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LABORATORY METHODS USED TO ASSESS THE MECHANICAL PROPERTIES OF SOFT SOILS IMPROVED BY DEEP MIXING

BY

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Abstract. In ground improvement projects by deep mixing, the laboratory experimental program is an important stage by which, the suitable binder and quantity are chosen and geotechnical performances of improved soil are evaluated. In current practice, the design process of lime-cement columns is mainly based on unconfined compressive strength and the corresponding secant Young's modulus evaluated by unconfined compression tests. In this paper, the main laboratory methods used to assess the mechanical properties of improved soil mixed with lime and cement in deep mixing are reviewed. Laboratory preparation of the samples and testing procedures for unconfined compression tests, triaxial tests and oedometer tests are presented. In addition, some experimental results of tests conducted on soft soils mixed with lime and cement are analyzed and commented.

Key words: dry soil mixing; lime-cement-soil mixture; unconfined compressive strength, shear strength.

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1. Introduction

Deep mixing by lime-cement columns are frequently used for ground improvement of soft soils in the Scandinavian countries. Dry deep mixing methods as used today were originally developed concomitantly in Sweden and Japan in the mid-70s in order to improve the stiffness, permeability and strength characteristics of soft soils with high natural water content (Kitazume & Terashi, 2013; Topolnicki, 2013). From technological point of view, dry mixing methods involve introducing dry powder binders into the ground by compressed air and in-situ mechanical mixing of the soil with the binders, e.g. lime and cement. Construction and supervision requirements are covered by the European execution standard for deep mixing, EN 14679.

The main applications associated to lime-cement columns are: settlement reduction of roads or railroads embankments, increasing stability for small and medium sized embankments, enhancing bearing capacity of foundation soils for lightweight buildings and vibration mitigation (Larsson, 2003; EuroSoilStab, 2002). Other occasional applications are: reducing the active loads on retaining structures and increasing the passive earth pressure in front of the retaining walls, improving the stability of different kinds of excavations, stabilization of contaminated soils (Ignat, 2015). It is easy to anticipate that the geotechnical performance of lime-cement columns will not be the same for each project and that they are dependent on a number of factors related to: natural soil conditions of the site, type and quantity of the binder, execution technology and operational parameters and of course curing and loading conditions. Over time, these factors and their impact on the mechanical properties have been extensively investigated by researchers and specialists in the field (*e.g.* Baker, 2000; Åhnberg 2003, 2005, 2006, 2009; Larsson 2001, 2003, 2005; Jacobson *et al.*, 2005; Löfroth, 2005; Filz *et al.*, 2005, Kitazume & Terashi, 2013).

In order to achieve the desired result, optimize the costs, laboratory tests, field trials and post construction tests are performed. Laboratory tests are used mainly in a first stage to analyze the treatment possibilities and sometimes in further stages, as part of quality control and quality assurance programme, to verify the performances obtained (EuroSoilStab, 2002; Kitazume *et al.*, 2015). This paper presents the main laboratory methods used to evaluate the mechanical performances of improved soil. Taking into account that deep mixing methods have not been applied yet in Romania, this article is the first approach at national level regarding laboratory investigations conducted worldwide in order to assess the geotechnical performances achieved by mixing the soil with lime and cement. The article aimed also to analyze the results obtained in the laboratory tests and to evaluate the improvement effect of mixing different kind of soils with dry lime and cement.

2. Sample Preparation

For the ground improvement of soft soils by lime-cement columns, it is indispensable to perform tests on samples prepared in the laboratory before the design can be prepared. The main purpose is to evaluate the improvement effect of different types and amounts of binders.

The properties of binder-soil mixture are directly influenced by manufacturing and curing procedures (Marzano *et al.*, 2009; Åhnberg & Holm, 2009; Kitazume *et al.*, 2015). The preparation of soil-binder samples is usually carried out according to standard procedures. In Sweden, the common procedure used to prepare specimens is described in SGF Report 4:95E (Carlsten & Ekström, 1997) and in Design Guide Soft Soil Stabilisation (EuroSoilStab, 2002). In Japan, the standard procedure for sample preparation is presented in Japanese Geotechnical Society Standard (Kitazume & Terashi, 2013). Currently, there is the concern to establish an international guideline for laboratory programme which to contain an universal procedure of samples preparation and in this way, the tests results performed all over the world, could be realistically compared (Kitazume *et al.*, 2015).

