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A methodology for evaluating the level of improvement of the soils by physical and chemical mixing and its application in several projects in Romania

Une méthodologie pour évaluer l'efficacité du traitement physique ou chimique des sols par malaxage et l'application à des projets en Roumanie

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ABSTRACT: The paper is a synthesis of previous researches conducted in the field of improving difficult foundation soils. Particular emphasis will be placed on improving the soils sensitive to wetting (loessoid / collapsible soils) and high swellings-shrinkage soils improved by physical mixing (in addition with bentonite, sand or gravel) and chemical mixing (different types of hydraulic binders). Theoretical aspects, laboratory tests, but also case studies and experimental in situ test pad results will be presented. The chapter of conclusions will analyse the main methods of soil improvement in order to highlight the most effective methods depending on the type of soil to be improved. It will also be emphasized that there is no single recipe for the soil improvement.

RÉSUMÉ: L'article est une synthèse des recherches antérieurs menées dans le domaine du traitement des sols difficiles. Un accent particulier est mis sur le traitement des sols colapsibles et des argiles gonflants améliorés en utilisant des mélanges physiques (avec bentonite, sable, gravier) et des mélanges chimiques (avec des différents types de liants hydrauliques). On présente les aspects théoriques, les tests de laboratoire et in-situ ainsi que des études de cas. Le chapitre de conclusions analyse les principales méthodes du traitement des sols par malaxage pour mettre en évidence les méthodes les plus efficaces en fonction de chaque type de sol traité. Il faut souligner qu'il n'existe pas une recette unique pour le traitement d' un sol.

KEYWORDS: soil improvement, collapsible soils, expansive soils, soil mixtures, hydraulic binders.

1 INTRODUCTION

Collapsible soils (loess and loessoid soils) (NP 125, 2010) and expansive soils (fat clays) (NP 126, 2012) are considered to be active in relation with water and are included in the category of difficult foundation soils. Collapsible soils, if wetted, have additional settlements due to their own weight and/or to the loads transmitted by the foundations, becoming very compressible soils. Expansive soils cyclically change their volume following changes in water content – they increase their volume when the moisture content is increasing and shrink when the the moisture content decreases.

1.1 *Improvement methods for difficult foundation soils*

Difficult foundation soil improvement methods are continuously progressing, not only quantitatively, but also qualitatively, as a result of both the development of new technologies and the recognition of economic and environmental protection benefits of modern methods. In the construction of embankments, it is necessary to improve the physical and mechanical properties in order to use active soils in relation to water. Thus, for collapsible soils, the aim is to irreversible reduce / eliminate additional settlements (by reducing the porosity), as well as to improve the mechanical characteristics (compressibility and shear strength). In the case of expansive soils, the aim is to reduce / eliminate the swelling / shrinkage potential and to improve the mechanical characteristics (reducing the swelling pressure and increasing the shear strength). These objectives can be achieved by mass improvement of the soil using various mixtures and compaction. Preparatory activities in the laboratory and in experimental test pads are required in order to obtain optimal results.

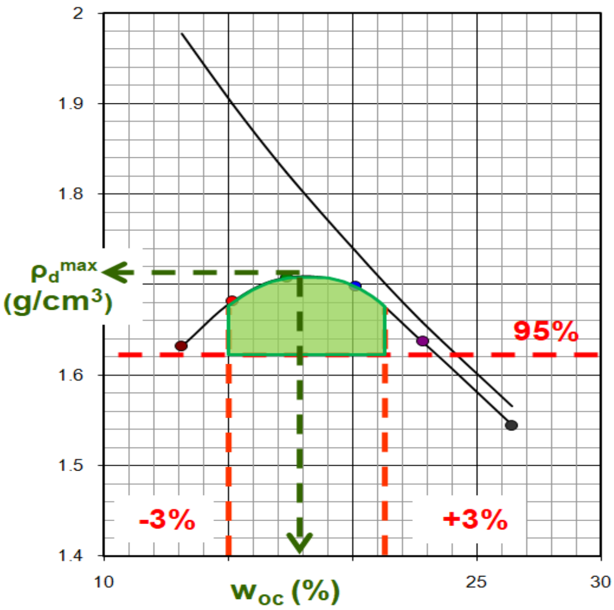
1.2 *Laboratory tests on compacted samples*

A decisive step for achieving improved foundation soils by compaction and/or by using mixtures is the determination of the optimum compaction parameters (water content, density and compaction energy). The exact correlation between the compaction characteristics obtained in the laboratory and those obtained in-situ is generally achieved in a field that is established by the Proctor test (ρ_d^{max} and w_{oc}).

