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Research paper

IMPROVING THE MECHANICAL PROPERTIES OF CLAYEY SOIL BY ADDING WASTE MATERIAL - FLY ASH AND ROCK FLOUR

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Abstract

Stabilization of clayey soil with an inadequate physical and mechanical properties in its natural state represents one of the actual challenges in contemporary geotechnical engineering. Among numerous stabilization techniques, chemical stabilization stands out as an effective technique for stabilizing clayey soils. By applying this technique, various types of stabilizers may be used, whereby they react with soil particles and modify its structure, contributing to the permanent improvement of the physical and mechanical properties of the soil. In this study, waste materials obtained as a product of industrial processes, such as fly ash and rock flour, were considered as chemical stabilizers. A comparative analysis of the effects of adding fly ash and rock flour on improving the uniaxial compressive strength (UCS) and the shear strength parameters of clayey soil was performed, while simultaneously monitoring the durability of the achieved effects.

Key words: *chemical stabilization, clayey soil, fly ash, rock flour, UCS, shear strength parameters*

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1. INTRODUCTION

Chemical stabilization of soils is a widely applied technique aimed at enhancing the engineering properties of soils that, in their natural state, fail to meet required performance criteria. With the advancement of industrial processes, increasing attention is being paid to the use of industrial by-products as adequate alternative substitutes for conventional stabilizing agents. This trend is evident across all branches of civil engineering, including geotechnical engineering. Among the by-products with high potential for such applications are fly ash, a residue from thermal power plants, and rock flour (filler), a material generated through the mechanical crushing of rock masses in quarries [1-4].

Traditionally, soil stabilization has relied on the use of binding agents such as cement and lime. However, the production of these materials is associated with considerable CO_2 emissions, high energy consumption and substantial economic costs [5]. Consequently, recent research has increasingly focused on the use of alternative materials—particularly industrial waste products—that can function as reagents, activators, or supplementary stabilizers. These materials not only reduce the overall cost of soil treatment, but also promote environmental sustainability through waste recycling.

The aim of this study is to investigate the effect of fly ash and rock flour on the mechanical properties of clayey soils, with a specific focus on improving the soil uniaxial compressive strength (UCS) and shear strength parameters (cohesion and internal friction angle). The study is based on controlled laboratory testing and a comprehensive evaluation of the technical and environmental feasibility of this soil stabilization approach, and consists of two phases. Firstly, clayey soil samples with each of the selected stabilizers in three different percentages are prepared under laboratory conditions and tested using the UCS test, with the aim of determining the optimal content of each stabilizer in the mixture. Secondly, the influence of the optimal content of each of the tested stabilizers is considered on the soil shear strength parameters. In both phases of the conducted research, the tests are carried out at three different time intervals after soil treatment (3, 14 and 28 days), in order to determine the durability of the effects of the applied chemical stabilization.

2. MATERIALS

The clayey soil used in this study was sourced from the Crvena Reka site, located in the southeastern region of the Republic of Serbia. It was sampled during landslide stabilization activities carried out as part of the construction of the E-80 Highway.

The mineralogical composition of the natural clayey soil was determined using X-ray diffraction (XRD) analysis, which is the most commonly used for the qualitative identification of soil mineral content. The spectrum shows that calcite is the most abundant mineral in the soil (39%), followed by quartz (25%) and clay minerals present at more than 10%: montmorillonite (15%), illite (11%) and chlorite (10%).

The physical and mechanical properties of natural clayey soil were determined by laboratory tests in the accredited Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of Niš, and are presented in Table 1.

