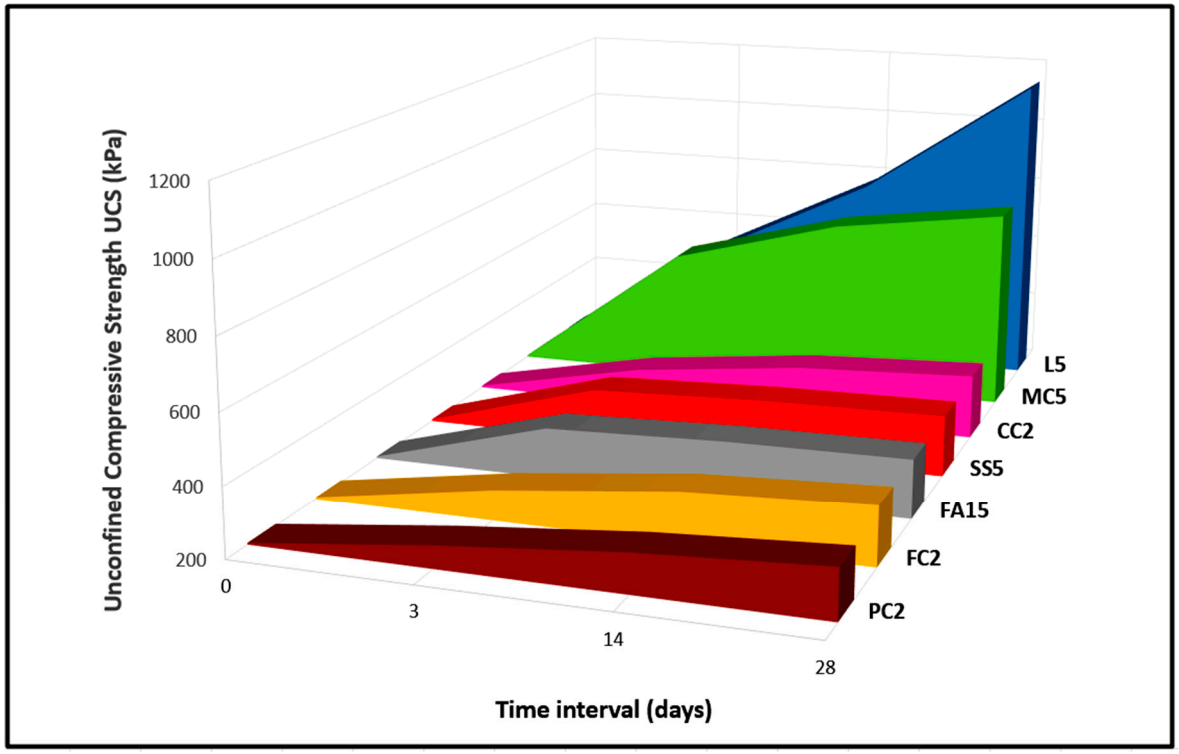


Figure 5. Comparison of the trend in the UCS change over time after the chemical stabilisation of clayey soil with the corresponding optimal content for each of the selected stabilisers.

With the addition of lime (L5), or magnesium carbonate (MC5), a rapid increase in the UCS value was observed during the first 3 days after the treatment. At subsequent test intervals of 14 and 28 days, the traditional stabiliser (lime) maintained a noticeable upward trend in UCS values, whereas for the soil with an added alternative stabiliser (magnesium carbonate), slower progress was observed. A milder increase in the UCS value, after the rapid increase during the first 3 days after treatment, was also observed in the case of sodium silicate (SS5) and fly ash (FA15). An almost linearly increasing trend over time was observed in the case of each of the considered chlorides (CC2, FC2, KC2), and it might be useful in future research to examine the UCS value after 28 days after treatment as well.

The effectiveness of the considered stabilisers in terms of improving the UCS value of clayey soil was also examined with the aid of statistical analysis. Taking into account the durability of the effect for each of the applied stabilisers, the results for 28 days after the treatment were analysed using the analysis of variance (ANOVA) method [50,51], which is a statistical test used to analyse the means (average values) of more than two groups. One-way ANOVA, performed in the present study, uses one independent variable, which should have at least three different groups (in this case, these are seven stabiliser types, with three different content percentages each), and one quantitative dependent variable (in this case, the UCS value of the treated clayey soil). If any of the group means is significantly different from the overall mean, then the null hypothesis (H_0) of equality between the group means is rejected. ANOVA uses the F-test for statistical significance, which compares the variance in each group mean to the overall group variance. If the variance within groups is less than the variance between groups, the F-test will result in a higher F statistic value and, therefore, a higher likelihood that the difference observed is real and not due to chance. The *p*-value of the F statistic value is used to evaluate the validity of the null hypothesis that all the means are the same. If the F statistic value is large enough, the *p*-value will be sufficiently small, and vice versa. When the *p*-value is less than the standard significance

level α (usually 0.05), the null hypothesis is rejected, implying that there are significant differences between the means of the groups.

