Annals of the Academy of Romanian Scientists
Series on Engineering Sciences
ISSN 2066 – 8570 Volume **5**, Number **2**/**2013**

PHYSICO-CHEMICAL PHENOMENA IN SOIL STABILIZATION FOR ROADS OR HIGHWAYS INFRASTRUCTURES

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Rezumat. *Reducerea impactului realizării căilor de comunicaţii terestre asupra mediului se poate face şi prin reutilizarea sau reciclarea anumitor materiale. În acest context, tendinţa actuală constă în utilizarea de materiale care să nu aibă un impact nefavorabil asupra mediului, dar care, să constituie o soluţie pe termen lung. Un astfel de material local pentru realizarea infrastructurii căilor de comunicaţii este reprezentat de argilele active. Lucrarea prezintă structura fizico-chimico-mineralogică a argilelor şi comportamentul acestora în interacţiunea cu apa. Un efect negativ al acestei interacţiuni îl reprezintă umflarea, contracţia şi, respectiv, presiunea de umflare. Acestea produc efecte (fisuri, crăpături) în structura drumurilor, autostrăzilor şi, respectiv, pistelor de aeroport. Autorii analizează posibilitatea de reducere a acestor efecte prin stabilizarea argilelor cu lianţi minerali (ciment, var). Sunt prezentate rezultatele amestecurilor cu var prin prisma proprietăţilor fizice şi mecanice, stabilind totodată şi procentele optime ale amestecurilor. Se conchide că soluţia de stabilizare este şi economic mai eficientă decât cea clasică de înlocuire a stratului de argilă din patul drumurilor cu alte materiale de adaos transportate din alte zone.*

Abstract. *Reducing the impact on the environment of constructing transportation infrastructures can be achieved through reusing or recycling certain materials. In this context, the current trend is to use materials that do not have a negative impact on the environment and provide a long term solution. Such local materials for the construction of transportation infrastructure are the active clays. This paper presents the physico-chemical and mineralogical structure of clays and their behavior regarding the interaction with water. A negative effect of this interaction is the swelling, the contraction and, respectively, the swell pressure. These produce effects (fissures, cracks) in the structure of roads, highways and, respectively, airport runways. The authors analyze the possibility to reduce these effects by clay stabilization with mineral binders (cement, lime). Results on lime mixtures testing are presented in terms of physical and mechanical properties, and optimum percentages of the mixtures are presented. It is also concluded that this solution is more cost-effective than the classical one as replacing the clay layer from the roadbed with other filling materials transported from other areas.*

Keywords: active clay, chemical stabilization, mineral binder, physical properties

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1. The purpose of chemical stabilization of clays

Clays are present on 42% of the earth crust [1-3] therefore comes the need to study their behavior when used as building material or foundation soil. These types of soil are detritic sedimentary rocks composed of particles with the maximum size of 2 μm.

The nature and the arrangement of atoms in a solid particle have a significant influence on the permeability, compressibility and strength of clayey soils. There are certain clay minerals that give the soil that contains them a special behavior. Such examples are the smectites, namely those dioctahedral (montmorillonite, beidellite, nontronite) and trioctahedral (saponite, hectorite, sauconite). These minerals generate the strong expansive character of active clays [4]. The swelling of clayey soils is mainly caused by the adsorption of water molecules in the spaces between the packages of smectitic minerals; the expansive nature is directly influenced by the nature of the adsorbed cations as well.

Sodium smectites (with Na^+ exchangeable cations) present a higher swell potential and increased colloid properties compared to calcium smectites (with Ca^{2+} exchangeable cations). Cation exchange capacity is one of the most important properties of smectite rich soils, which is strictly related to their chemical activity. The specific surface area is one of the fundamental factors that influence the intensity of the solid-liquid-gas interface phenomena and thus the swelling-shrinkage and rheological properties of smectitic clays. When an active clay presents volume changes through increased or decreased thickness of the adsorbed water layer, in its structure different processes occur, such as: when decreasing water content, the soils volume decreases by contraction, appearing cracks caused by the internal stress in the dried sample; when increasing water content, the clay volume increases as a result of swelling, closing the cracks and resulting in volumetric expansion on all three directions. After the cracks caused by drying are closed, the deformations become unidirectional and limited to the vertical direction [5]. Since volume changes occur unevenly in the built environment, additional stresses are induced within structures that initiate the generation of degradations.