Table 1. Properties of the natural clayey soil

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
Optimal Moisture Content	OMC (%)	18.5
Liquid Limit	LL (%)	49
Plastic Limit	PL (%)	23
Plasticity Index	PI (%)	26
pH Value	pH (–)	9.5
Modulus of Compressibility	Mv (MPa)	12.945
California Bearing Ratio	CBR (%)	2.71
Swelling	s (%)	2.91
Uniaxial Compressive Strength	UCS (kPa)	205
Cohesion	c (kPa)	16.9
Internal Friction Angle	φ (°)	16.5

In contemporary engineering practice, the utilization of *electrostatic precipitator* fly ash has increasingly expanded beyond its traditional role in the concrete industry. While approximately 65% of the total fly ash produced is still predominantly employed in the manufacture of concrete products, its significance in the field of geotechnical engineering—particularly for soil and waste stabilization—has become increasingly evident. Currently, around 7% of total fly ash output is used for such geotechnical applications [6]. Accordingly, recent literature increasingly recognizes fly ash as a standard stabilizing agent, alongside conventional binders such as lime and cement. Numerous studies have demonstrated that fly ash can exert a stabilizing effect even without additional activators, owing to its chemical composition and pozzolanic activity [7-11].

In Serbia's thermal power sector, the annual coal consumption ranges between 35 and 40 million tons, generating approximately 7 million tons of fly ash annually. This accounts for nearly 80% of the country's total industrial waste. Despite its considerable potential, only about 3% of the generated fly ash is currently utilized in the cement industry, highlighting substantial underutilization and indicating ample opportunity for its broader application in geotechnical works, particularly in the stabilization of soils with low bearing capacity. In this study, fly ash sourced from the Kostolac thermal power plant was used, characterized by a dominant content of silicon dioxide (56.38%), alumina (17.57%), ferric oxide (10.39%), calcium oxide (7.46%) and magnesium oxide (2.13%). The effectiveness of stabilization is influenced by several factors, including the properties of the native soil, the proportion of fly ash in the mixture with the soil, curing time and moisture content. Previous research suggests that the optimal fly ash content ranges between 10% and 30%, depending on the soil type and the specific characteristics of the fly ash.

Rock flour, a by-product of rock extraction and crushing in quarries, represents another promising alternative material for soil stabilization. Approximately 20% of the total extracted rock mass converts into this fine fraction during crushing operations. Traditionally used as a surface layer in road construction, recent studies have highlighted its considerable potential in enhancing geotechnical properties of various soil types, including expansive and lateritic soils [9,10]. Notably, improvements have been reported in terms of the soil reduced plasticity and increased load-bearing capacity, depending on the rock flour content in the mixture with the soil. In most cases, the recommended optimal content of rock flour for soil stabilization does not exceed 15%.

The rock flour sourced from the Gradac quarry ("Straževica" – Batočina) was used in the present research. The mineralogical composition of the rock flour was predominantly dolomite, with secondary minerals including calcite and muscovite.

In the scope of this study, for the sake of determining the optimal stabilizer content in the mixture with the soil, clayey soil samples were analyzed with the addition of 10%, 15% and 20% fly ash, on the one hand, and 5%, 10% and 15% rock flour, on the other hand.

3. METHODS AND RESULTS

All tests were performed in the accredited Laboratory for Geotechnics of the Faculty of Civil Engineering and Architecture of Niš, according to the valid national SRPS EN standards that are in accordance with the European regulations [12,13]. In addition, all samples were prepared with the optimal natural soil moisture content of 18.5% (Table 1), for reasons of adequate and relevant comparability of results.

3.1. Uniaxial Compressive Strength (UCS)

For the purpose of determining the soil UCS value, tests were made on samples with the addition of fly ash in the amount of 10%, 15% and 20% and on samples with the addition of rock flour in the amount of 5%, 10% and 15% in relation to the dry weight of the soil sample. It is noticeable that the time interval that has passed since the chemical treatment had no significant effect and that both stabilizers contributed to a certain increase in the UCS value.

The maximum UCS values obtained with the addition of fly ash in the amount of 10% (307 kPa) and 20% (342 kPa) were lower than those with the addition of 15% fly ash (371 kPa). This result indicates that the optimal fly ash content can be considered to be 15%. The UCS value obtained by the test performed 3 days after treatment did not change significantly with further passage of time.

