

Analysis of the effect of adding various additives to fine-grained soil on the improvement of the soil shear strength parameters

Nemanja Marinković, Zoran Bonić, Elefterija Zlatanović, Nebojša Davidović, Nikola Romić, Snežana Djorić-Veljković

University of Niš, Faculty of Civil Engineering and Architecture of Niš, Serbia, nemanja.marinkovic@gaf.ni.ac.rs

ABSTRACT: Fine-grained soils generally have low bearing capacity, so improving their strength parameters (cohesion and internal friction angle) represents one of the greatest challenges in geotechnical engineering. For this purpose, chemical soil stabilization is most often applied in engineering practice. This paper presents and analyzes the results of testing fine-grained soil to which various additives were added, in order to evaluate their effectiveness. For each additive used in this research (cement, rock flour, magnesium carbonate, and calcium chloride) the optimal content in the treated soil was determined based on unconfined compressive strength testing. After that, a series of direct shear tests were carried out on the samples with the optimal content of each additive. The samples were tested 3, 14 and 28 days after adding the reagent. The results obtained in this research revealed that all considered additives contribute, to a greater or lesser extent, to the improvement of the shear strength parameters of fine-grained soil. The presented results indicate the importance of adequate (careful) selection of an additive depending on both the properties and the planned purpose of the fine-grained soil, and the paper itself provides guidelines for optimizing the stabilization process of fine-grained soil in construction industry projects.

KEYWORDS: Clayey soil, chemical stabilization, additives, shear strength, cohesion, angle of internal friction.

1 INTRODUCTION

Fine-grained soils, due to their specific texture and physico-chemical characteristics, often represent a challenge in geotechnical engineering. Low bearing capacity, high compressibility and tendency to swell under the influence of water, make this type of soil unsuitable for direct application without prior improvement of its engineering properties (Chittoori et al., 2011; Ademila, 2017; Seco et al., 2020). In practice, one of the most commonly applied approaches to improve the properties of these soils is chemical stabilization – a process that involves adding reagents to the soil in order to improve its physical, chemical and mechanical properties (Han, 2015; Zafirovski et al., 2024).

This study is focused on examining the effects of four different additives – cement, rock flour, magnesium carbonate and calcium chloride – on improving the unconfined compressive strength and particularly the shear strength of clayey soil. Research was conducted in two stages. In the first stage, for each of the additives used, the optimal additive content in the soil mixture was determined based on the results of the unconfined compressive strength (UCS) tests. After that, in the second stage, direct shear tests were conducted on soil samples with the optimal content of each additive at different time intervals – 3, 14 and 28 days after the treatment. In this way, it was possible to monitor the change in the shear strength of the soil over time, with the aim of assessing the durability of the stabilization effects.

Therefore, the goal of this research was to determine, through a comparative analysis of the effects of different additives, which of them provides the most favorable results in improving the mechanical properties of clayey soil. Special attention was paid to the effects of the type of additive and the curing time on the change in cohesion and angle of internal friction, as the most important parameters in geotechnical engineering. The results presented in this paper can serve as guidelines in the selection of additives in accordance with specific engineering requirements and soil characteristics, thus contributing to a more efficient and economical design of engineering structures.

2 MATERIALS AND METHODS

Clayey soil taken from the area around Crvena reka, which is located along the route of the E-80 Niš–Dimitrovgrad Highway in the southeastern part of the Republic of Serbia, was used for the research purposes. During the construction of this section of the Highway, an activated landslide was observed at the specified location. As part of the planned remediation measures, the construction of a retaining structure in the form of a curtain of bored piles was foreseen. Clayey soil for the purposes of this study was taken precisely during the execution of these works, from the depth at which the existence of a sliding surface was determined.

2.1 Properties of soil

The basic physico-mechanical properties of clayey soil in its natural state are given in Table 1. All laboratory tests were carried out in the Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of the University of Niš.

Table 1. Physico-mechanical properties of clayey soil in its natural state.

Property of soil	Symbol (unit)	Value
Particle density	Gs (–)	2.705
	Gravel (%)	1.2
Grain size distribution	Sand (%)	4.9
	Silt (%)	40.6
	Clay (%)	53.3
USCS soil classification	Symbol (–)	CL
Maximum dry density	MDD (g/cm ³)	1.903
Optimal moisture content	OMC (%)	18.5
Liquid limit	LL (%)	49
Plastic limit	PL (%)	23
Unconfined compressive strength	UCS (kPa)	205
Cohesion	c (kPa)	16.9
Internal friction angle	φ (°)	16.5

2.2 Properties of additives

For stabilization with **cement**, there are almost no restrictions when it comes to the type of soil, but clays with a plasticity index of up to 20% are considered to be one of the most suitable types of soil for this type of additive (Chittoori et al., 2011). The optimal content of cement for clayey soils with a liquid limit (LL) of 40% to 60% is from 4% to 12% in the mixture with the soil (Horpibulsuk et al., 2010). In the present research, HRB E2 cement was used. In order to determine the optimal content of cement in the mixture with clayey soil, in this research, samples with the addition of 5%, 10% and 15% of cement in the soil mixture were tested.