To limit or even cancel the negative effects of volume changes on constructions, one can alter the clay by adding mineral binders (such as cement, lime and fly ash) that chemically interact with clay, modifying both its physical and mechanical properties [6-10].

Once treated with cement and/or lime, the improvements that occur are numerous, some of them appearing even in the first few minutes of the mixing. Among these benefits, one can mention: increased workability, higher mechanical strength, lower sensitivity to volume changes and improved durability [1].

In general, it is known that soil stabilization can be chemical and with bituminous additives, yet choosing the proper solution depends directly on the type of soil and its characteristics. If in sand stabilization, bituminous and hydraulic additives may be included, for soft soils only the mineral ones are accepted, as hydraulic or non-hydraulic binders [1, 9].

Chemical stabilization of soils primarily eliminates the costs and time needed for the poor soil replacement with a granular processed one. This leads to significant savings and also reduces the demand of non-renewable materials that leave traces in the environment [1].

2. Mineral binders for chemical stabilization of clayey soils for roads and highways infrastructures

Lime stabilization is a soil improvement technique known for centuries that was (partially) used at the construction of the Great Wall of China, at Roman roads and after the Second World War when was further developed, for road structures [11].

The chemical stabilization purpose is to harness local materials by improving their mechanical behavior and plastic characteristics, in order to become suitable for earthworks. To select an adequate additive one has to consider factors such as the type of soil to be stabilized, the category of works that require stabilization, the stabilization type, the quality level desired by strength and durability needed, and also the financial and environmental conditions.

By stabilizing active clays with mineral binders, an improvement of their properties is obtained (strength, compressibility, hydraulic conductivity, workability, swell potential [12]), both in terms of resistance and durability (the behavior under water content changes and frost). This stabilization mainly occurs by reducing the surface activity and at the same time, also by modifying and stiffening the structure [13].

For a given type of soil there are several additives to be added. However, there are certain general rules that indicate the appropriate stabilizers for a given soil, based on its particle size distribution, plasticity and texture [5, 10].

Active clays are materials that already contain the necessary mineralogical compounds for their hardening in the presence of a mineral binder derived from limestone and of water, the most suitable stabilization options being those with quicklime, Portland cement (hydraulic binder) and a hydraulic binder obtained by gradually mixing lime and Portland cement.

Hydraulic lime is commonly used to stabilize soils without or with a low fraction of clayey particles, such as low plasticity silts, silty sands and silty gravels [10]; quicklime is inefficient to obtain increased resistance and durability, this binder being mainly used for active clays.

Clays are reactive materials that need an addition of calcium ions in order to balance their reactivity. A soil with a high percentage of fractions over 2 μm is less possible to be stabilized with quicklime due to its low or nonexistent reactivity, while another containing mostly or entirely clay fraction will need a high percentage of mineral binder to ensure a 12.4 *pH* value and a sufficient amount of calcium ions. Thus, the presence of clay minerals in the soil is a defining factor in choosing the mineral binder for the stabilization, the use of lime or quicklime being more suited to clays compared to sandy soils, in which case is indicated to use only hydraulic binders without additional calcium ions for the reactivity reduction.

3. Quicklime stabilization of soils

The interaction between lime and clay is characterized by a succession of complex physico-chemical processes with different evolution times that change the chemical and mineralogical properties of clayey particles, and therefore the physical and mechanical ones. The first process which occurs is the dehydration of clay, the hydration of lime, respectively, by the formula:

$$1 \quad (1)$$

Subsequently, the calcium hydroxide Ca(OH)2 is dissociated in water, resulting in an increase of the electrolyte concentration and water pH:

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^- \quad (2)$$

and liberating the SiO_2 (silica) and Al_2O_3 (alumina) from the clay particles [7, 14, 15].