Table 4 presents the results of the one-way ANOVA analysis performed.

Table 4. Results of the one-way ANOVA analysis.

ANOVA SUMMARY—Unconfined Compressive Strength UCS (kPa) After 28 Days							
Groups		Count	Sum	Average	Variance		
Traditional stabilisers							
Lime	L3	3	2688	896.00	39.00		
	L5	3	3435	1145.00	31.00		
	L7	3	3533	1177.67	54.33		
Fly Ash	FA10	3	921	307.00	19.00		
	FA15	3	1113	371.00	79.00		
	FA20	3	1025	341.67	89.33		
Alternative materials							
Magnesium Carbonate	MC3	3	1366	455.33	82.33		
	MC5	3	2231	743.67	41.33		
	MC7	3	2408	802.67	34.33		
Sodium Silicate	SS3	3	874	291.33	66.33		
	SS5	3	1138	379.33	54.33		
	SS7	3	1117	372.33	34.33		
Ferric Chloride	FC1	3	842	280.67	58.33		
	FC2	3	1107	369.00	25.00		
	FC3	3	1040	346.67	26.33		
Calcium Chloride	CC1	3	1114	371.33	44.33		
	CC2	3	1173	391.00	7.00		
	CC3	3	1099	366.33	44.33		
Potassium Chloride	PC1	3	1010	336.67	44.33		
	PC2	3	1026	342.00	37.00		
	PC3	3	938	312.67	12.33		
ANOVA RESULTS—Unconfined Compressive Strength UCS (kPa) After 28 Days							
Source of variation	Sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	*F*-value	*F,crit*	*p*-value	Standard significance level (α)
Between groups	4,679,232.98	20	233,961.65	5319.23	1.8258	<0.0001	0.05
Within groups	1847.33	42	43.98				
Total	4,681,080.32	62					

As shown in Table 4, the resulting *p*-value was much less than 0.0001. Since this value was below the so-called standard significance level α of 0.05, the null hypothesis was rejected, i.e., the sample data provided strong enough evidence to conclude that the mean UCS values for the seven considered stabilisers were not equal. In addition, since the obtained F-value of 5319.23 was considerably higher than the F,crit value of 1.8258, this also confirmed the rejection of the null hypothesis and the conclusion that there was a significant difference between the mean UCS values for the seven stabilisers considered. Therefore, based on the one-way ANOVA test, it was shown that the seven considered stabilisers differed in their effectiveness.

However, there is a limitation to ANOVA, since it can only indicate whether there is a significant difference between the mean values of the groups, but cannot identify which particular differences between pairs of means are significant. To determine this, there was a need to use post hoc tests to supplement the ANOVA results, such as the two-by-two comparisons (using multiple *t*-tests), which compare the mean values of precisely two

groups [50]. In the case of the *t*-test the same conditions apply, in the sense that if the calculated t-value is greater than the critical t-value (t,crit), then the null hypothesis of equality between the group means is rejected in favour of the alternative hypothesis. Here again, the *p*-value is the most important statistic. Due to the performance of multiple *t*-tests, there was a need to adjust the standard significance level α of 0.05 in order to avoid errors (Bonferroni correction), taking into account the number of pairwise comparisons made (in this case 21). The adjusted α-value used for making a decision whether the groups were significantly different was 0.0024. Therefore, if the *p*-value was less than the adjusted significance level of 0.0024, the difference between the means was considered statistically significant.

Using multiple *t*-tests, the results were obtained for the pairwise comparisons of the seven stabilisers considered with their optimal content, as presented in Table 5 (the rows of the table represent the first group, and the columns represent the second group considered in the mutual comparisons). Based on the results shown, it can be seen that in the case of some pairwise comparisons, negative t-values were obtained. The analysis of a negative t-value requires examination of its absolute value in comparison with the critical t-value, and if the absolute value of the experimental t-value is less than the critical value, then the means of the two groups can be said to be significantly different. In general, a positive t-value indicates that the first group has a higher mean than the second group in the pairwise comparison, whereas a negative t-value indicates the opposite.

Table 5. Results of the *t*-test analyses.