Rock flour is waste from stone quarries and is successfully used for making asphalt mixtures for road construction. It is created during the production of crushed stone, where about 20% of the rock material is turned into waste material – rock flour. Research has shown that adding up to a maximum of 15% rock flour can successfully improve the geotechnical properties of soils (Ademila, 2017). Accordingly, in the present research, samples with 5%, 10% and 15% rock flour in the soil mixture were examined.

Magnesium carbonate, as an additive, represents an alternative to traditional calcium-based binders, due to its ability to react with soil in the presence of water. Compared to cement, soil reactions with magnesium carbonate are slower and require a longer time to achieve an increase in the mechanical strength of the soil. For this reason, magnesium carbonate is more often used as a supplementary or secondary additive, in combination with other additives (Seco et al., 2020). In the present research, samples with 3%, 5% and 7% magnesium carbonate in the soil mixture were examined.

Chloride-based compounds can be applied directly to the soil layer before compaction or injected under pressure into deeper layers (Marto et al., 2014). When it comes to the optimal content of chloride-based additives, the literature states that sometimes less than 1% chloride is the optimal content required for stabilization (Vinod et al., 2021). In the present research, the soil was treated with the addition of 1%, 2% and 3% **calcium chloride**.

Percentage shares of additives in the soil mixture considered in the study, along with the corresponding labels of the mixtures, are summarized in Table 2.

Table 2. Percentage shares of additives in the soil mixture considered in the study.

Additive	Percentage share of additive in the soil mixture	Label of the mixture
Cement	5%	C5
	10%	C10
	15%	C15
Rock flour	5%	RF5
	10%	RF10
	15%	RF15
Magnesium carbonate	3%	MC3
	5%	MC5
	7%	MC7
Calcium chloride	1%	CC1
	2%	CC2
	3%	CC3

2.3 Research methods

The soil material from the mentioned location was brought to the laboratory. Firstly, it was dried in an oven at a temperature of 105°C for 24 h. After that, the soil was crushed and then sifted on a 4 mm sieve, with the aim of eliminating sporadic coarse-grained fractions. Selected additives were added individually to the clayey soil prepared in this way, with the considered percentage shares in the mixture with the soil in relation to the dry weight of the soil.

The unconfined compressive strength (UCS) test was applied to all specimens according to the national standard SRPS EN ISO 13286-41:2022 (ISS, 2022), which is harmonized with European Norms. Each sample had been compressed until ultimate load was achieved, where the applied load was recorded by a data acquisition system. The UCS tests were used to determine the unconfined compressive strength both of the clayey soil in natural conditions and the chemically treated soil for each of the four considered additives.

The direct shear test was also performed according to the corresponding national standard, harmonized with European Norms, SRPS EN ISO 17892-10:2019 (ISS, 2019). The samples were of square shape at the base, with dimensions of 6.0 cm × 6.0 cm, and with height of 2.0 cm. During testing, the samples were treated with normal stress of 50 kPa, 100 kPa and 200 kPa. The shear rate was 0.0083 mm/min.

The samples for these tests were prepared with a moisture content equal to the optimum moisture content of natural soil obtained according to the standard Proctor test (Table 1, OMC = 18.5%), for the sake of comparability of the results of the natural and the treated clayey soil. 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.

3 ANALYSIS AND RESULTS

3.1 Unconfined compressive strength (UCS)

The clayey soil samples underwent testing for various contents of additives in the mixture with the soil and different curing times, specifically at intervals of 3, 7 and 28 days after the chemical treatment. The results of the UCS tests for the treated soil are presented in Figure 1, in which each data point represents the average value of three tested samples per additive, for each percentage share of the additive in the soil mixture and for each curing time interval.

Overall, the results confirmed that each of the considered additives contributed to improvement in the UCS of the treated soil. Cement and magnesium carbonate exhibited the most pronounced effects, with significant strength increase over time. Conversely, rock flour and calcium chloride produced more modest improvements in the UCS, highlighting their comparatively lesser impact.