As a result of the hydration reaction, the concentration of Ca^{2+} and $(OH)^-$ ions from the pore water increases substantially. This ions dissociation leads to a series of reactions that vary depending on the mineralogy and the pore water chemistry and to a replacement of the free cations in the clay body with calcium ions, respectively [14].

The entire physico-chemical phenomenon of stabilization is characterized by two main effects: the immediate and the long-term ones. The immediate effects are those that occur in the immediate minutes after the mixing and include the cationic exchange, followed by particle flocculation and finalized with a soil structure modification and a plasticity index decrease.

The long-term effects are those that give the material some obvious improved mechanical properties, as a result of the pozzolanic reaction that produces the cementation products (hydrated calcium silicate and hydrated calcium aluminate) (figure 1), resulted from the reactions occurring in the presence of water, between lime and alumina and silica from the clayey soil [6].

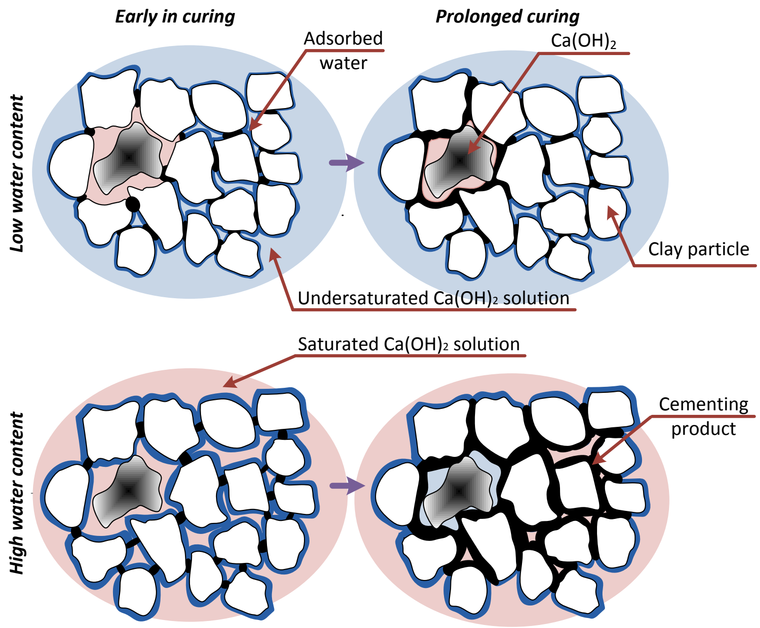

Fig. 1. The evolution scheme of the cementation products by curing time and water content [6, 8].

By adding lime into a clay, its *pH* will increase, being necessary to obtain a minimum value of 12.4 in order to achieve and complete the pozzolanic reaction according to Eades and Grimm [8]. The optimum lime content for the reactions to complete successfully can be determined by measuring the *pH* values of lime-clay mixtures. The smallest amount of lime that gives the mixture a 12.4 *pH* is considered the optimum lime content to be added for the modification of the structure and the improvement of its compaction characteristics. For further resistance gains, one can increase the lime content, performing laboratory tests on the mixed samples to determine the required quality level.

4. Cement stabilization of soils

The efficiency of cement stabilization appears when it is mainly applied to non-cohesive soils (sands or calcareous materials). These soils can be stabilized directly with cement for a significant contribution on the mechanical strength, cohesion, frost and wetting stability.

Regarding clayey soils, it is recommended to be familiar with the field condition of the soil in order to choose how to stabilize it with cement, directly or with an initial addition of lime in case of high water content (in this case it is better to use quicklime in order to improve the workability characteristics) [16]. Portland cement can be also chosen as treating solution for fine-grained soils if these have a liquid limit of less than 40% and a plasticity index of less than 20% [17].

This binder has four main components: *tri-calcium silicate* (C_3S), *di-calcium silicate* (C_2S), *tri-calcium aluminate* (C_3A) and *ferric tetra-calcium aluminate* (C_4A). When the pore water from the soil comes in contact with the cement constituents, the hydrated calcium silicate (CSH), hydrated calcium aluminate (CAH) and hydrated lime ($Ca(OH)_2$) are formed [18].