The first step consists in sampling soil from the site that is intended to be improved and afterwards, by testing them, to determine their physical, chemical and mechanical characteristics. Step two is the preparation of the binder-soil samples, blending the soft soil with the binder, using a mixing machine equipped with blades e.g. a dough or kitchen mixer. Before adding the dry binders, the soil has to be disaggregated by mixing alone, and only after that, should be mixed with the binders, until an homogeneous consistency of the mixture is obtained *e.g.* 5-6 min (Carlsten & Ekström, 1997) or 10 minutes (Katazume & Terashi, 2013). For lime-cement applications the usual proportion is 50% cement, and 50% lime but this proportion may vary depending on the soil type. It is more and more common to use mixtures including blast furnace slag. The total number of the samples for a specific site may vary depending on the type and amount of the binder, curing time and type of the tests, but regularly, at least three specimens are prepared for each different mixing and curing condition.

Immediately after the mixing, the lime-cement-soil mixture is placed in molds, in layers with a thickness of approximately 30 mm, which are compacted at constant pressure for 5-10 s (Carlsten & Ekström, 1997). It is recommended to avoid the delay between mixing and placing in the molds (Åhnberg and Holm, 2009). The cylindrical molds, often plastic tubes, usually have the inner diameter of 50 mm and a minimum length of 100 mm, but it can be used other dimensions with the condition that the height to diameter ratio of the samples is maintained equal to 2. The next step is sealing the molds and storing them in a climate-controlled room for the curing process. There are some particularities concerning the organic soils, for example: the mixing time must be carefully chosen, in such a manner that to ensure the homogeneity of the mixture and in the same time to not destroy fibrous structure of organic soil ,and during the curing time the samples are immersed in water and loaded in order to obtain an increased strength due to the consolidation of the specimens (Hebib & Farrell, 1999; Pousette *et al.*, 1999). The last step, before testing the samples is extraction of the specimens from the molds, after the curing period and if it is necessary, the extremities are smoothed so that the top and the bottom of the sample to be perfect parallel (EuroSoilStab, 2002).

Laboratory tests may be performed also on core samples taken after curing of installed columns, but in reality, it is very difficult to core samples from lime-cement columns without disturbing their structure due to their brittle character. These types of samples can be collected in the field trials phase or in the post construction quality assessment stage. The core samples can be taken by using a rotary core-drilling machine or a piston sampler. After the withdrawal, samples should be stored immediately in double plastic bags until laboratory testing (EN 14679, 2005).

Hereinafter are presented several laboratory methods currently used for determining the deformability and strength parameters of the soft soils mixed with lime and cement.

3. Unconfined compression tests

Due to their simplicity, rapidity and low costs, the unconfined or simple compression tests (UCT) are the most common laboratory methods used today to assess the stiffness and strength properties of the improved soil. Unconfined compression test is a particular case of the triaxial undrained test because cylindrical samples are tested in compression without lateral confinement. The test consists in axial loading of the samples, at a strain rate between 0.5 and 2 %/min, in order to determine the unconfined compressive strength q_u and its corresponding axial strain ε. The unconfined compressive strength is considered the compressive stress corresponding the failure of the specimen (ASTM International, 2013). Unconfined compression test it is regarded as being performed in undrained conditions, so the undrained shear strength s_u for saturated cohesive soils is calculated as half of q_u (ASTM International, 2013).

Unconfined compression tests (*UCT*s) are usually conducted on specimens manufactured according to the procedures described in the previous section at different period of time after the mixing, *e.g.* 7, 28, 56, 90, 180, 360 days. To date, the majority of laboratory testing programme carried out on soils-binders mixtures were based mainly on *UCT*s by which are obtained q_u, s_u and the secant modulus of elasticity E_{50}.

Over the time, the *UCT*s have been used to investigate the possibility to improve the organic soils, e.g. peat and gyttja (Hebib & Farrell, 1999; Cortellazzo & Cola, 1999; Åhnberg & Holm, 1999, 2009; Åhnberg & Johansson, 2005; Hermandez-Martinez & Al-Tabbaa, 2005; Jacobson *et al.*, 2005) by mixing them with dry binders, mainly cement, but also with lime, blast furnace slag or pulverized fly ash, which varied between 100 kg/m^3 and 300 kg/m^3. All this tests have showed that the strength of the organic soils, especially peat, is substantially increased by mixing with cement, so the higher amount of cement, the higher strengths will be obtained. Cortellazzo & Cola (1999) reported that by mixing an Italian peat with an amount of 200 kg/m^3 of dry cement, lime and fly ash, the s_u obtained was roughly 40 kPa while by mixing only with cement, with the same dosage, the s_u obtained was 180 kPa. The *UCT*s conducted by Åhnberg and Holm, (1999) have revealed an approximate value of 320 kPa for the q_u for two types of Swedish peat mixed with an amount of 200 kg/m^3 of cement and lime and the maximum values range from 750 kPa up to 800 kPa by using the same amount of cement and slag.