In current practice, the verification of compacted soils is made using the degree of compaction ($D = (\rho_d/\rho_d^{max})*100$, %) and other physical and mechanical parameters of interest for the project (permeability, swellinge pressure, compressibility, shear strength, etc…). Depending on the nature and type of the soil to be improved by compaction, as well as on the importance and the use of the construction, the values of the degree of compaction, D, are recommended to be between 95% and 100%. These are usually achieved for water contents in the w_{oc} ± 3% domain (Figure 1.a.).

The starting point of the research methodology was the recommendation of researchers Daniel and Benson (1990) on finding the optimal characteristics of compacted materials, which consist in determining the physical and mechanical properties of several laboratory compacted samples (samples with different water content and dry density values) and an "acceptable area" for all the studied properties (Figure 1.b.).

Following laboratory tests conducted on compacted loess, it has been observed that, in what concerns the samples used, there are differences of the dry density values. These differences appeared although the analyzed samples were taken from the same compacted cylinder, but from different depths (Figure 1.c.). It results that the dry density obtained from the Proctor test is an average value, the dry density varying actually with the height of the compacted cylinder (Burlacu, 2012).



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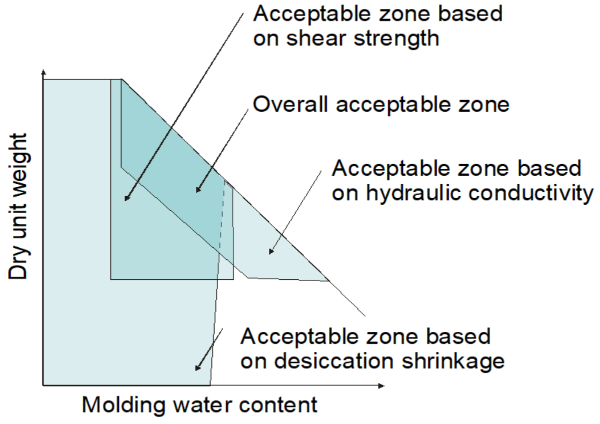

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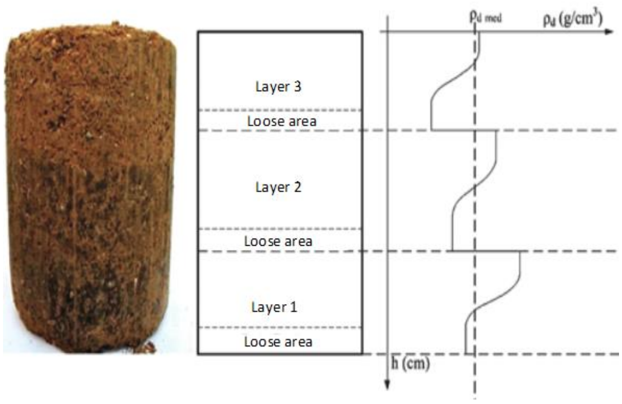

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Figure 1. Evaluating compaction characteristics: a) optimal compaction characteristics for D ≥ 95%; b) highlighting of the “acceptable area” (Daniel & Benson, 1990); c) dry density variation on a sample height (Burlacu, 2012)