Two-by-Two Comparisons—Unconfined Compressive Strengtd UCS (kPa) After 28 Days							
First Group / **Second Group**	L5 (Mean: 1145.00)	FA15 (Mean: 371.00)	MC5 (Mean: 743.67)	SS5 (Mean: 379.33)	FC2 (Mean: 369.00)	CC2 (Mean: 391.00)	PC2 (Mean: 342.00)
L5 (mean: 1145.00)	/	t_{value}: 127.82 *t,crit*: 3.18 p_{value}: <0.0001	t_{value}: 81.73 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 143.56 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 179.61 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 211.86 *t,crit*: 3.18 p_{value}: <0.0001	t_{value}: 168.66 *t,crit*: 2.78 p_{value}: <0.0001
FA15 (mean: 371.00)	t_{value}: −127.82 *t,crit*: 3.18 p_{value}: <0.0001	/	t_{value}: −58.84 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: −1.25 *t,crit*: 2.78 p_{value}: 0.2794	t_{value}: 0.34 *t,crit*: 3.18 p_{value}: 0.7565	t_{value}: −3.73 *t,crit*: 4.30 p_{value}: 0.0648	t_{value}: 4.66 *t,crit*: 2.78 p_{value}: 0.0096
MC5 (mean: 743.67)	t_{value}: −81.73 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 58.84 *t,crit*: 2.78 p_{value}: <0.0001	/	t_{value}: 64.52 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 79.68 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 87.86 *t,crit*: 3.18 p_{value}: <0.0001	t_{value}: 78.60 *t,crit*: 2.78 p_{value}: <0.0001
SS5 (mean: 379.33)	t_{value}: −143.56 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: 1.25 *t,crit*: 2.78 p_{value}: 0.2794	t_{value}: −64.52 *t,crit*: 2.78 p_{value}: <0.0001	/	t_{value}: 2.01 *t,crit*: 2.78 p_{value}: 0.1149	t_{value}: −2.58 *t,crit*: 3.18 p_{value}: 0.0818	t_{value}: 6.77 *t,crit*: 2.78 p_{value}: 0.0025
FC2 (mean: 369.00)	t_{value}: −179.61 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: −0.34 *t,crit*: 3.18 p_{value}: 0.7565	t_{value}: −79.68 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: −2.01 *t,crit*: 2.78 p_{value}: 0.1149	/	t_{value}: −6.74 *t,crit*: 3.18 p_{value}: 0.0067	t_{value}: 5.94 *t,crit*: 2.78 p_{value}: 0.0040
CC2 (mean: 391.00)	t_{value}: −211.86 *t,crit*: 3.18 p_{value}: <0.0001	t_{value}: 3.73 *t,crit*: 4.30 p_{value}: 0.0648	t_{value}: −87.86 *t,crit*: 3.18 p_{value}: <0.0001	t_{value}: 2.58 *t,crit*: 3.18 p_{value}: 0.0818	t_{value}: 6.74 *t,crit*: 3.18 p_{value}: 0.0067	/	t_{value}: 12.79 *t,crit*: 3.18 p_{value}: 0.0010
PC2 (mean: 342.00)	t_{value}: −168.66 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: −4.66 *t,crit*: 2.78 p_{value}: 0.0096	t_{value}: −78.60 *t,crit*: 2.78 p_{value}: <0.0001	t_{value}: −6.77 *t,crit*: 2.78 p_{value}: 0.0025	t_{value}: −5.94 *t,crit*: 2.78 p_{value}: 0.0040	t_{value}: −12.79 *t,crit*: 3.18 p_{value}: 0.0010	/

In certain pairwise comparisons, it was observed that the obtained *p*-value was below the critical threshold of α = 0.0024, meaning that sample data supported the hypothesis that the stabiliser means were different. Additionally, the corresponding t-value was greater than the critical value t,crit, which also confirmed the advantage of one stabiliser over another considered in their mutual comparison.

Specifically, such results were observed in the case of the comparison of lime with each of the remaining six considered stabilisers (pairwise comparisons L5–FA15, L5–MC5, L5–SS5, L5–FC2, L5–CC2, and L5–PC2), with the resulting *p*-value much less than 0.0001, showing that lime had a significantly higher mean value than each of the remaining stabilisers. This finding confirmed the previously derived conclusion that adding 5% lime

to clay soil achieved the best effect in terms of increasing the UCS value. When it came to magnesium carbonate, except in comparison with lime, this stabiliser showed a more dominant effect on the UCS value of the treated clayey soil compared to the remaining five stabilisers (pairwise comparisons MC5–FA15, MC5–SS5, MC5–FC2, MC5–CC2, and MC5–PC2), which was also in line with the previously drawn conclusion about the effect of adding 5% magnesium carbonate to the clayey soil on the achieved UCS value. By comparing CC2–PC2, it was observed that the addition of CC2 resulted in a higher mean UCS value compared to the value of PC2, which was ultimately consistent with the results and the displayed order of stabilisers in terms of their effectiveness given in Figure 5.