Prior to setting and hardening phenomena, when Portland cement is in contact with water, some specific successive reactions occur: the hydration (the combination with water) and hydrolysis (decomposition) [19], the resulting products being crystalline or strongly hydrated gels. In the presence of water, the calcium ions from alite and partially from belite goes into solution to which they give a strong alkaline character (pH=10÷12).

The hydration and hydrolysis reactions of the mineralogical compounds of the clinkered binder are produced as following [19, 20]:

$$3CaO \cdot SiO_2 + mH_2O \rightarrow \underset{gel}{xCaO \cdot SiO_2 \cdot pH_2O} + (3\text{-}x)\underset{cristals}{Ca(OH)_2} \quad (3)$$

$$2CaO \cdot SiO_2 + nH_2O \rightarrow \underset{gel}{xCaO \cdot SiO_2 \cdot pH_2O} + (2\text{-}x)\underset{cristals}{Ca(OH)_2} \quad (4)$$

where: x≤2 and 2,4<p<4

$$2CaO \cdot Al_2O_3 + 6H_2O \xrightarrow[cristals]{} 3CaO \cdot Al_2O_3 \cdot 6H_2O \quad (5)$$

$$4CaO \cdot Al_2O_3 \cdot Fe_2O_3 + nH_2O \rightarrow \underset{gel}{3CaO \cdot Al_2O_3 \cdot 6H_2O} + \underset{cristals}{Ca(OH)_2} + \underset{gel}{Fe_2O_3(n\text{-}7)H_2O} \quad (6)$$

Following the hydration and hydrolysis reactions, some new crystalline products appear such as: firstly the hydro-sulfo-aluminates and hydro-calcium-aluminates, then the calcium hydroxide and calcium hydro-silicates films around the cement grains. As the gel films increase, the binder granules come to unite, encapsulating in their mass the crystalline products [20].

The increased mechanical strength after cement stabilization is attributed to the pozzolanic reaction that produces the same effect on lime-stabilized soils. Lime and cement contain the adequate quantity of needed calcium for the pozzolanic reaction initiation, but the origin of the necessary silica and alumina differs. In lime stabilization these two components result from the modification of the clay particle, as cement already contains these components, without additional particle decomposition [7, 10]. It therefore follows that, unlike lime-stabilization, the cement one covers a wider range of soils, with the possibility to be also used for soils with low or inexistent reactivity (soils without clay fractions and thus without reactive products) [8, 10].

As mentioned above, cement-stabilization is often combined with a prior addition of lime, in order to decrease the plasticity index and thus, to improve the workability characteristics.

Subsequently, cement–stabilization will be more effective as a result of the soil structure modification, fact highlighted by Stavridakis through a decreasing efficiency series of the cement-stabilization of clayey soils: *active soils< cohesive soils with a LL≈60% < cohesive soils with a LL<60% < cohesive soils with a LL<40%* [5].

Regarding the optimum cement content selection, there must be carried out, at first, tests to determine the physical and mechanical properties of the soil and then, based on these results, one can establish the necessary cement percentage. For example, according to the U.S. regulations, for rock fragments, gravels and sands it is recommended to use between 3 and 8% cement, for fine sands from 7 to 10% and for clayey or silty sands and gravels, from 5 to 9%. Although there are no compulsory tests to be performed in order to establish the optimum cement content for soil stabilization, one would indicate an approximate value of 4%±0,5% by the dry mass of soil [12].

5. Quicklime stabilization of the Bahlui clay

5.1. Materials and methods

The investigated soil in this paper is the Bahlui clay that was characterized on several occasions [21-23] as an active soil with a high content of clay fractions. The predominant mineral was determined as being the montmorillonite.

The lime used for treating the soil was procured as lumps containing approximately 95% CaO.