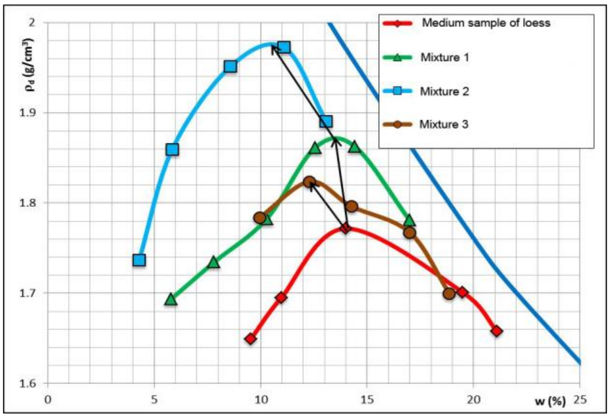
2. IMPROVING DIFFICULT FOUNDATION SOILS - ACTIVE / SENSITIVE TO WATER

In the Laboratory of Geotechnical and Foundation Engineering Laboratory form the Technical University of Civil Engineering Bucharest several experimental programs were proposed and conducted, aiming to obtain ecological mixtures (with natural materials and inert waste) so that the difficult foundation soils (loessoid and clayey soils) to turn into “proper foundation soils”.

2.1. *Research on improving collapsible soils*

2.1.1 *Soils mixtures with mineral materials (sand, bentonite) (Burlacu, 2012)*

Various mixtures of loess with different natural mineral materials have been proposed, in view of eliminating water sensitiveness, improving mechanical parameters and limiting permeability. To this purpose, a series of mixtures have been proposed: loess with sand 1-2 mm (C_u = 1.5) and loess with sand and bentonite powder addition in two variants of mixture: Mixture 1: 80% loess + 20% sand (1-2 mm); Mixture 2: 60% loess + 40% sand (1-2 mm); Mixture 3: 50% loess + 40% sand (1-2 mm) + 10% bentonite; Mixture 4: 50% loess + mixture from (40% sand (1-2 mm) + 10% bentonite). The difference between the last two mixtures consisted in the way they were mixed. In the first case, all the three materials were simultaneously mixed and then water was added to reach different degrees of moisture content in order to perform the normal Proctor test, while for the last mixture, the sand was first mixed with the bentonite and with water and then, after this mixture has dried, it was also mixed with loess.



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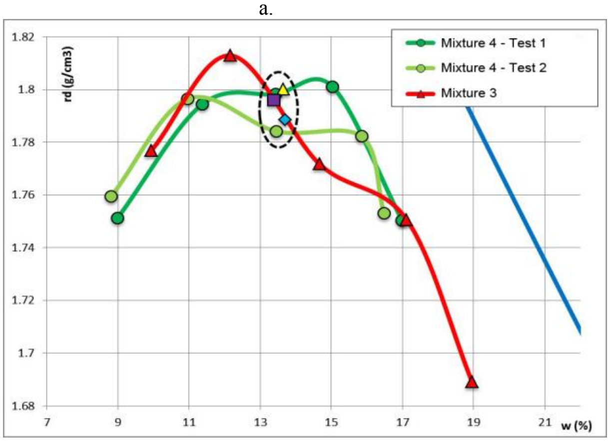


b.

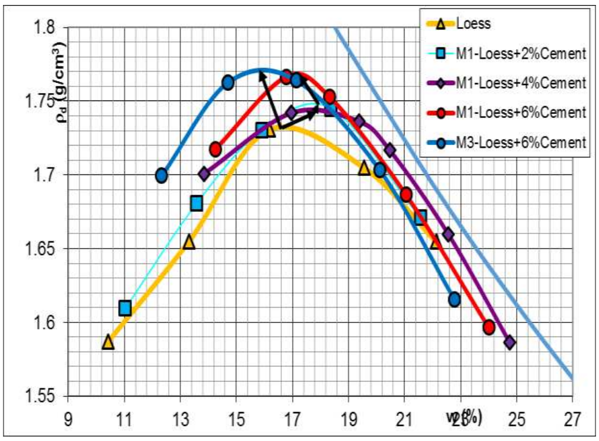
Figure 2. Results of the Proctor tests for: a. all the mixtures; b. mixtures 3 and 4.

For mixture 3 the Proctor diagram has a maximum point (ρ_d^{max}, w_{oc}), but, in case of mixture 4, the same compaction state was obtained for water content values between 11% and 15% (Figure 2). Given that moisture content plays a key role in the real scale compaction process, the last indication regarding mixture 4 is important because it allows compaction at moisture content values belonging to wider domains.