On the other hand, in the comparisons of the corresponding pairs among FA5, SS5, FC2, and PC2, no significant difference was observed in the achieved mean values (i.e., the corresponding p-values were greater than 0.0024 and the t-values were less than the critical t-values).

However, bearing in mind that the reliability and quality of statistical analysis rely on the number of samples included, the importance of conducting UCS tests on a larger number of samples than was considered in this study should be emphasised, which would ultimately be reflected in a greater significance, adequacy, and meaningfulness of the statistical analysis of the results.

3.2. Soil Shear Strength

The shear strength is one of the most important geomechanical properties of soil. It is defined by the Coulomb–Mohr failure criterion, which gives the dependence of shear stress (τ) and normal stress (σ) in the form $\tau = \sigma \cdot \mathrm{tg}\varphi + c$, where c and φ are the shear strength parameters of the soil, i.e., cohesion and internal friction angle. These parameters were determined as part of the research by a direct shear test.

The tests were performed on samples with the optimal content for each of the selected stabilisers obtained from the UCS test. The tests were carried out at three time intervals—3, 14, and 28 days after mixing the stabiliser with the natural soil. For each of the considered stabilisers and for each of the considered time intervals after soil treatment, in accordance with the specified standard (Section 2.2), three specimens from one soil sample were prepared for shearing under three different vertical pressures to allow the shear strength parameters to be determined.

The shear stress at failure (τ) of the clayey soil mixtures with the considered stabilisers under normal stresses (σ) of 50 kPa, 100 kPa, and 200 kPa is shown in Table 6. The shear stress values at failure of the natural clayey soil for applied normal stresses σ of 50 kPa, 100 kPa, and 200 kPa were 30.9 kPa, 49.8 kPa, and 78.1 kPa, respectively. It can be seen that the shear strength increased over time in the case of all the considered stabilisers. According to these results, all the maximum shear strength values were obtained at the test time of 28 days after the treatment, at a normal stress of 200 kPa. For example, for traditional stabilisers—lime (L5) and fly ash (FA15)—the maximum shear stress value was 167.8 kPa and 93.2 kPa, respectively. The values obtained on the samples with the addition of lime also represent the highest recorded values among all the tested samples.

The results obtained by adding fly ash were among the weakest in this test, since only the addition of ferric chloride (FC2) and potassium chloride (PC2) also resulted in a smaller increase in shear strength (88.6 kPa and 85.7 kPa, respectively). Although much lower than the others, these values are still higher than the shear strength of natural clayey soil (78.1 kPa).

A similar trend was observed at normal stresses of 50 kPa and 100 kPa. It is interesting to note that at a normal stress of 50 kPa, the mixture with the optimal content of fly ash had the lowest shear strength value.

Table 6. Recorded stresses at failure (τ) for applied normal stresses (σ) in the direct shear test.

Stabiliser (Label of a Mixture)	Normal Stress σ (kPa)	Shear Stress at Failure τ (kPa) *		
		After 3 Days	After 14 Days	After 28 Days
Traditional stabilisers				
Lime (L5)	50	48.1	61.4	72.2
	100	80.2	85.7	108.0
	200	117.7	141.3	167.8
Fly Ash (FA15)	50	32.4	35.7	38.7
	100	54.6	56.7	60.8
	200	81.1	89.1	93.2
Alternative materials				
Magnesium Carbonate (MC5)	50	40.1	41.4	44.6
	100	71.4	78.9	82.8
	200	103.1	109.2	119.9
Sodium Silicate (SS5)	50	36.2	41.5	42.1
	100	58.7	63.7	65.1
	200	94.2	101.2	114.0
Ferric Chloride (FC2)	50	31.5	36.2	39.4
	100	47.7	49.1	51.8
	200	79.5	83.6	88.6
Calcium Chloride (CC2)	50	34.3	40.8	44.9
	100	48.3	53.7	54.6
	200	83.6	90.1	95.2
Potassium Chloride (PC2)	50	30.1	34.1	39.4
	100	49.2	46.7	48.0
	200	77.1	83.8	85.7

* The shear stress values at failure (τ) of the natural clayey soil for the applied normal stresses (σ) of 50 kPa, 100 kPa, and 200 kPa were 30.9 kPa, 49.8 kPa, and 78.1 kPa, respectively.

During the test, the ratio of changes in shear stress (τ) and displacement (δ) along the failure plane was also recorded, which is illustrated in Figure 6. The diagrams represent the dependence of these values at normal stresses of 50 kPa, 100 kPa, and 200 kPa, 3 and 28 days after the treatment.