The samples treated with **cement** demonstrated the highest UCS values after the treatment (Fig. 1(a)). A clear improvement in UCS was observed as the percentage share of cement in the mixture with the clayey soil increased. Regardless of the quantity of cement added, substantial improvements in UCS were evident over time. For instance, after a 3-day curing period, the UCS increased from 205 kPa (untreated clayey soil) to 307 kPa for soil treated with 5% cement (C5), whereas the addition of 15% cement (C15) resulted in an UCS increase to 776 kPa. After 28 days of curing, the UCS rose to 785 kPa and 1425 kPa for the 5% and 15% cement contents in the mixture, respectively.

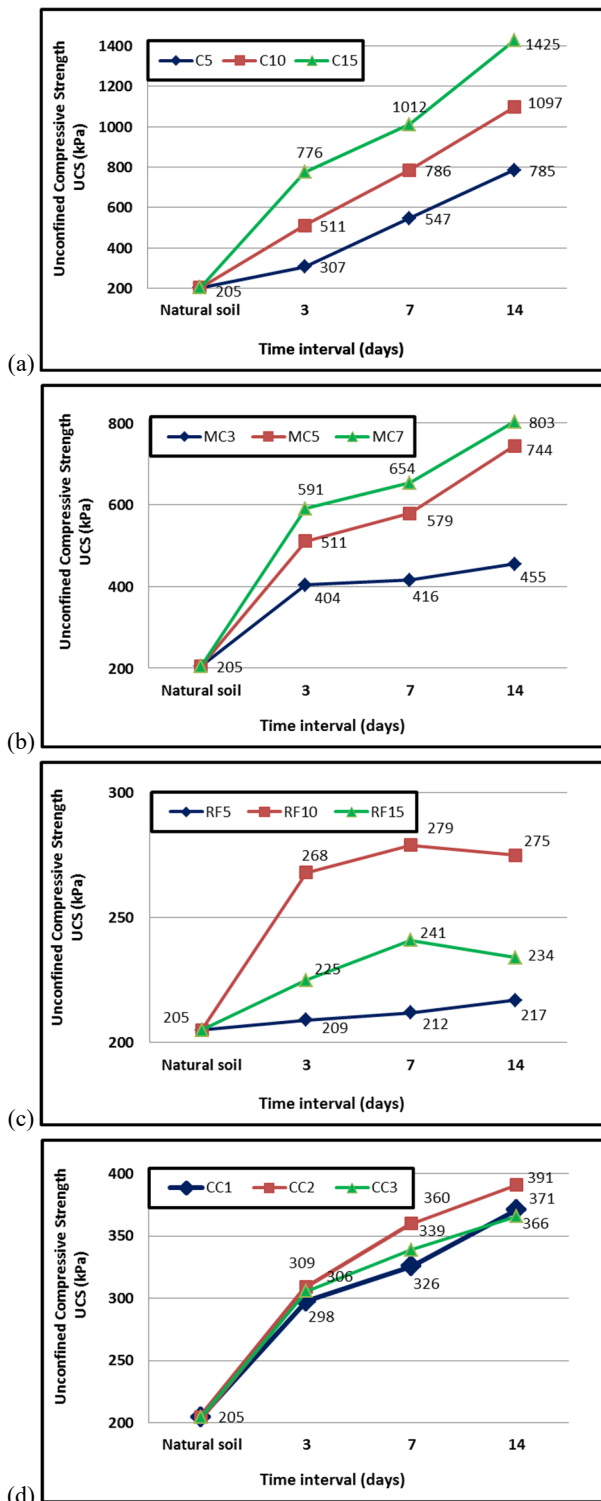


Figure 1. Changes in the soil UCS values with increasing additive content in the mixture over time: (a) cement; (b) magnesium carbonate; (c) rock flour; (d) calcium chloride.

The addition of **magnesium carbonate** yielded results comparable to those obtained with cement, particularly at 5% (MC5) and 7% (MC7) content levels, but this similarity was only observed during the first 3 days of curing. By the end of 28 days, the samples treated with magnesium carbonate exhibited UCS values significantly lower than those treated with cement (Fig. 1(b)). In addition, the increase in UCS values was more pronounced when the magnesium carbonate content was raised from 3% to 5%, rather than from 5% to 7%. For instance, after 3

days of curing, the UCS values were 404 kPa for 3% magnesium carbonate (MC3) and 591 kPa for 7% (MC7). After 28 days of curing, the UCS values were 455 kPa and 803 kPa for magnesium carbonate contents of 3% and 7%, respectively.