A similar trend in the change in the UCS value was observed in the samples with the addition of rock flour. Namely, compared to the natural state of the soil (205 kPa), the maximum improvement (289 kPa) was achieved with the addition of 10% rock flour, 14 days after treatment. Similar results were obtained after 3 days (268 kPa) and after 28 days since the treatment (275 kPa). The addition of 5% and 15% rock flour did not contribute to a significant increase in the UCS value. This finding indicates the conclusion that 10% can be considered the optimal content of rock flour.

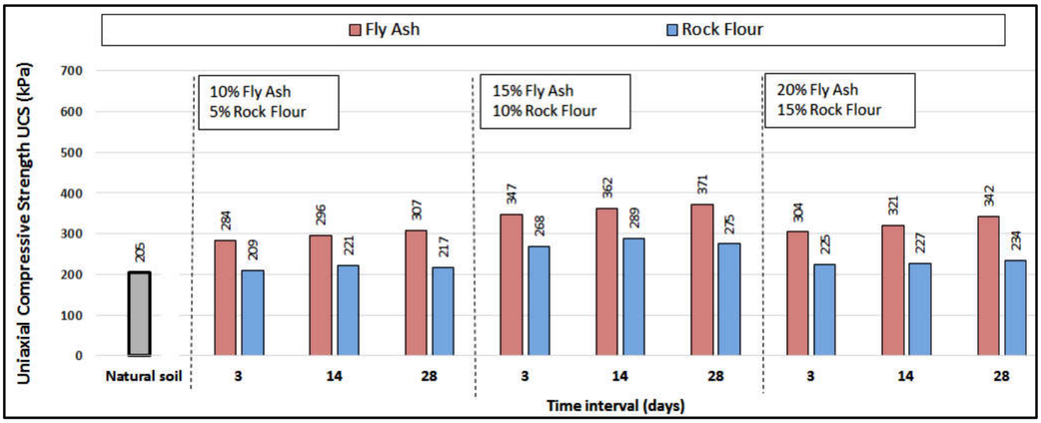

Figure 1. Comparison of the soil UCS value obtained after the chemical treatment for the selected contents of the considered stabilizers in the mixture with clayey soil

3.2. Soil Shear Strength

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 $\tau = \sigma \cdot tg\varphi + c$, 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 samples with the optimal content for each of the selected stabilizers obtained from the UCS test. The tests were carried out in three time intervals, i.e. 3, 14 and 28 days after mixing the stabilizer with the natural soil.

Shear stress at failure (τ) of clayey soil mixtures with the considered stabilizers under normal stress (σ) of 50 kPa, 100 kPa and 200 kPa is shown in Table 2. It can be seen that the shear strength increased over time in case of all the considered stabilizers. 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.

Table 2. Variation of shear stress at failure (τ) of clayey soil mixtures with the optimal content of the considered stabilizers under various levels of normal stress (σ) and over time

Soil conditions	Normal stress σ (kPa)	Shear stress at failure τ (kPa)		
Natural soil	50	30.9		
	100	49.8		
	200	78.1		
Stabilized soil		Time elapsed after treatment		
		3 days	14 days	28 days
Fly ash (15%)	50	32.4	35.7	38.7
	100	54.6	56.7	60.8
	200	81.1	89.1	93.2
Rock flour (10%)	50	40.6	42.7	46.7
	100	59.8	66.7	65.2
	200	91.7	97.5	98.7

From Figure 2, it can be seen that the addition of fly ash does not significantly affect the increase in cohesion, whereas the increase in the angle of internal friction is more pronounced. With regard to rock flour, on the other hand, there is a significant increase in cohesion, whereas the increase in the angle of internal friction is approximately the same as in the case of adding fly ash.

