CHEMICAL STABILIZATION OF SOIL USING LIME AS A CHEMICAL REAGENT

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One of the techniques that is increasingly used in geotechnical practice in order to improve the properties of soil is chemical stabilization. It is based on modifying the properties by adding a chemical reagent, which will react with the minerals in the soil. The efficiency of the method will largely depend on numerous factors, primarily on the type of soil, type and amount of chemical reagent, as well as on the achieved chemical reactions between stabilizer (chemical material) and soil minerals (pozzolanic materials). In practice, lime, cement and fly ash are most often used as chemical stabilizers, which ultimately contribute to increasing soil strength, reducing water permeability and reducing the potential of swelling. The paper deals with the general principles of chemical soil treatment, whereby a special attention is paid to the application of lime as a chemical stabilizer, which has been shown to be particularly effective in the case of clayey soil. Lastly, the advantages and limitations of this soil stabilization technique are considered, as well as possible directions for its improvement.

Keywords: chemical stabilization, clayey soil, geotechnical properties, lime

1. INTRODUCTION

When constructing civil engineering structures, it is often not possible to avoid locations with soils of poor quality and low bearing capacity. Hence, for such soils that can't meet the minimum requirements in terms of bearing capacity and quality, it is necessary to carry out the procedure of soil stabilization and improvement. In order to choose an adequate soil stabilization technique, it is first necessary to properly consider the problem and discover the cause of its occurrence. The stabilization method that will give the best results depends on the type of soil, location and purpose of the facility to be built.

The concept of soil improvement means a set of measures (techniques) that are implemented to improve the physical and mechanical properties of the soil and that allow the safe construction of structures for various purposes

[1]. Improvement techniques can be of a temporary or permanent character. When considering temporary techniques, the effects of improving soil properties last relatively short (usually only during the construction stage, e.g., water table lowering, soil freezing), whereas in the latter case the effects last for a longer period of time (e.g. grouting, reinforcement, dynamic compaction) [2]. In general, there are about 30 different soil stabilization techniques aimed at improving soil properties and stabilization, such as material replacement, chemical stabilization, strengthening by steel reinforcement or geosynthetics, drainage, vibration compaction, consolidation, electroosmosis, medusoil and others [3]. Many techniques can be used in combination with others, and as a result, new methods can emerge. According to the more recent classification of Schaefer et al. [4], 46 soil stabilization methods have been identified. This categorization is a result of the fact that some of the methods for soil improvement can be included in one or more categories.

Improving soil properties is nowadays recognized as one of the main subdisciplines of geotechnical engineering. Soil improvement techniques have developed significantly over the past decades and are today almost routinely used in most procedures during the construction of various structures. Each of these methods has its advantages, but also shortcomings. The increase in the number of soil stabilization techniques, as well as products and engineering tools, has been expanding recently due to extensive research in this area and a large number of available technologies. A significant progress in this development has been noted at many conferences, workshops, as well as in a number of papers and reports.

2. PRINCIPLES OF CHEMICAL SOIL TREATMENT

Improving soil properties by chemical treatment is based on modifying the soil properties by adding a chemical reagent, which will react with the minerals in the soil. However, there are also mechanical additives, which are not able to change the chemical soil properties, but enable an improvement of the natural properties of the treated soil. There are numerous additives that are used to improve soil properties, but in practice, in over 80% of cases, cement, lime and fly ash are most often used [5].

In most cases, stabilizers are added to the soil using appropriate construction equipment. The method to be used depends on the location of the construction site and availability of the equipment, whereas the selection of additives mainly depends on the type of soil. One additive can affect various soil types differently. Chemical treatment is mostly used to improve the properties of fine-grained, clayey soil, because this type of soil is susceptible to high water content. There are 18 different chemical mechanisms (that is cation exchange, anion exchange, adsorption, fixation, formation of new minerals, cementation, salt conversion, modification of aqueous films, modification of capillary forces, modification of electrical surface tension of clay minerals), which can result in an improvement of the properties of clay [6]. However, inadequate use of reagents can lead to reactions such as flocculation of the particles, heat generation during chemical reactions, etc. Today, chemical stabilization is used as a routine technique worldwide (primarily stabilization with lime and cement), but research in the field of finding new reagents and their combinations is still ongoing. The principles of chemical soil treatment in order to improve the geotechnical soil properties using lime as a chemical stabilizer are explained below.