The measured UCS values achieved with the addition of rock flour and calcium chloride (Figs. 1(c) and (d)) were notably lower compared to those obtained with cement and magnesium carbonate. Nonetheless, their use still led to a measurable improvement in the soil's unconfined compressive strength. Specifically, the highest UCS value recorded for **rock flour** was 275 kPa, achieved with 10% additive content (RF10) after 28 days of curing (Fig. 1(c)). Interestingly, the results demonstrated that with 10% rock flour content, slightly higher UCS values were observed than with 15% content (RF15), over corresponding curing periods.

The samples treated with **calcium chloride** achieved a maximum UCS value of 391 kPa with a content of 2% (CC2) after 28 days (Fig. 1(d)). It was also observed that the UCS values between 3 and 28 days had a smaller increase compared to the initial period after treatment, regardless of the percentage of calcium chloride used. As with rock flour, with a higher calcium chloride content of 3% (CC3), the results were lower than with a content of 2% (CC2), at the same time intervals.

The observed improvement in soil strength during the curing process can be attributed to the formation of a gel-like material with strong binding properties. This material forms due to chemical interactions between the soil and the stabilizing agent, which enhances unconfined compressive strength of the treated soil.

When determining the optimal content of additives in the mixture with the clayey soil, UCS values and rational consumption of additives were considered. Accordingly, the following values of the optimal content of additives were determined: for cement 15%, for magnesium carbonate 5%, for rock flour 10% and for calcium chloride 2%.

3.2 Shear strength of the soil

The shear strength of the soil is one of the most important geomechanical properties of the 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 $\tau = \sigma \cdot \tan \varphi + c$, where c and φ are the shear strength parameters of the soil, i.e. cohesion and angle of internal friction. These parameters were determined as part of the research by direct shear tests. The tests were performed on soil samples with the optimal content for each of the selected additives obtained from the UCS tests. The tests were carried out at three time intervals – 3, 14 and 28 days after mixing the additive with the natural soil.

Shear stress at failure (τ) of clayey soil mixtures with the considered additives under normal stress (σ) of 50 kPa, 100 kPa and 200 kPa is shown in Table 3. It can be seen that the shear strength increased over time for all additives considered. 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.

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 $\varphi = 16.5^\circ$) are given in Figure 2.

The **cement-based additive** (C15) significantly contributed to the increase in shear strength parameters compared to the natural state of the soil. The improvement of these soil properties is noticeable for all the test time intervals. The increase in shear strength parameter values with time was quite pronounced, both in terms of the increase in the value of cohesion (after 28 days, 2.5 times), and in terms of the increase in the angle of internal friction (after 28 days, two times).

Table 3. Recorded stresses at failure (τ) for applied normal stresses (σ) in the direct shear test.

Additive (label of the mixture)	Normal stress σ (kPa)	Shear stress at failure τ (kPa)*		
		3 days after treatment	14 days after treatment	28 days after treatment
Cement (C15)	50	55.2	61.4	75.7
	100	87.9	90.2	115.1
	200	131	135.7	178.6
Rock flour (RF10)	50	40.6	42.7	46.7
	100	59.8	66.7	65.2
	200	91.7	97.5	98.7
Magnesium carbonate (MC5)	50	40.1	41.4	44.6
	100	71.4	78.9	82.8
	200	103.1	109.2	119.9
Calcium chloride (CC2)	50	34.3	40.8	44.9
	100	48.3	53.7	54.6
	200	83.6	90.1	95.2

* 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.

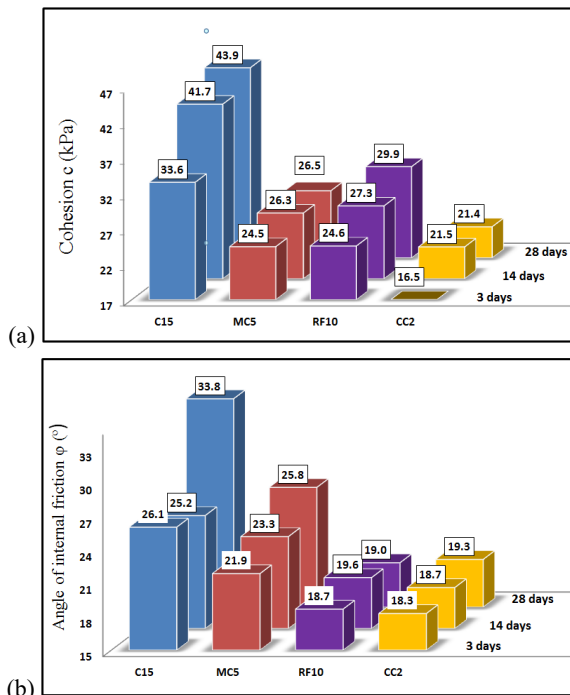


Figure 2. Changes in the soil shear strength parameters over time after chemical stabilization of soil with the optimal content of selected additives: (a) cohesion; (b) angle of internal friction.