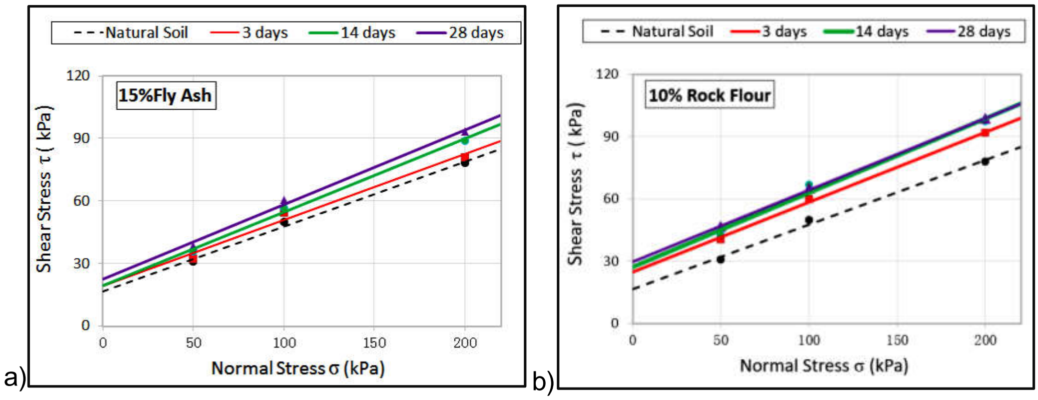

Figure 2. Coulomb–Mohr lines of clayey soil mixtures with the optimal content of the considered stabilizers, for the selected time intervals after the soil treatment: a) fly ash (15%); b) rock flour (10%)

The recorded changes in the values of shear strength parameters (cohesion (c) and internal friction angle (φ)) relative to the natural state of clayey soil (c = 16.9 kPa and φ = 16.5°) are presented in Table 3. Both stabilizers contribute to the improvement of soil cohesion and the internal friction angle. The best results are achieved 28 days after treatment. The optimal amount of fly ash contributes to a maximum increase in cohesion of 22.5 kPa and an internal friction angle of 19.3°. On the other hand, the addition of rock flour significantly affects the increase in cohesion value (29.9 kPa), whereas the internal friction angle value is also slightly increased (19.0°) as in the case of the addition of fly ash. The maximum value of the internal friction angle with the addition of rock flour is achieved after 14 days, amounting to 19.6°.

Table 3. Variation of shear stress parameters of clayey soil mixtures with the optimal content of the considered stabilizers over time

Soil conditions	Shear strength parameters			
	Symbol (unit)	Value		
Natural soil	c (kPa)	16.9		
	φ(°)	16.5		
Stabilized soil		Time elapsed after treatment		
		3 days	14 days	28 days
Fly ash (15%)	c (kPa)	18.5	19.5	22.5
	φ(°)	17.6	19.3	19.3
Rock flour (10%)	c (kPa)	24.6	27.3	29.9
	φ(°)	18.7	19.6	19

4. CONCLUSION

In this study, the individual effects of adding different materials (based on by-product) using the chemical stabilization technique on improving the mechanical properties of clayey soil were investigated.

The study consisted of two phases. First, clayey soil samples with each of the selected stabilizers in three different percentages were prepared under laboratory conditions and tested using the UCS test. This phase of the research aimed to determine the optimal content of each stabilizer in the mixture. Changes in the UCS values of the tested samples were also monitored at different time intervals after treatment (3, 14 and 28 days), in order to determine the durability of the effects of the applied chemical stabilization. Based on the obtained UCS values, the greatest improvement in quality was achieved with the addition of 15% fly ash (UCS value increased around 2 times) and 10% rock flour (UCS value increased around 1.5 times).