In this paper there are compared results on 3 types of samples: clay with an addition of 0%, 5% and 10% lime by dry clay mass, 7 days cured. The samples were statically compacted at 1.56 g/cm^3 dry density and 24.80% water content. After mixing the soil, water and lime, the mixture was left 1h at rest in a protected environment to allow the development of immediate reactions between lime and clay particles. During the curing period (7 days), the samples were protected with plastic wrap and stored at about 20 °C.

For the determination of the particle size distribution and Atterberg consistency limits, ASTM D421-58 and, respectively, ASTM D4318 U.S. standards were used. With regard to mechanical tests, for compressibility and swelling pressure there have been made cylindrical samples of 71.5 mm diameter and 20 mm height; the test was carried out according to ASTM D4546-03 (Method A). The unconfined compressive strength was measured on samples of 39 mm diameter and 78 mm height.

5.2. Results and discussions

Grain size distribution and Atterberg consistency limits

From figure 2 and table 1 it is observed that with the increasing amount of lime added, the clay content decreases from 45.57% in natural state, to 7.86% when stabilized with 5% quicklime and, respectively, to 5.92% for a 10% added quicklime, maturated 7 days. Therefore, the phenomenon that modifies the clay structure by flocculation/ agglomeration is proved right. Regarding the Atterberg consistency limits, there is also observed a significant decrease of the plasticity index values of approximately three times in both cases.

Tabel 1. The values of the clay content and Atterberg consistency limits

Material	Coloidal clay content [%]	Liquid Limit [%]	Plastic Limit [%]	Plasticity Index [%]
Natural Bahlui clay	45.47	69.68	24.5	45.63
5% lime-stabilized Bahlui clay	7.86	50.34	35.88	14.46
10% lime-stabilized Bahlui clay	5.92	49.54	32.71	16.83

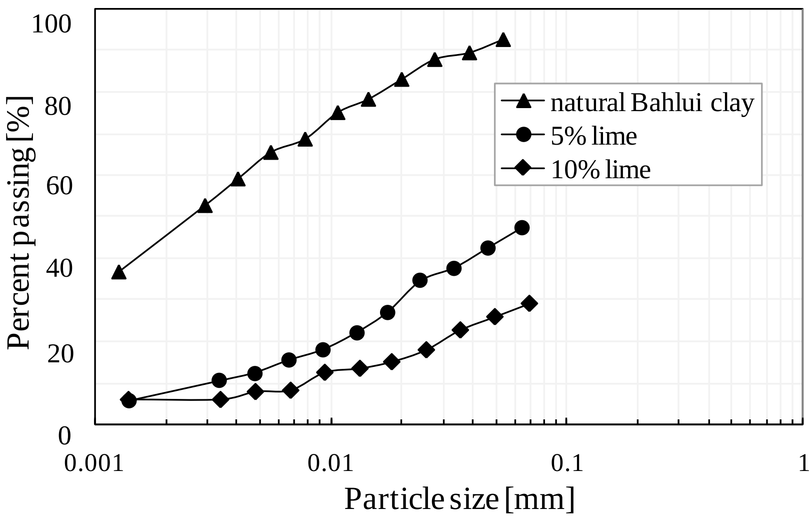

Fig. 2. The Bahlui clay grain size distribution variation in natural state and stabilized with 5% and 10% quicklime.

Clay activity

As it can be seen from figure 3, the natural Bahlui clay is a soil with high or very high activity which can be interpreted as a soil with high swell potential. As it is chemically stabilized with quicklime, the swell potential becomes low or medium, according to the graphs used for its characterization.