It can be clearly seen that the greatest changes occurred in the case of the mixture with the addition of lime (L5). In addition to significantly higher values of shear stress, the shape of the diagrams has a pronounced peak, indicating a brittle failure.

Considering the alternative stabilisers, the sample with the addition of magnesium carbonate (MC5) alone indicated the occurrence of a brittle fracture. All other samples indicated a ductile failure; that is, without a great change in the shear force, there was a significant displacement along the failure plane.

The registered changes in the values of shear strength parameters (cohesion (c) and internal friction angle (φ)) in relation to the natural state of the clayey soil (c = 16.9 kPa and φ = 16.5°) are given in Figures 7 and 8.

The lime-based stabiliser significantly contributed to an increase in shear strength parameters compared to the natural clayey soil. The improvement in these soil properties was noticeable for all the test time intervals.

With the addition of lime (L5), the trend of increasing shear strength parameter values with time was almost linear, both in terms of the increase in the value of cohesion (after 28 days, the increase in the value of c was 2.5 times), and in terms of the increase in the internal friction angle (after 28 days, the increase in the value of φ was two times).

The addition of fly ash (FA15), compared to lime, had a smaller effect on the change in the strength parameters of the clayey soil (the increase in the value of c was 33%, and the value of φ was 17%).

Alternative stabilisers also contributed to improving shear strength parameters, to a lesser extent than the traditional one—lime, however.