The improvement in the strength parameters was also recorded with the addition of **magnesium carbonate** (MC5). After 28 days, the increase in the values of c and ϕ was 50%.

By adding **rock flour** (RF10), the cohesion values were significantly improved over time compared to the natural soil state, and after 28 days, the increase in the value of c was around 75% (Fig. 2(a)). On the other hand, the increase in the value of the internal friction angle did not change significantly over time and amounted to around 20% (Fig. 2(b)).

The weakest results in terms of increasing the strength parameters were achieved by adding **calcium chloride**. The cohesion value increased after 14 days, when it reached a maximum value (an increase in the c value of about 25%). On

the other hand, the value of the angle of internal friction increased after 3 days and did not change significantly over time (an increase in the ϕ value of about 15%).

4 CONCLUSION

The results presented in this paper confirmed that the improvement in soil properties can be successfully achieved by applying cement, magnesium carbonate, rock flour, and calcium chloride as additives to clayey materials. Each of the considered additives, added to the natural clayey material, contributed to a significant increase in the shear strength parameters of the clayey soil and thus enabled its application for various practical construction purposes.

In terms of cohesion, cement proved to be the most effective additive, followed by rock flour, magnesium carbonate and finally calcium chloride. Regarding the internal friction angle, the most effective additive was again cement, followed by magnesium carbonate, whereas the effects of rock flour and calcium chloride were almost the same.

In general, given the shear strength of the soil, the best improvement was achieved by adding cement; the effect of adding magnesium carbonate was weaker, whereas rock flour and calcium chloride resulted in the same effect as the weakest.

5 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Science Fund of the Republic of Serbia in the scope of the scientific-research project "A New Concept in Improvement of Geotechnical Properties of Ground – Chemical Electrokinetic Treatment of Soils (ElectroSoil)", Grant No. 7742530.

6 REFERENCES

- Ademila, O. 2017. Stabilization of lateritic soils with rock flour in highway pavement layers construction. *African Journal of Renewable and Alternative Energy*, 2(2), 6-15.
- Chittoori, S., Pedarla, A., Puppala, A. J., Hoyos, L. R., Nazarian, S., and Saride, S. 2011. Leachate studies on lime and portland cement treated expansive clays. *In Geo-Frontiers 2011: Advances in Geotechnical Engineering*, 4479-4488. [https://doi.org/10.1061/41165\(397\)458](https://doi.org/10.1061/41165(397)458)
- Han, J. 2015. *Principles and practice of ground improvement*. Hoboken, NJ, USA : John Wiley & Sons.
- Horpibulsuk, S. 2012. Strength and microstructure of cement stabilized clay. *In Scanning electron microscopy. Intech Open*. <https://doi.org/10.5772/35225>
- Institute for Standardization of Serbia, 2022. *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*. Belgrade: ISS.
- Institute for Standardization of Serbia, 2019. *SRPS EN ISO 17892-10:2019; Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 10: Direct Shear Tests*. Belgrade: ISS.
- Marto, A., Latifi, N. and Eisazadeh, A. 2014. Effect of non-traditional additives on engineering and microstructural characteristics of laterite soil. *Arab. J. Sci. Eng.*, 39, pp. 6949-6958. <https://doi.org/10.1007/s13369-014-1286-1>
- Seco, A., del Castillo, J.M., Espuelas, S., Marcelino, S. and Garcia, B. 2020. Sulphate soil stabilisation with magnesium binders for road subgrade construction. *Int. J. Pavement Eng.*, 23(6), pp. 1840-1850. <https://doi.org/10.1080/10298436.2020.1825711>
- Vinod, B.R., Shobha, R., Varun Purad, A.T. and Mansi, S. 2021. Analysis of engineering properties of expansive soil treated with ferric chloride and bagasse ash. *Int. J. Contemp. Arch. - New Arch*, 8(2), pp. 460-467.
- Zafirovski, Z., Markovski, M., Ognjenovic, S., Gacevski, V., Nedevska, I., and Ristov, R. 2024. Subbase stabilization with fly ash. *Facta Univ. Ser. Arch. Civ. Eng.* 22, pp. 79-88. <https://doi.org/10.2298/FUACE230630033Z>