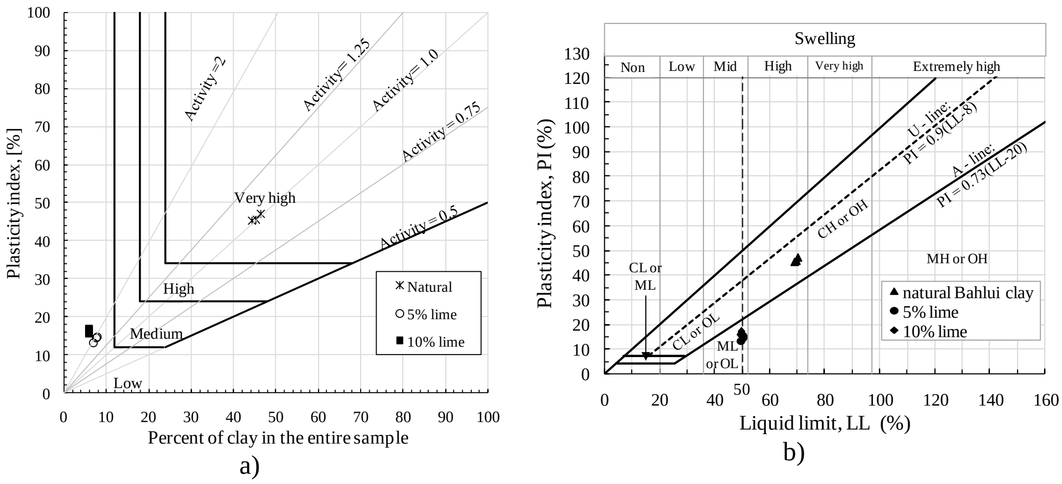

Fig. 3. Swell potential classification for natural and stabilized Bahlui clay based on the graphic representation of the most important geotechnical properties: a – after Van der Merwe, b – after the Unified Soil Classification System.

Compressibility characteristics

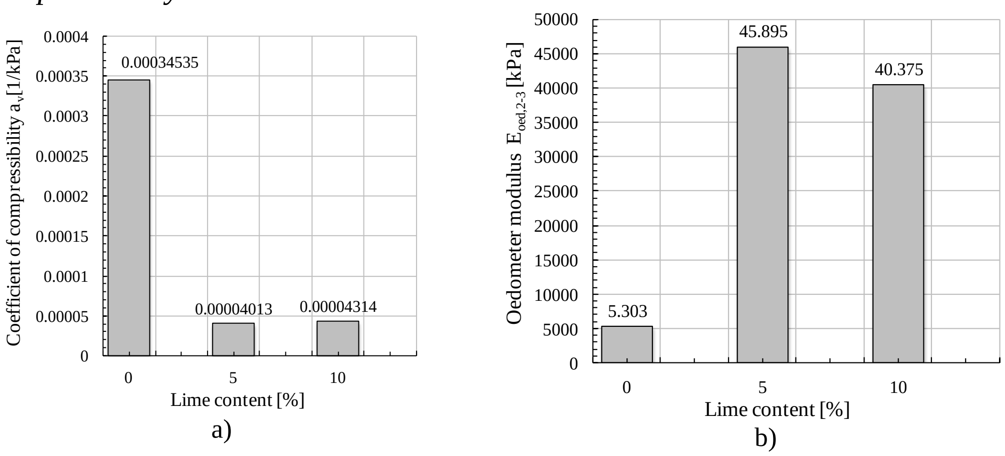

Fig. 4. The compressibility characteristics resulted from oedometer test: a – the compressibility coefficient by lime content, b-the oedometer modulus by lime content

The compressibility characteristics of soils can be highlighted through the oedometer modulus, E_{oed} and the compressibility coefficient a_v, using the oedometer test, for the 200÷300 kPa pressure range in particular [HYPERLINK \l "Stanciu06" 24]. If remolded, the natural Bahlui clay develops an oedometer modulus of E_{oed2-3}=5303 kPa and a compressibility coefficient of a_v=0.000345, indicating that is a high compressible soil and corresponding to plastic consistent clays 24] – table 4.2; as quicklime is added, the values of these indicators are improving significantly (figure 4), classifying the material as being in the low compressibility category (E_{oed2-3} is from 20000 to 50000 kPa and a_v taking values between 0.00003÷0.0001), the equivalent of medium compacted sands.

Swelling pressure

The quantitative problem of clay swelling extends on both the empirical aspect and the practicality of the laboratory tests levels. In this case, the swelling pressure was determined using the oedometer test and thus resulting a value of 119.51 kPa for the natural soil, while after 7 days curing, the 5% stabilized Bahlui clay presented a swelling pressure of 54.7 kPa and, respectively, of only 18.5 kPa when stabilized with 10% lime (figure 5). In figure 6 the swelling inhibition process through stabilization is also shown, the swell percent decreasing from 2.24% in natural state to 0.16% and 0.07% when stabilized with 5% quicklime and, respectively, 10%.