The synthesis of the oedometer compressibility tests, based on the oedometric moduli values indicated that the same values $E_{oed\ 200\text{-}300}$ could be obtained for the mixture containing an addition of sand of 20%, at smaller moisture content values and at a better compaction state than in case of the natural loess samples. This trend disappeared once the percentage of sand in the mixture was increased. In what concerns samples with bentonite, similar values of oedometric moduli were obtained at a better compaction state than in case of medium samples of loess, but at a reduced compaction state than in case of samples with sand, which was also confirmed by the values obtained following Proctor tests.

2.1.2 *Soil mixtures with hydraulic binders (cement) (Ngueyen Cong, 2019)*

The experimental program aimed to obtain an optimal mixture of water sensitive soil with cement in order to eliminate its water sensitiveness. For this purpose, several methods of mixing loess with different percentages of cement were performed: Method 1 (M1): loess was mixed with water, hydrated for 24 hours, then mixed with cement (2%, 4%, 6%) and compacted immediately; Method 2 (M2): loess was mixed with cement (4%), then mixed with water, hydrated for 24 hours and compacted; Method 3 (M3): loess was mixed with cement (6%), then mixed with water and compacted immediately.



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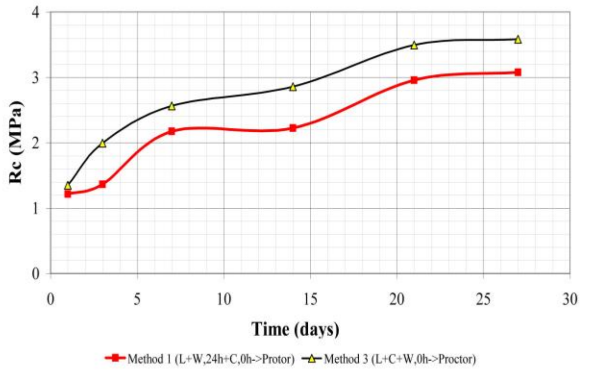

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Figure 3. a. Results of the Proctor tests for all the mixtures; b. Unconfined compressive strength test results for M1 and M3

After analyzing the Proctor results, it was observed that the M2 wasn't that effective. In what concerns the oedometer compressibility tests, the results, for both mixing methods (M1 and M3), were similar. Also, unconfined compressive strength tests were conducted for these two mixing methods (Figure 3.b), resulting in significantly higher values for M3.

2.2 *Researches on improving expansive soils*

2.2.1 *Soil mixtures with granular materials (slag, sand with gravel, gravel) (Ivasuc, 2013)*

The experimental program aims to determine the optimal solution for improving expansive clay (local material) with granular materials in order to ensure the stability of a hilly site on which an ecological landfill needs to be built. According to technical norms (NP 126, 2012), the natural soils are very active clays – expansive clays which can't be used for the construction of embankments, these soils fits into the category of „very bad" materials in the Cassagrande nomograme. For desensitization of the expansive clay, by mixing with a non-cohesive material, was proposed the following: Mixture 1: Clay + 10%, 20% and 40% Slag; Mixture 2: Clay + 10%, 30% and 50% Sand with Gravel; Mixture 3: Clay + 30% and 40% Gravel.