3. IMPROVING SOIL PROPERTIES BY ADDING LIME

Adding lime is a suitable technique for stabilization of fine-grained, clayey soils. Lime affects certain soil modifications, which are reflected in the decrease of water content, plasticity index, water permeability and swelling, change of grain size distribution and increase of compressive strength, bearing capacity and optimum moisture content. Due to the improvement of all these properties, a clay with the addition of lime presents a modified, much better material than the basic soil. Soils with such improved properties also provide technically preferable and often more economic solutions.

Chemical reactions that, in the presence of water, take place in the soil after lime is added and distributed (spotted), and then compacted, lead to significant, easily noticeable changes in the structure of the material and in its physical and mechanical properties. Due to its composition and electrostatic relations on the surface and inside the lattice of clay minerals, clay soil is very sensitive to changes in water content. If water is added to dried clays, which are stable and solid in that state, they will change their consistency, that is they become semi-solid, then plastic and finally liquid, which is accompanied by smaller or larger changes in volume. With increasing the clayey soil water content, its load bearing capacity decreases drastically, so that in the case of materials in liquid state consistency, the bearing capacity of the soil is practically non-existent. In addition, high water content is a great problem in execution of construction works, because the required soil compaction cannot be achieved.

In relation to the mass of dry soil, the optimum amount of lime added to the soil is in the range from 3% to 6%. The value to be added is determined based on the pH test (the Eades and Grim test) where it is necessary to reach a pH value of approximately 12.4. The optimum percentage of lime must be verified on the basis of the examination of the change in shear strength before and after the soil treatment. The effect of lime on the soil takes place through three main stages: reduction of the water content in the soil, modification of the soil and increase of the soil strength (stabilization).

A review of the effects that can be achieved by treating clayey soil in the corresponding way by adding lime is shown in Figure 1. It should be noted that some soil properties can adversely affect the course of the described reactions (highly organic soils, high pH value). The change in the structure of soil particles occurs slowly and depends on the type of clay. Clays of a medium to high plasticity are suitable for stabilization with lime, and this method can also be applied to gravelly and sandy soils if they contain a sufficient amount of clay fractions. In the case of low-plastic clays, as well as silts and pure cohesionless materials, lime alone is not an efficient solution; however, some pozzolanic materials can be added in addition to lime, such as slag, fly ash, cement and other. In geotechnics, the effect of lime is determined by laboratory testing of soil mixtures. The soil stabilization effects are established by examining the parameters of strength, load bearing capacity, compressibility and water permeability.

Lime can be used in various forms: quicklime, slaked lime and liquid lime. It is noticed that lime is not an independent stabilizer, but the stabilizing effect is achieved just after the reaction of lime with clay components of the soil. For that reason, chemical stabilization with lime is used in the case of clayey soils, whereby the mineral composition of the clay has a great influence on the intensity and rate of the reaction.

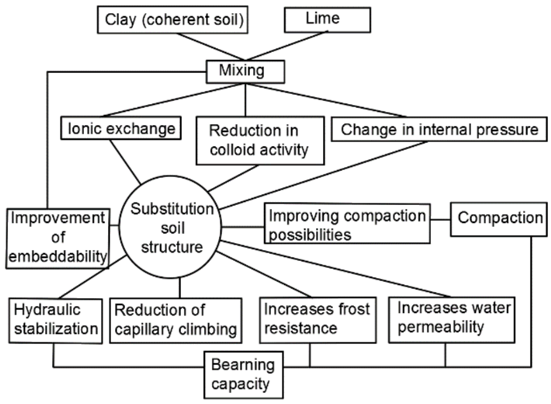

Figure 1. Effects of added lime on clayey soil (according to W. Brand) [7]

The process of soil stabilization with lime on a construction site consists of homogeneous mixing of soil with an appropriate amount of lime, where the mixture must, as a rule, have the optimum water content. The method is suitable for large surfaces, as it is relatively easy and fast to perform (e.g., in construction of roads). It is recommended that the soil and lime mixture are compacted in layers up to 50 cm thickness with corresponding technique over a certain period of time until the required properties are achieved. To make one of the layers of the road, stabilization by adding lime can be done by mixing in place. Figure 2 presents the process and the equipment that is most often used in chemical treatment of soil by adding lime during road construction.