The unconfined compression tests were carried out also by Baker (2000) on samples prepared in the laboratory and on samples cored from mixed in place lime-cement columns. The samples prepared in the laboratory were obtained by mixing a Swedish clay with 92 kg/m^3 of stabilizing agent composed by 50% lime and 50% cement. Samples taken from columns with 0.6 m diameter, installed in the field had the same lime-cement content of 92 kg/m^3. The unconfined compression tests carried out at 56 days of curing have shown that the q_u of core samples was higher than the q_u of samples prepared in the laboratory, aspect that can be deducted according to Fig. 1 and Table1 (Baker, 2000). In contrast, according to Bruce *et al.* (2013) and EuroStabSoil (2002) in the most of the cases, the strength values of the in-situ mixed samples are 20% to 100% of the laboratory prepared samples.

By analyzing the mixing process whereby the samples are prepared currently in the laboratory, it is somehow expected that the strengths of the samples to differ from strengths of the taken from in situ stabilized soil, even if there are used the same type and the same quantity of the binder (Topolnicki, 2013; Kitazume & Terashi, 2013). The laboratory specimens are mixed with the binders with a simple mixing tool, for whom the factors that affect, in reality the mixing process *e.g.* rotation speed, penetration or retrieval rate, are unknown or disregarded. Therefore, in order to establish a reliable relationship between the strength of the laboratory samples and samples collected from the in situ mixed elements, the mixing procedure used in the laboratory should correspond as much as possible to the execution technology used in the field (Larsson, 2003).

Besides the q_u values, Table 1 shows also a comparison with respect to E_{50} values at 56 days of curing between laboratory samples and field samples.

Again, E_{50} values for field test are higher than E_{50} values for laboratory prepared samples.

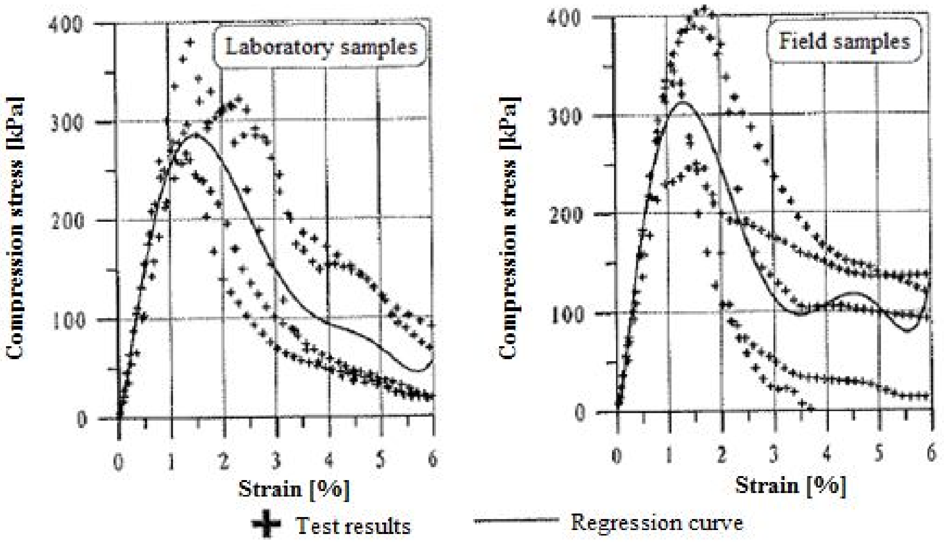

Fig. 1 – Compression stress versus axial strain for laboratory and field samples with curing time of 56 days (Baker, 2000).

Based on the values presented in Table 1 it may conclude that for this analyzed case that the ratio between the secant modulus E_{50} and the q_u is ranging from 70 to 110 for laboratory samples and from 80 to 120 for field samples. The value of E_{50} to q_u ratio, obtained by Löfroth (2005) for the samples drill out from in situ the lime-cement columns, was approximately 220. Bruce et al. (2013) reported, values of the E_{50} to q_u ratio, for dry mixing, ranging between 50 and 250.