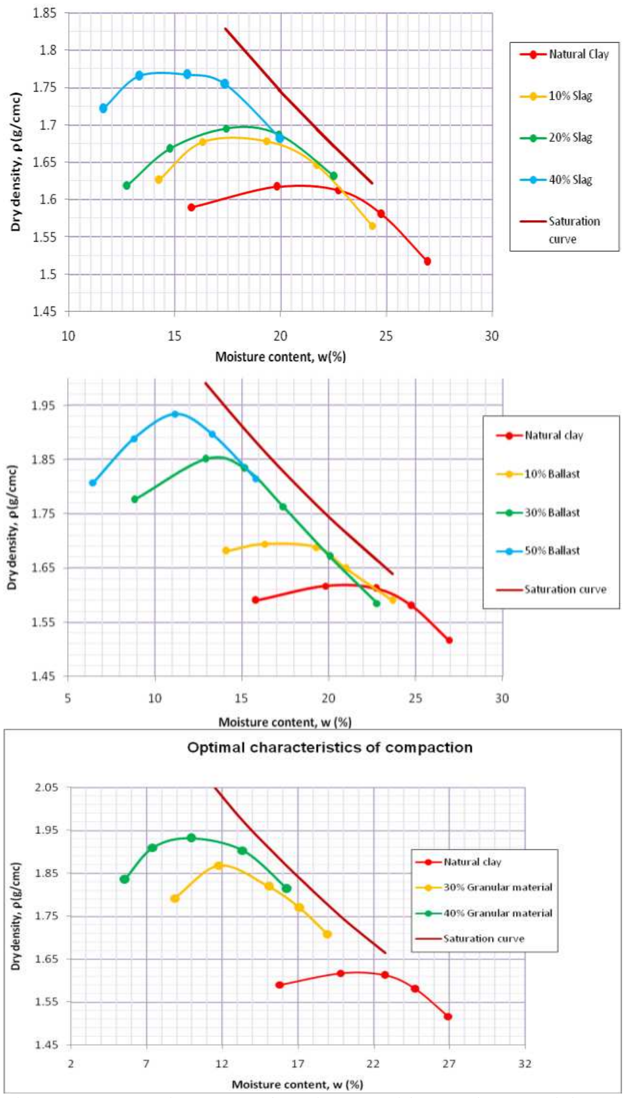


Figure 4. Compaction curves for mixtures with granular materials: (a) slag, (b) sand with gravel, (c)gravel

On the samples around the optimal compaction parameters, were determined the following properties: swelling pressure, the shear strength parameters, the oedometric modules and the swelling under no load. Based on the laboratory tests, graphs of variation of swelling and swelling pressure were drawn versus the difference in moisture content compared to the optimal compaction moisture content. From the mixture between 90% clay and 10% slag, from Figure 5, results the fact that the initial swelling and the swelling pressure register very high values, even higher than the values registered for the natural clay, behaviour justified by the fact that the compaction effect is higher than the desensitization effect (ρ_d^{max} increases from 1.62 g/cm^3 to 1.68 g/cm^3). Such diagrams constitute a solid support for the determination of the technological solution of soil stabilization with inactive materials.

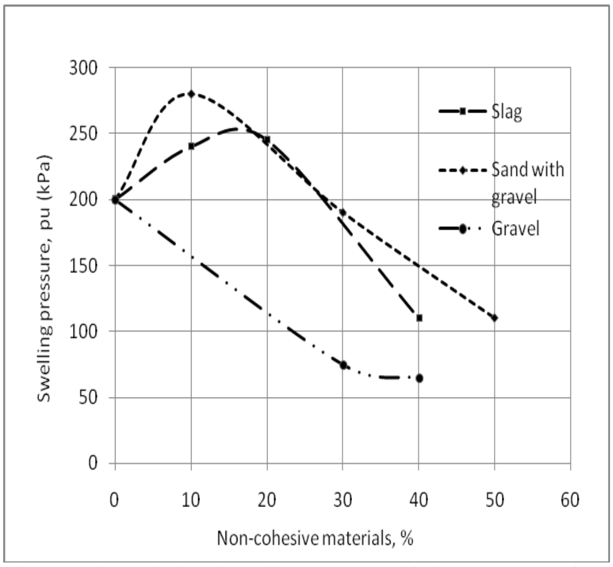


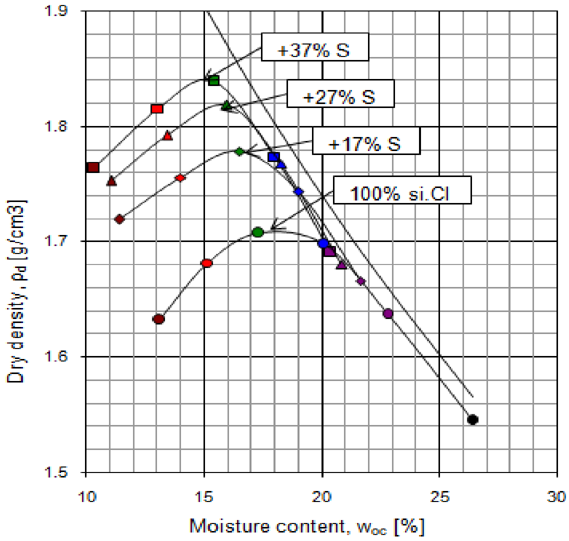
Figure 5. The variation of swelling pressure with the percentage of non-cohesive (granular) material added