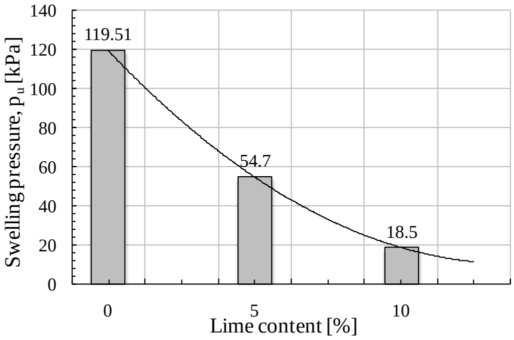

Fig. 5. Swelling pressure by lime content

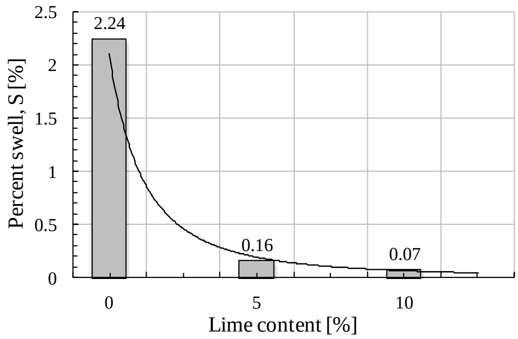

Fig. 6. Percent swell by lime content

Unconfined compressive strength

The unconfined compressive strength determination is one of the most used laboratory tests with respect to the chemical stabilization of soils, being the indicator that quantifies the mechanical properties improvement [HYPERLINK \l "Aniculăesi13" 25].

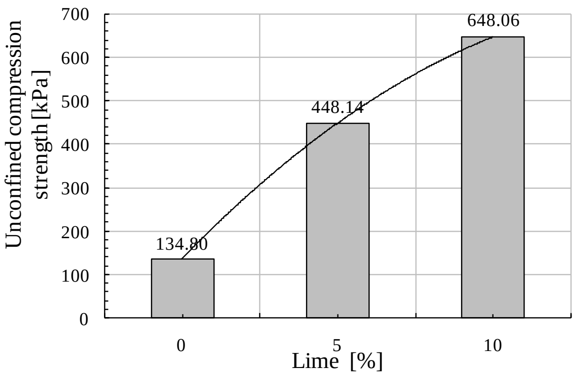

Fig. 7. The unconfined compressive strength variation wit the lime percentage

Tests carried out on the natural and stabilized samples show an increase of the unconfined compressive strength from 134.9 kPa to 448.14 kPa (when 5% lime is added) and 648.06 kPa (when 10% lime is added) (Fig. 7), the latter ones presenting a brittle behavior and not a plastic one as in the case of natural soil samples.

Conclusions

The cementation products resulting from lime-stabilization are the same as in the cement-stabilization case, with the difference that, regarding the latter case, these result from the calcium silicates hydration, while in the former one the gel is formed only after the quicklime attacks and releases silica and alumina from the clay particles.

The apparent ineffectiveness of the hydraulic binder stabilization of smectite-rich clays can be ascribed to their active character and affinity for water, preventing the crystallization of cement hydrates. It follows that it is appropriate to first treat these soils with lime prior to cement stabilization, for a considerable calcium ions contribution necessary to modify the soil structure.

After the chemical stabilization phenomenon is initiated, the active soil presents a modified physical behavior and structure, transforming from a soft soil into a more resistant one with a different grain size distribution, less plastic (and thus with obviously improved workability properties), with a higher resistance to water (by swelling pressure reduction) and more resistant from the mechanical point of view, as compressibility decreases and unconfined compressive strength gains.

R E F E R E N C E S

[1] Hotineanu, A., Lungu, I., Stanciu, A. *On the behavior of natural active clays or stabilized with binders to freeze-thaw action,* Cluj-Napoca **2012**, Proceedings of the First International Conference for Ph.D. students in Civil Engineering, 340-347.