Table 1

Unconfined Compressive Strength and Secant Young's Modulus Values for Laboratory and Field Samples with Curing Time of 56 days (after Baker, 2000)

Depth, [m]	Unconfined compressive strength, [kPa]		Secant Young's modulus E_{50}, [kPa]	
	Laboratory	Field	Laboratory	Field
1	314	344	30,500	34,000
2	330	407	23,000	33,000
3	261	332	22,000	36,000
4	278	250	30,000	30,000
5	380	390	31,000	34,500

The unconfined compression tests were performed in Swedish Geotechnical Institute as part of an international collaborative study, on samples of two types of Swedish clay mixed with cement and quicklime with the aim to analyze the influence of different molding procedures on the unconfined compressive strength of the samples at 28 days after mixing (Åhnberg & Andersson, 2015; Kitazume *et al.*, 2015). The tested samples were manufactured using the following three molding procedures: by tapping, rodding and static compaction. These tests and others international tests performed with the same purpose, brought into the light that the unconfined compressive strength and its variability are strongly affected by the molding procedure and its choice has to be done depending on the consistency of the soil-binder mixture in order to correctly assess the effectiveness of the stabilizing agent. Considering the s_u of soil-binder mixture as a reference parameter, the tests showed that the tapping and rodding procedures can be used with good results for the mixtures with s_u less than 10 kPa, the rodding procedure for s_u ranging between 10 and 20 kPa and static compactation or rodding procedures for s_u higher than 20 kPa (Kitazume *et al.*, 2015).

By economic point of view, the unconfined compression tests are the best solutions to evaluate the properties of the samples obtained by mixing the soil with different types of binders and/or different conditions. The main disadvantage of *UCT*s is that it allows the determination only of the undrained strength while, for the comprehensive studies about the behavior of the soil-binder specimens under various loading conditions and the effective parameters, triaxial tests are recommended.

4. Triaxial tests

The triaxial tests are complex laboratory tests by which may be determined the shear strength and stiffness parameters of improved soil. This tests allow the variation of principal stresses (σ_1 and $\sigma_2 = \sigma_3$) and record the pore water pressure, volume strain and axial strain. The tests are carried out, in triaxial cell, on cylindrical specimens, which are laterally confined by an elastic rubber membrane to prevent the penetration of the cell fluid into the specimen. Considering the field situation and the followed parameters during the tests, it can be performed three types of triaxial tests: Unconsolidated Undrained test (UU), Consolidated Undrained test (CU) and Consolidated Drained test (CD). Triaxial tests involve subjecting specimens to a hydrostatic pressure before and during the shearing. The vertical load is applied in the shear stage until the failure of the specimens (SIS, 2005).

In order to render the stress state from the field, in a realistic way, there are two types of triaxial tests: compression or active tests and extension or passive tests. If, in the field, the stabilized soil by lime and cement columns will be subjected to compressive loading then, it is obviously that the triaxial compression tests are relevant for determining their mechanical characteristics.

In Fig. 2, the stresses, which are acting on the cylindrical sample in the triaxial compression test, are schematically represented. By pressuring the fluid from triaxial cell, which surround the specimen, the confining stress is applied. In compression tests, the confining stress σ_c is equal to the radial stress σ_r or minor principal stress σ_3. The axial stress σ_a or major principal stress σ_1 it is equal to confining stress σ_c plus the deviator stress q. The deviator stress appears as a result of axial strain e_a applied on the specimen and can be evaluated as ratio between axial load and cross-sectional area of the specimen. For triaxial extension tests, the radial stress σ_r become the major principal stress and the axial stress σ_a become the minor principal stress (Rees, 2013).

If the principal stresses are equal $\sigma_1 = \sigma_3$ the stress state is considered isotropic and if they are different $\sigma_1 \neq \sigma_3$, the stress state is considered anisotropic.