2.2.2 *Soil mixtures with mineral materials and hydraulic binders (Olinic et all., 2019)*

The experimental program aims to find the technical solution for the construction of an industrial platform located in a flooded area of the Danube meadow from Romania. In terms of protection from flooding has become mandatory to upraise the ground level with minimum 2 m by making a compacted soil cushion on which all technological objects will be founded.

The geotechnical study shows that the foundation soil fits into the category of difficult foundation soils consisting of highly compressible layers and expansive soils. In order to realize the compacted cushion, it was desired to use a local material identified as a Silty clay, which has developed a swelling pressure of 120 kPa. For the study of the mechanical behavior of soil-mixtures, the following percentages of added material were proposed: Mixture 1: Clay + 17%, 27% and 37% Sand; Mixture 2: Clay + 1.5%, 2.5% and 3.5% Hydraulic binder 1 (D); Mixture 3: Clay + 1.5%, 2.5% and 3.5% Hydraulic binder 2 (C) (Figure 6).

In order to determine the optimal soil mixture, the swelling pressure was determined on all the samples around optimal of compaction and were established the variation diagrams regarding the swelling pressure depending on the moisture content difference towards the optimum moisture content of compaction for the Mixture 1 and 3 (Figure 7). In the case of Mixture 2 it has been noticed that the swelling pressure is zero resulting that the materials obtained do not have the behavior of a swelling – shrinkage material.



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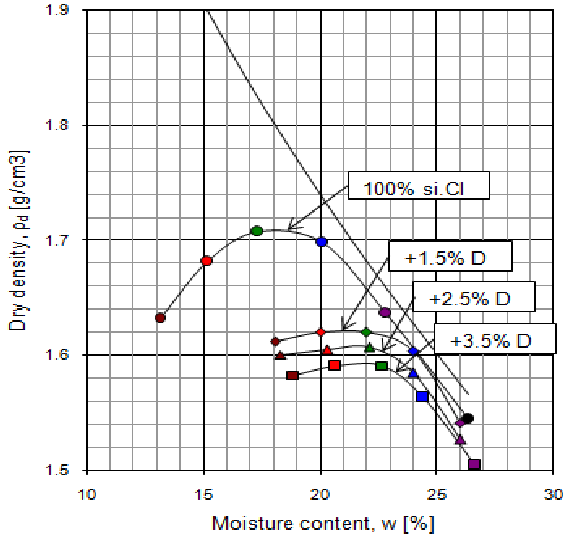
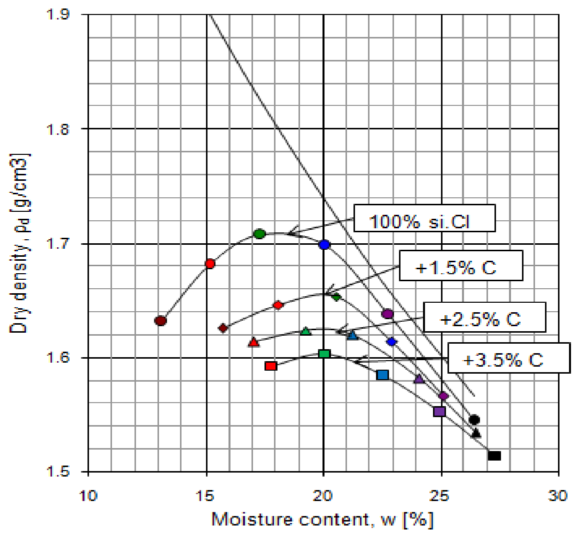