[2] Kharrat, A., *Comportement hydromecanique des argiles plastiques traitées à la chaux.* Universite d'Orléans, Orléans, **2010**.

[3] Wakim, J., *Influence des solutions aqueuses sur le comportement mécanique des roches argileuses*. Orléans, **2005**.

[4] Lambe, W., Whitman, R. *Soil Mechanics*. John Wiley& Sons, New York, **1969**.

[5] Al-Rawas, A.A., Goosen, M., *Expansive Soils: Recent advances in characterization and treatment*. Taylor & Francis Group, London, **2006**.

[6] Hotineanu, A., *Mecanismul stabilizării argilelor active cu var*. Iaşi 2013, Al VI-lea Simpozion Naţional "Creaţii Universitare, **2013**".

[7] Geiman, C., *Stabilization of soft clay subgrades in Virginia*. Virginia Polytechnic Institute and State University, Blacksburg, **2005**.

[8] Ingles, O.G., Metcalf, J. B., *Soil Stabilization*, John Wiles & Sons, New York, **1973**.

[9] Milburn, J., Parsons, R., *Performance of soil stabilization agents,* University of Kansas, Lawrence, **2004**.

[10] Nicolescu, L., *Consolidarea şi stabilizarea pământurilor*, Editura Ceres, Bucureşti, **1981**.

[11] Maubec, N., *Approche multi-échelle du traitement des sols à la chaux: Etudes des interactions avec les argiles,* Université de Nantes, **2010**.

[12] *Design Procedures for Soil Modification or Stabilization*, Office of Geotechnical Engineering, Indiana, **2008**.

[13] Nicolescu, L., *Argila în construcţia terasamentelor*, Centrul de documentare şi publicaţii tehnice, 1974.

[14] Boardman, D. I., Glendinning, S., Rogers, C.D.F., *Development of stabilization and solidification in lime-clay mixtures*, Geotechnique, LI, 6 (August **2001**), 533-543.

[15] Deneele, D., *Processus physico-chimique et comportement geotechnique des sols traites,* Nantes, **2008**.

[16] *Treatment of soils with lime and/or hydraulic binders*, Service d'études sur les transports, les routes et leurs aménagements, **2008**.

[17] EM 1110-3-137: *Soil stabilization for pavements*, Department of the Army Corps of Engineers, Washington, **1984**.

[18] Al-Zoubi, M. S., *Undrained shear strength and swelling characteristics of cement treated soil.* Jordan Journal of Civil Engineering, II, 1, **2008**.

[19] Rujanu, M., *Materiale de construcţii*. Editura Spiru Haret, Iaşi, **2011**.

[20] Bob, C., Velica, P., *Materiale de construcţii*. Ed. Didactică şi Pedagogică, Bucureşti, **1978**.

[21] Aniculăesi, M., Stanciu, A., Lungu, I., *Reducerea potenţialului de umflare-contracţie a pământurilor expansive*. (Iaşi **2012**), A XII-a Conf. Naţională de Geotehnică şi Fundaţii, 489-498.

[22] Stanciu, A., Lungu, I., Aniculăesi, M., Hotineanu, A., *Tehnologii şi metodologii de identificare şi caracterizare a pământurilor cu umflări şi contracţii.* (Iaşi **2012**), A XII-a Conf. Naţională de Geotehnică şi Fundaţii, 457-472.

[23] Boţi, N., Stanciu, A., Lungu, I., *Estimation of the swelling pressure.* Proceedings of the International Symposium Constructions 2000 (Cluj-Napoca **1993**), 561-570.

[24] Stanciu, A., Lungu, I., *Fundaţii*. Editura Tehnică, Bucureşti, **2006**.

[25] Aniculăesi, M., Stanciu, A., Lungu, I., *The effect of the Portland and Eco-cement Stabilization on the Physical and Mechanical Behaviour of the Bahlui Clay*. Advanced Engineering Forum, 8-9 (**2013**), 361-369.