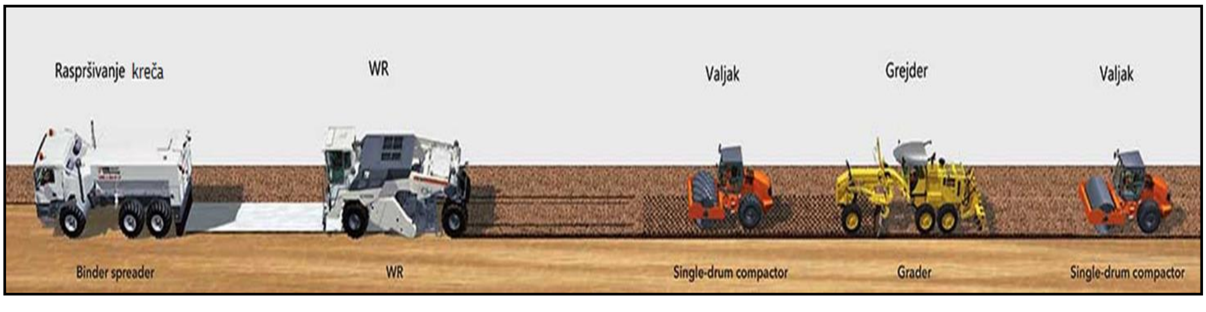

Figure 2. Chemical treatment procedure by mixing the soil with lime on a construction site (www.frekomos.hr)

Table 1. Test results for improving the geotechnical properties of fine-grained soil by adding lime and dry mixing

Author(s)	Type of soil and stabilizer(s) in chemical treatment	Results (effects) of chemical soil treatment
Bell, 1996 [8]	Kaolinite, montmorillonite, quartz, treated with lime	Decrease in the plasticity (particularly typical for montmorillonite) and increase in the dry density during compaction and compressive strength. Significant improvements in soil properties were achieved by the addition of 4% or more lime.
Susinov and Josifovski, 2013 [9]	Local soil, disturbed soil samples were obtained from excavation pit at 2.0 m depth	The mixture of lime and silty soil material has significantly improved the mechanical properties. At 2% of lime, a reduction of moisture content and the plasticity index is around 40% and 45%, respectively. The CBR has improved up to 16 times when 8% of lime is added to soil and cured 7 days and even better results are expected for longer period of time. About 4% of lime can increase the compressibility modulus up to six times. The largest increase UCS is observed in specimen with 4% lime, the stabilized soil shows 2 times greater strength compared to the unstabilized soil.
Kumar and Dutta, 2014 [10]	A mixture of soil with bentonite and lime, reinforced with sisal fibers	Examined series of bentonite with the addition of lime (2%, 4%, 6%, 8% and 10%) - Series I. Then a different percentage of phosphogypsum (0.5%, 1%, 2%, 4%, 8%) was added to the mixture of bentonite and lime (8%) - Series II. In Series III, a different percentage of sisal fibers was added to the mixture of bentonite, lime and phosphogypsum. Soil improvements in terms of compaction and unconfined compressive strength were investigated. The results show that, for the examined Series I, II and III, the improvement occurs 7 days, 14 days and 28 days after the treatment, respectively.
James and Pandian, 2015 [11]	Local soil treated by adding lime and phosphogypsum	The results indicate that the use of phosphogypsum in soil stabilization depends on the percentage share of lime. For a soil mixture with the addition of up to 3% lime, it is necessary to add more than 2% phosphogypsum, whereas for the soil with the addition of 7% lime it is necessary to add only 0.5% phosphogypsum, in order to achieve the same or even better results than those when only lime is used as a stabilizer. The effects of stabilization in terms of reduction of liquid limit, plasticity index and swelling index were investigated.
Garzon et al., 2016 [12]	Phyllite, clay, treated with lime	Numerous geotechnical properties of the treated soil were investigated. The addition of 3%, 5% and 7% lime had the effect of reducing the consistency limits, improving the compaction results and CBR values, as well as reducing the swelling potential and water permeability.
Amidi and Okeiyi, 2017 [13]	Red local clay, treated with quicklime and slaked lime	2.5%, 5%, 7.5% and 10% of both types of lime were added, and quicklime was found to reduce plasticity, whereas slaked lime resulted in a higher dry bulk density and a higher compressive strengths according to triaxial testing for unconfined compression test, in particular at higher amounts (7.5% and 10%).
Jahandari et al., 2017 [14]	Kaolin clay, application of lime and geogrid	In addition to the treatment by adding lime, geogrids have also been added. Beside the improvement of almost all geotechnical properties, a decrease in the deformability index of the treated soil was observed.
Innocent and Okonta, 2018 [15]	Local soil, treatment with pre-compression, addition of lime and fly ash	In addition to lime, fly ash was used in small percentages (up to 1%). The The pre-compression stresses were applied after 4 h, 8 h and 24 h. The results after 7 days revealed that optimum strength of 3.5 MPa was mobilised by un-precompressed specimens at 0.75% fiber content. Pre-compression with 10% UCS showed maximum strength of 2.8 MPa at 0.25% fiber content whereas 20% UCS indicated optimum strength of 3.04 MPa at 0.25% fiber content. In comparison, pre-compressed specimens exhibited lower strength values than un-precompressed specimens. The maximum strengths of specimens for both pre-compression levels occurred after 24 h of curing.
Salih and Abdalla, 2020 [16]	Low-plasticity clay, treated with lime	2.5%, 5%, 7.5% and 10% lime were added and it was found that the addition of lime contributed to the reduction of the plasticity index up to 20%, as well as that the load bearing capacity of the treated soil increased 5.5 times (from 174 kPa to 960 kPa). It was determined by the Proctor test that the optimum water content of the treated soil was reduced by 10%, while the dry density was increased by nearly 15%.