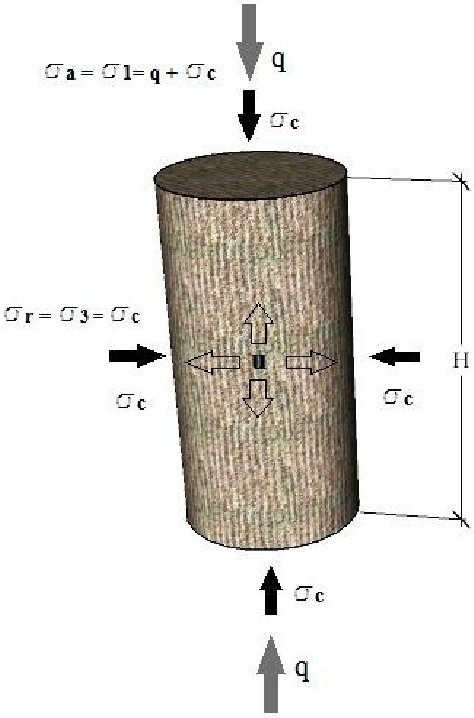

Fig. 2 – Specimen stress state during triaxial compression test.

Usually, both consolidated undrained and drained triaxial compression tests are used to assess the effective cohesion and the effective angle internal friction of stabilized soils mixed with different type of binders (Åhnberg, 2006, 2007; Baker, 2000; Löfroth, 2005; Balasubramaniam *et al.*, 2005; Bergado *et al.*, 2005). However, there are few laboratory investigations reported in the literature about triaxial tests performed on soil mixed with dry lime and cement. Triaxial tests are conducted through following main stages: saturation, consolidation and shearing (SIS, 2005; BS 1377, 1990).

The *saturation stage* means filling all the voids of the sample with water in order to get an accurate measurement of pore pressure during undrained shearing and correct volume change measurements during drained shearing. The saturation can be performed either by applying the back pressure to the specimen with simultaneous increase of the cell pressure, or simply by increasing the cell pressure.(SIS, 2005; BS 1377, 1990). Triaxial tests carried out on soil-binder specimens, indicate values of the back pressures applied to saturate the samples of 300 kPa (Hebib & Farrell, 1999), 400 kPa (Åhnberg, 2006; 2007) and 400-500 kPa (Ignat, 2015). The specimen can be considered saturated if the B value, Skempton pore pressure coefficient, is equal to or greater than 0.95 (BS 1377, 1990).

The *consolidation stage* is performed in order to bring the sample to a state of effective stress necessary for carrying out the last step, the shearing stage. The effective consolidation pressure (σ_3') is calculated as being the difference between the cell pressure σ_3 and the back pressure u_b. Consequently, to reach the effective stress in the specimen, the cell pressure is increased and the back pressure is adequate chosen (BS 1377, 1990). The effective consolidation pressure applied to the specimens has to correspond to the real pressure from the level where the sample was taken.

Consolidated undrained and drained triaxial compression tests was conducted, by Åhnberg (2006), on a Swedish clay mixed with quicklime and powder cement with the aim to investigate the influence of different consolidation stresses on the strength of stabilised soils. Cylindrical samples were consolidated for 7.5 h at effective cell pressures (s_3') of 20, 80, 160 and 240 kPa. The test results have indicated that both the drained and undrained strengths are dependent on the consolidation stresses and if this dependence is neglected then the estimated values of strength at increasing depths will be lower than in reality.

The shearing stage for both consolidated undrained or drained triaxial tests involve to shear the specimen at a constant rate of axial deformation until the failure, while cell pressure is kept constant. In undrained tests, the drainage of pore water from the specimen is not allowed so the volume deformation is null, whereas in drained tests the drainage is permitted. In undrained tests, the pore pressure changes are measured, while in drained tests, the pore pressure remains practically constant and the volume changes are measured. During this stage should be recorded, at different intervals of time, the deformations, the axial load applied and pore pressure or volume change (BS 1377, 1990; ASTM D4767, 2011). Due to the different loading conditions, the failure mode specific to the active triaxial tests will take place in a different way in comparison with the passive triaxial tests. Therefore, for compression triaxial tests the failure usually occur under a single plane failure while for extension triaxial tests the sample is elongated and the failure take place along a horizontal plane (Ignat, 2015).

The triaxial tests conducted on specimens obtained by mixing the soil with dry lime and cement have revealed that the stabilized soil behaves like a overconsolidated soil when the consolidation stresses values are lower than the quasi-preconsolidation pressures (Åhnberg, 2007; Ignat, 2015). The values of drained shear strength parameters reported by Ignat (2015) in consolidated undrained compression tests, are the following: effective friction angle ϕ' ranging between 36° and 37° and effective cohesion c' varying with the depth from where the sample was taken, between 39 kPa up to 92 kPa. The excess pore water pressure Δu development is directly influenced by the consolidation stresses. For samples consolidated using low confining pressures, at the beginning of the shear stage and until reaching the peak deviator stress q_{peak}, the excess pore water pressure start to increase, showing positive values and then, post - peak deviator stress value, negative excess pore water pressure values begin to develop (Ignat, 2015).