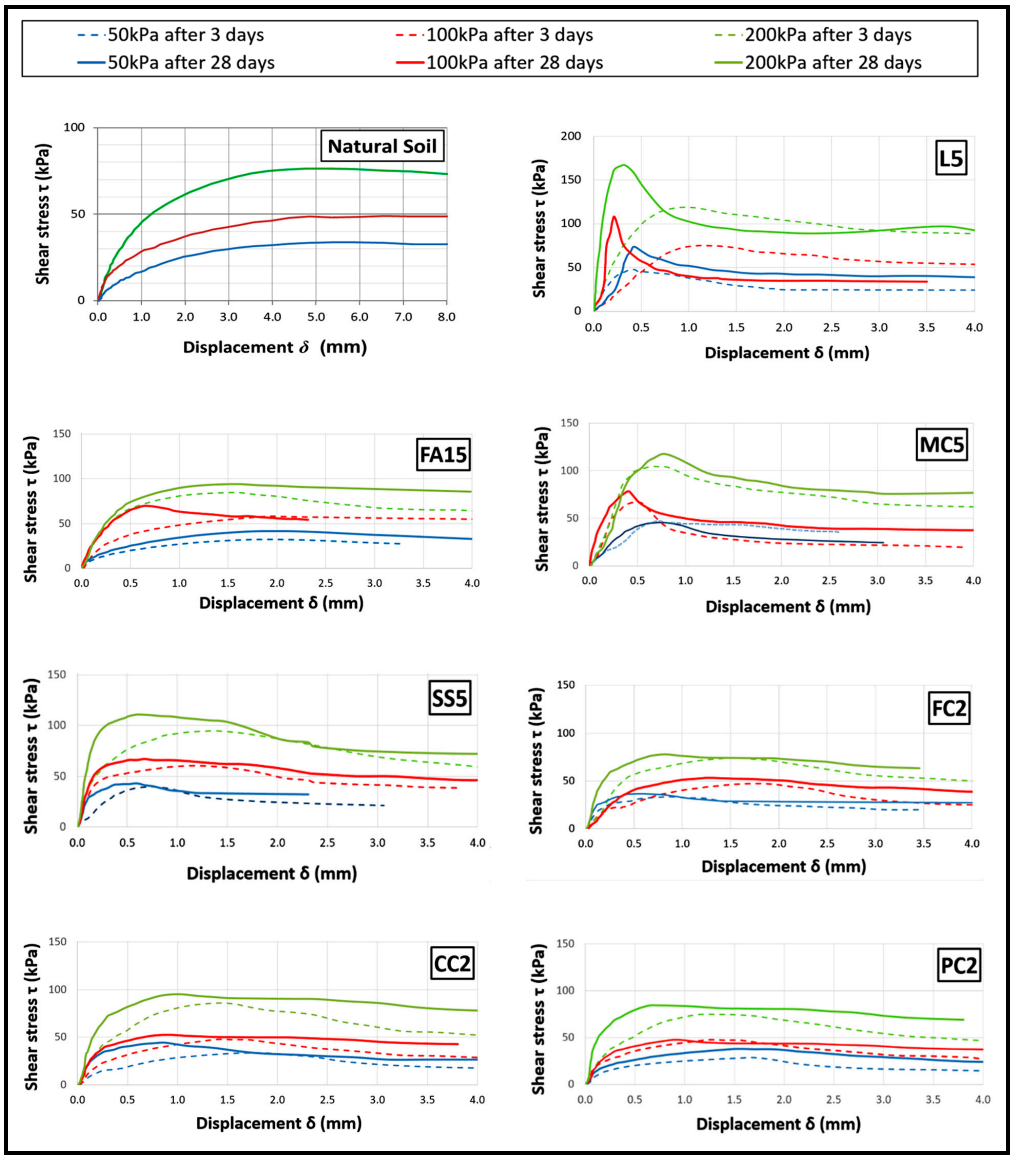


Figure 6. Shear stress–displacement behaviour at normal stresses of 50 kPa, 100 kPa, and 200 kPa, 3 days and after 28 days after the treatment of clayey soil with the optimal stabiliser content for each of the selected stabilisers.

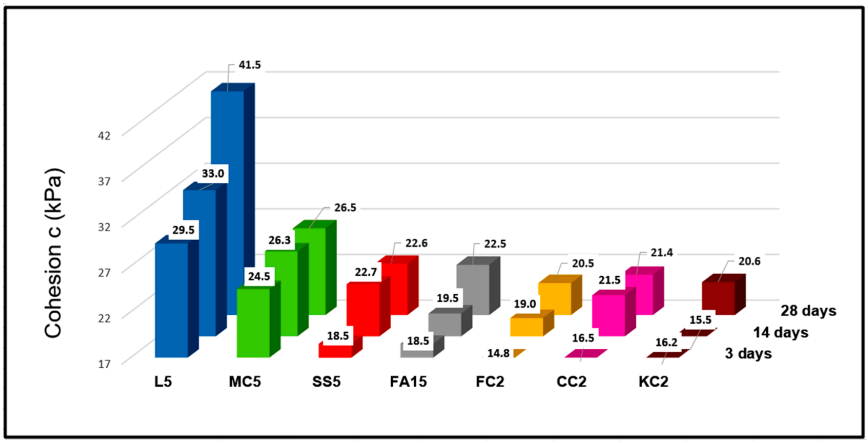


Figure 7. Comparison of the trend of change in cohesion over time after the chemical stabilisation of clayey soil with the corresponding optimal content for each of the selected stabilisers.

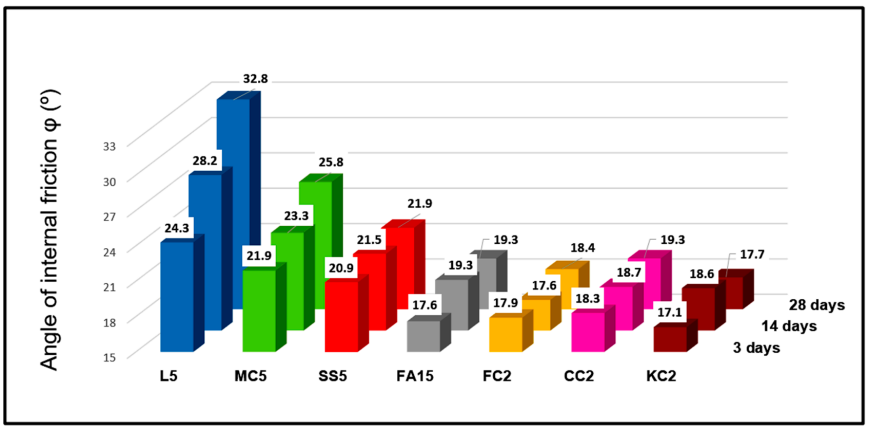


Figure 8. Comparison of the trend of change in internal friction angle over time after the chemical stabilisation of clayey soil with the corresponding optimal content for each of the selected stabilisers.

The greatest improvement in the strength parameters was recorded with the addition of magnesium carbonate (MC5) as an alternative material (after 28 days, the increase in the value of c was 50%, and the increase in the value of φ was the same).

With the addition of sodium silicate (SS5), the values of the soil shear strength parameters were also improved compared to the natural state—the results for the cohesion value after 14 days and 28 days were very similar in value, whereas the increase in the value of the internal friction angle was already apparent in the initial period of 3 days after the treatment, and that value did not significantly change over time (the increase in both the c value and the φ value was about 35%).

For each of the considered chlorides (FC2, CC2, PC2), the cohesion was slightly reduced after 3 days compared to the cohesion value of the natural clayey soil, whereas the internal friction angle increased. After 14 days, with the addition of potassium chloride (PC2), the value of cohesion was still lower than the value of soil cohesion in its natural state, whereas 28 days after the treatment, in the case of each of the considered chlorides, an improvement in the initial values of the strength parameters was observed (values of c and φ were increased by about 15%).