Prior to the beginning of a stabilization process, the surface of the soil layer should be prepared according to the design. The layer is then spread, but also left in a loose state in order to be mixed more easily with the lime. The thickness of the loose material should be produced in such way that, after mixing with lime and compaction process, the layer of a designed thickness can be achieved. The required amount of lime per unit surface is then spread over the pre-prepared soil. Spreading is done by a construction plant, which ensures uniformity of the stabilizer in all parts of the soil layer. After that, the soil is mixed with lime until a homogeneous mixture is obtained (which can be checked according to the color of the mixture). During mixing, a certain amount of water is added optionally in order to obtain the optimum water content of the mixture, and vice versa, if the material is too wet, it is previously exposed to sun and wind in order to reduce its water content to the required extent. Finally, the material is spread and compacted using a padfoot drum compactor (roller), grader and smooth drum compactor.

An overview of previous studies on the effects of chemical stabilization of soil using lime in order to improve the geotechnical properties of clayey soil is given in Table 1.

Recently, numerous studies have been related to the addition of "new" chemical reagents in combination with lime, such as CaCl2 or NaOH, which can further improve soil properties. Nevertheless, a rather small number of studies have been conducted regarding the effects of the mentioned combinations on the improvement of geotechnical properties of soils. Some of them are presented in papers [17,18].

4. CHEMICAL ELECTROKINETIC TREATMENT

The electrokinetic soil treatment can be carried out at greater soil depths and below existing structures; however, the effects of such treatment are not permanent. A graphical interpretation of the principal processes that take place in fine-grained clayey soil under electrokinetic soil treatment is shown in Figure 3. By passing a direct current through the soil, the process of electro-osmotic flow of water in the soil from the anode (positively charged electrode) toward the cathode (negatively charged electrode) occurs. The result of this process is a decrease in soil moisture content, which begins in the anode zone and then spreads into the surrounding soil, thus resulting in a decrease in pore pressure, an increase in effective stresses in the soil, and improved physical and mechanical properties of the soil.