5. Oedometer Tests

The oedometer test is a classical laboratory test, which allows to evaluating the compressibility and consolidation properties of stabilized soils by mixing with binders. The stress-strain behavior of the treated soil is highlighted by following the settlements of the natural moisture or saturated specimens, which are restrained laterally and subjected to axial loads. The drainage during axial loading is allowed through the porous stones placed on the top and bottom of the specimen. There are two types of oedometers tests by which the consolidation properties of the soil mixed with binders can be determined: incremental loading (IL) and constant rate of strain (CRS). By conducting these tests can results the following parameters: compression index C_c, oedometer modulus M, coefficient of volume compressibility m_v, vertical preconsolidation stress σ_{pv}' coefficient of consolidation C_v, coefficient of permeability k (ASTM D2435/D2435M, 2011; ASTM D4186/D4186M, 2012).

Incremental loading rate of strain oedometer tests (IL) was conducted on two Italian peat mixed with dry lime, cement and fly ash in order to determine the improvement effect on the compression characteristics of the peat after stabilization (Cortellazzo & Cola, 1999). The peats mixed with binders shown an important improvement of the strength-strain behavior due to the increasing of the pre-consolidation pressure from 100 kPa to 150 kPa for one of the peats and from 15 kPa to 90 kPa for the other one (Cortellazzo & Cola, 1999).

The constant rate of strain oedometer tests (CRS) was used by Åhnberg (2003) to investigate the permeability of a Swedish clay mixed with quicklime and cement. The results of tests revealed that the permeability of the samples decrease as the strength increases. After mixing the clay with the dry binders, an initial increase of the permeability was observed and then, with time, the permeability begins to decrease and this phenomenon might be explained by occurrence of the cementation processes and their cementitious products (Åhnberg, 2003).

5. Conclusions

Irrespective of the samples type, either prepared in laboratory or cored from installed elements, laboratory testing program cannot miss from the deep soil mixing projects by lime-cement columns. This is the reason why all specialists in the field must know the procedures of tests, what kind of results can be obtained within them and how to interpret these results. This article presents some laboratory testing methods through which the mechanical parameters of soft soils mixed with lime and cement are assessed. The simplest and most used type of tests are unconfined compression tests, even if they do not provide information about the influence of stresses and cannot measure pore water pressures. Triaxial tests are time - consuming tests but, in the same time, they render similar to the in-situ site conditions and allow evaluating the drained and undrained strength under different loading conditions.

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* * * *Test Method for One-Dimensional Consolidation Properties of Saturated Cohesive Soils Using Controlled-Strain Loading.* ASTM International D4186/D4186M, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States (2012).

METODE DE LABORATOR UTILIZATE PENTRU EVALUAREA PROPRIETĂȚILOR MECANICE ALE PĂMÂNTURILOR MOI ÎMBUNĂTĂȚITE PRIN MALAXARE ÎN ADÂNCIME

(Rezumat)

În cadrul proiectelor de îmbunătățire a terenurilor prin metode de stabilizare în adâncime a pământurilor prin malaxare, programul experimental de laborator reprezintă o etapă importantă prin care sunt alese liantul şi cantitatea acestuia şi sunt evaluate performanțele geotehnice ale pământului stabilizat. În practica curentă, procesul de proiectare al terenurilor stabilizate prin malaxare cu var şi ciment pulbere este bazat în principal pe rezistența la compresiune monoaxială şi modulul de elasticitate secant corespunzator, evaluate în cadrul testelor de compresiune monoaxială. În această lucrare sunt analizate principalele metode de laborator utilizate pentru evaluarea proprietăților mecanice ale pământurilor malaxate cu var şi ciment. Sunt prezentate procedura de pregătire a probelor în laborator precum şi procedurile de testare pentru testele de compresiune monoaxială, testele de compresiune triaxială şi testele efectuate în edometru. De asemenea, rezultate ale unor teste efectuate pe pământuri moi amestecate cu var şi ciment sunt analizate şi comentate.