In the second part of the study, the influence of the optimal content of each of the tested stabilizers was considered on the soil shear strength parameters (cohesion and internal friction angle). In this phase, as in the previous one, the tests were conducted at the different time intervals with the same goal, to determine the long-term effectiveness of the improvements with the selected stabilizers. Given the soil shear strength parameters, the value of cohesion increased significantly with the addition of rock flour (around 1.8 times), whereas in the case of fly ash an increase was somewhat lower (around 1.3 times). On the other hand, considering internal friction angle, almost the same effect was achieved for both selected stabilizers (an increase of 1.15 times in the case of rock flour and 1.17 times in the case of fly ash). It was also observed that the values of the strength parameters increased over time.

The findings of this study have demonstrated that the enhancement of the mechanical properties of clayey soils can be effectively achieved through the application of alternative stabilizing agents derived from industrial by-products. Each of the investigated stabilizers, when added to untreated clayey soil, has exhibited the potential to improve its mechanical properties, thereby contributing to its suitability for diverse applications in engineering practice. It is important to note, however, that all conclusions drawn in this research are based on tests conducted on a locally sourced clayey soil with a specific mineralogical composition. Consequently, further extensive research is needed to evaluate the effectiveness of these stabilizers on clayey soils of different mineralogical and geotechnical characteristics.

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REFERENCES

[1] Ferguson G.: **Use of self-cementing fly ashes as a soil stabilization agent**. *ASCE Geotechnical Special Publication*, place not specified, 1-14, 1993.

[2] Vukićević M., Pujević V., Marjanović M., Jocković S., Maroš-Dragojević S.: **Stabilization of fine-grained soils with fly ash**. *Građevinar*, Vol. 67, 761-770, 2015, https://doi.org/10.14256/JCE.1281.2014.

[3] Zafirovski Z., Markovski M., Ognjenovic S., Gacevski V., Nedevska I., Ristov R.: **Subbase stabilization with fly ash**. *Facta Universitatis, Series: Architecture and Civil Engineering*, Vol. 22, No. 1, 79-88, 2024, https://doi.org/10.2298/FUACE230630033Z.

[4] Sol-Sánchez M., Castro J., Ureña C., Azañón J. M.: **Stabilisation of clayey and marly soils using industrial wastes: pH and laser granulometry indicators**. *Engineering Geology*, Vol. 200, 10-17, 2016, https://doi.org/10.1016/j.enggeo.2015.11.008.

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

[6] ACAA 2022 CCP Survey Results and Production & Use Charts. Available online: www.acaa-usa.org (*accessed on 18 April 2025*).

[7] Houanou K. A., Dossou K. S., Prodjinonto V., Ahouétohou P., Olodo E.: **Mechanical characteristics of Avlamè lateritic gravel improved with granite crushed for its use in road construction in Benin**. *World Journal of Advanced Research and Reviews*, Vol. 15, No. 02, 279-292, 2022, https://doi.org/10.30574/wjarr.2022.15.2.0820.

[8] Kolay P. K., Sii H. Y., Taib S. N. L.: **Tropical peat soil stabilization using class F pond ash from coal fired power plant**. *International Journal of Civil and Environmental Engineering*, Vol. 5, 71-75, 2011.

[9] Ene E., Okagbue C.: **Some basic geotechnical properties of expansive soil modified using pyroclastic dust**. *Engineering Geology*, Vol. 107, 61-65, 2009, https://doi.org/10.1016/j.enggeo.2009.03.007.

[10] Omowumi A.: **Engineering evaluation of lateritic soils of failed highway sections in Southwestern Nigeria**. *Geoscience Research*, Vol. 2, 210-218, 2017. https://dx.doi.org/10.22606/gr.2017.23006.

[11] Gbadamosi O. S.: **Improvement of Bearing Capacity of Lateritic Soil for Pavement Subgrade by Addition of Rock Flour**. *Federal University of Technology*, Minna, Nigeria, 2021.

[12] **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**. *Institute for Standardization of Serbia*, Belgrade, Serbia, 2022.

[13] **SRPS EN ISO 17892-10:2019; Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 10: Direct Shear Tests**. *Institute for Standardization of Serbia*, Belgrade, Serbia, 2019.