Figure 9 shows the Coulomb–Mohr failure line for all the stabilisers considered in this research, obtained by direct shear tests on samples tested 28 days after the clayey soil treatment. Regarding cohesion, which represents the interception on the shear stress axis (τ), approximate values in the range from 20.5 kPa to 26.5 kPa were recorded for all considered stabilisers, except lime (L5), in which case the largest increase in cohesion (41.5 kPa) was recorded in relation to the natural state of the soil (c = 16.9 kPa), which was an increase of almost 2.5 times.

On the other hand, there were significant changes in the value of the internal friction angle, which represents the slope of the Coulomb–Mohr line. The illustrated lines for each of the considered stabilisers have a clearly noticeable same or higher slope compared to the slope of the line for the natural soil (whose value of the internal friction angle is φ = 16.5°). It can be clearly seen that the greatest change was observed for the case of the addition of 5% lime (L5), whereby the registered value of the angle φ was 32.8° (therefore, almost twice the value was achieved).

In addition to lime, a significant change in the slope of the Coulomb–Mohr line was also observed in the case of the addition of magnesium carbonate (MC5, φ = 25.8°) and sodium silicate (SS5, φ = 21.9°). For the case of the remaining reagents, one observed an approximate translational shift of the Coulomb–Mohr line in relation to the one representing the natural soil, which indicates a small change in the internal friction angle of the soil. On

the other hand, the translational shift of the line indicates an increase in the cohesion of the examined mixtures and, therefore, a significant increase in the shear strength of the soil.

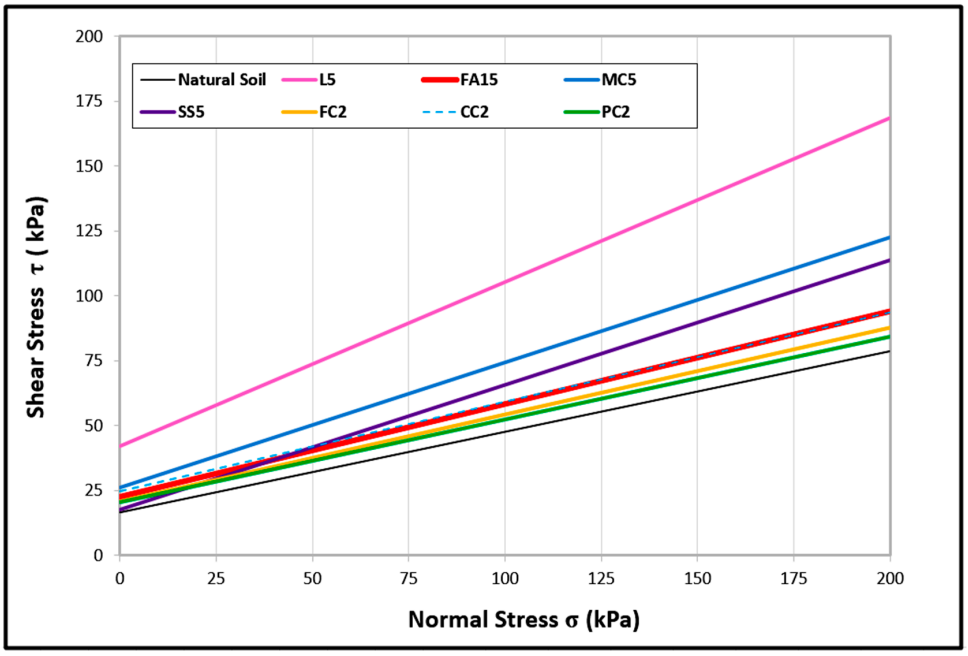


Figure 9. Comparison of the effects of each of the considered stabilisers on the shear strength parameters of clayey soil achieved 28 days after treatment.

4. Concluding Remarks

In this research, the individual effects of adding different materials using the chemical stabilisation technique on improving the mechanical properties of clayey soil were investigated, taking into account the traditional stabilisers (lime and fly ash), as well as alternative materials (magnesium carbonate, sodium silicate, and chloride-based compounds—ferric chloride, calcium chloride, and potassium chloride). The research consisted of two stages. First, clayey soil samples with each of the selected stabilisers at three different content percentages in the soil mixture were prepared under laboratory conditions and tested in UCS tests. This research stage aimed to determine the optimal content of each stabiliser in the mixture. Changes in the UCS value of the examined samples were also monitored at different time intervals after the treatment (3, 14, and 28 days) in order to determine the durability of the effects of the implemented chemical stabilisation. In the second part of the research, tests were conducted on the effect of the optimal content of each of the tested stabilisers on the shear strength parameters through a direct shear test. Here again, the test was carried out at the same time intervals and with the same goal: to determine the long-term effectiveness of improving soil properties with the selected stabilisers. The most important conclusions that can be drawn based on the research conducted are:

- In terms of UCS values obtained, when it comes to traditional stabilisers, lime proved to be a significantly better stabiliser than fly ash. With the addition of lime, an increase in the UCS value was recorded, both with an increase in the lime content and over time. A more significant increase in the UCS value was observed with an increase in lime content from 3% to 5% than from 5% to 7%, which indicates that 5% can be considered as the optimal lime content. The addition of fly ash also contributed to an increase in the UCS value compared to natural soil, and the highest values were recorded with the addition of 15%; significant changes in UCS values, however, were not recorded over time.

- Alternative stabilisers based on chloride have the least effect on increasing the UCS value of the soil, whereas the best results were achieved with the addition of magnesium carbonate. In the first 14 days, the UCS value with the addition of magnesium carbonate was similar to that with the addition of lime, but it did not increase significantly until the 28th day. With regard to the optimal content of alternative stabilisers, 5% magnesium carbonate and sodium silicate and 2% considering all chlorides (ferric chloride, calcium chloride, and potassium chloride) were determined.
- The above-given conclusions regarding the effectiveness of the considered stabilisers in terms of increasing the UCS value of clayey soil were also validated and confirmed by statistical analysis performed using the ANOVA method and two-by-two comparisons. The importance of conducting this test on a larger number of samples with the aim of confirming the reproducibility and effectiveness of the proposed soil improvement treatments should be emphasised.
- An increase in soil shear strength was observed with the addition of the optimal stabiliser content for each of the selected stabilisers. The greatest increase in the cohesion value was recorded 28 days after the treatment with the addition of 5% lime, whereas the smallest increase compared to the natural clayey soil was recorded with the addition of 2% potassium chloride. Of the alternative stabilisers, the greatest change was noted with the addition of magnesium carbonate, as well as with the addition of sodium silicate. Cohesion values of samples treated with any of the selected chlorides obtained 3 days after the treatment did not differ significantly from cohesion value in the soil's natural state, whereby with the addition of potassium chloride, no change was registered even 14 days after the treatment.
- An increase in the value of the internal friction angle was recorded with the addition of lime, magnesium carbonate, as well as sodium silicate, whereas for all other considered stabilisers, the obtained values of φ were close to the value of natural soil, regardless of the time elapsed after the treatment.
- During the direct shear test, changes in the failure mode of the treated soil can be observed based on the δ–τ diagram. Namely, the samples with the addition of lime and the samples with the addition of magnesium carbonate had a more pronounced peak at failure compared to the other stabilisers, which indicates a brittle failure of the soil. In the case of other stabilisers, ductile failure was recorded.

After conducting this research, the obtained results confirmed that improving the geomechanical properties of clayey soil can be achieved both by using traditional stabilisers, primarily lime, and by using alternative stabilisers, primarily magnesium carbonate and sodium silicate. Among the tested stabilisers, lime, with a 5% content in the mixture with clayey soil proved to be the most effective reagent, both in terms of UCS and in terms of soil shear strength parameters. Nevertheless, this study confirmed that alternative additives, in particular, magnesium carbonate or sodium silicate (both with a percentage content of 5% in the mixture), are also substantially promising as sustainable stabilisation materials considering the examined geotechnical properties of the soil. What should be kept in mind, though, is that in order to meet the requirements of a specific project, site-specific soil testing with the selected stabiliser should be mandatory. In everyday engineering practice, it is usual that in most cases, a 3% stabiliser content is considered quite sufficient; however, a large number of studies in this field, including the one presented, reveal that the optimal content of additives depends both on the stabiliser itself and on the composition of the specific type of soil.

Taking all of the above into account, it can be concluded that each of the considered stabilisers added to natural clayey soil would enable its application for various practical purposes in the field of construction. In particular, the technique of chemical soil stabilisa-

tion has a wide application in the field of road construction for the purpose of stabilising road subgrade layers. This method also has a potential application for improving the bearing capacity of soil, which will serve as a subsoil in the foundation construction. The chemical stabilisation technique is considered the best method of soil stabilisation in terms of cost-effectiveness and efficiency, as well as its eco-friendliness.

Finally, it should be emphasised that all the results presented in this paper refer to the local clayey soil of a specific mineralogical composition. Therefore, there is a need for further comprehensive research, which will analyse a wider range of soils with different mineralogical compositions.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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