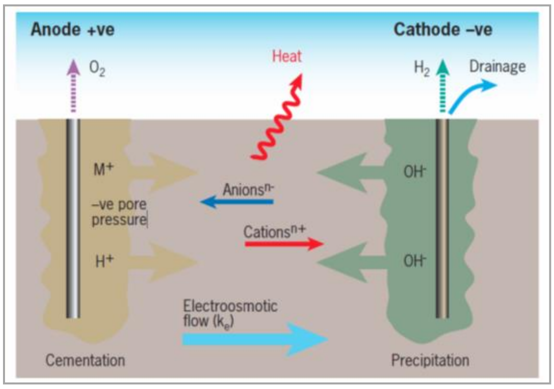

Figure 3. Principal processes active in a section of clayey soil under the electrokinetic treatment [19]

Chemical electrokinetic soil stabilization is a technique that overcomes the shortcomings of the aforementioned soil stabilization procedures. Namely, the technique of chemical electrokinetic soil stabilization is an enhancement of the technique of electrokinetic soil treatment using chemical agents (stabilizers), where the injection and movement through the soil of stabilizing agents takes place under the influence of a direct current, whereby the mechanism of stabilization itself can be explained by the principles of chemical stabilization. The combination of complex electrochemical processes under the influence of an electric field and in the presence of appropriate chemical agents should lead to a permanent improvement of the soil in terms of physico–chemical characteristics, and in particular the mechanical properties of fine-grained soil, which are of paramount importance in geotechnical engineering. Moreover, its advantage is that it can be applied to crucial geotechnical problems such as stabilization of slopes and landslides, increasing the bearing capacity of the foundation soil, reducing the soil moisture content under existing structures, as well as stabilizing the ground for construction of deep foundation excavations, tunnels, and other underground structures. Electrokinetic treatment of fine-grained soils in combination with chemical stabilizers has, to a very limited extent, been the subject of scientific research in the world over the past period [20,21]. The application of chemical stabilizers mainly on the basis of chlorides has been evaluated, mostly on soil samples tested in laboratory conditions, and without considering the time effect in terms of controlling the achievement of permanent improvement of the properties of the treated soil. All these facts indicate the necessity for detailed experimental research to better understand the nature, effects, efficiency, and scope of application of this soil stabilization technology, as well as with the aim of considering the possibility of applying new chemical agents that would contribute to the stabilization effect of a permanent character, which is of elementary importance in geotechnical engineering.

5. CONCLUDING REMARKS

The selection and application of the most adequate technique of soil stabilization can significantly contribute to the improvement of soil properties during the construction of foundations and earth structures, including embankments and cuts on roads and railways, earth dams, etc. In addition to improving soil properties, stabilization techniques may also contribute to a more economical solution. If it is not possible to perform works on the location planned for the construction of a structure, this problem can be solved in one of the following ways [22]:

1. To quit the location originally considered (replacing the planned facility to another location);
2. To adapt the facility to the existing conditions (e.g. pile foundation, construction of the facility as a very rigid or very flexible structure, etc.);
3. To remove the surficial or complete layer of the unsuitable (organic, compressible) soil;
4. To perform chemical treatment of the existing soil in order to improve its properties.

Chemical stabilization of soil contributes to the permanent improvement of physical, chemical and mechanical properties of soil, but due to the method of application it can be used only in surficial, easily accessible soil layers, which excludes its application in particularly important geotechnical problems such as slope stabilization, increasing the load bearing capacity of foundation soil, as well as reducing the water content and settlements of the soil beneath existing facilities. Owing to the high availability and accessibility of materials that can be used as reagents in improving soil properties, it is necessary to invest resources to further improve existing and discover new methods. Unlike the chemical stabilization technique, the electrokinetic treatment of soil can be carried out at greater soil depths and below existing structures. Electrokinetic chemical stabilization is a ground improvement technique in which stabilizing agents are induced into soil under a direct current. The movement of stabilizing agents into soil mass is governed by the principles of electrokinetic, while the mechanisms of stabilization can be explained by the principles of chemical stabilization. Further research may be seen in this direction.

In addition to the mentioned chemical stabilizers, in practice, bitumen is also used for chemical stabilization of soil (mixing problems may occur in the case of plastic clays, and thus the recommended optimum amount of the stabilizer ranges from 4% to 7%), chemical and synthetic materials (natural polymers, synthetic resins) or recycled materials. A combination of the electrokinetic soil treatment by the addition of chemical stabilizers would provide the possibility of using many other, less commonly used materials today (e.g. based on polymers, nanomaterials, etc.) that may be particularly suitable for the application of this soil stabilization technique.

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