b. Mixture 2: Clay + 1.5%, 2.5% and 3.5% D



c. Mixture 3: Clay + 1.5%, 2.5% and 3.5% C

Figure 6. Compaction curves for normal Proctor test

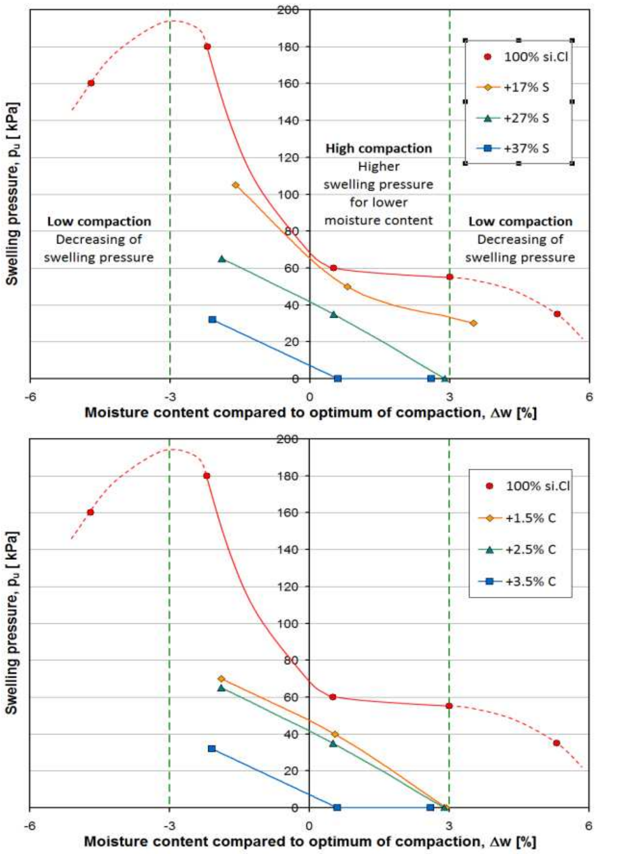


Figure 7. The variation of the swelling pressure versus the moisture content difference towards the optimum moisture content of compaction: a. physical mixture; b. chemical mixture

For the validation of laboratory tests in situ, were made the following test pads: Polygon 1: Clay + 30% Sand, Polygon 2: Clay + 2.5% D and Polygon 3: Clay + 2.5% C. The reaction time of hydraulic binders with filler material has been studied in previous research on collapsible and expansive soils (Figure 8). It was observed that by adding quicklime the temperature of the mixtures increases up to 41 ... 43°C, and the moisture content of the material decreases by 5...8%. Changes in temperature and moisture content occur as soon as the quicklime comes into contact with moist soil, which means that there is no need for a waiting time between the stage of spreading hydraulic binders, mixing and compacting materials in the field (Olinic, 2016).

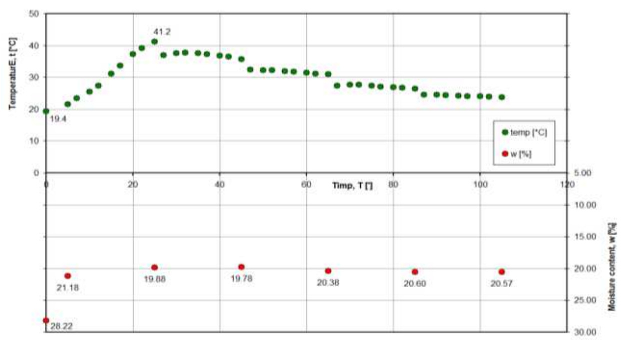


Figure 8. Variation of moisture content and temperature versus time, clay + quicklime mixture

2.3 *In situ works*

In situ, the soil mixtures are compacted in layers with a maximum thickness of 30 cm for a total height of 1…5 m. The equipment and technological methods of compaction differ depending on the nature of the soil which needs to be compacted, namely: compaction with roller (for cohesive soils) and compaction with roller + vibration (only in the case of non-cohesive soils).

The main steps of execution of a compacted cushion are: spreading natural soil, eliminating bounders / breaking (in particular for expansive soils), leveling, scattering filler material, leveling (in the case of mixtures of granular material), mixing the material in vertically with the mixer, leveling with the grader, compaction with the sheep foot cylinder and then compaction with the smooth cylinder. Cushion made of compacted material are made in layers; and the thickness of each layer, the compaction machine and the number of passes of the compaction machine are determined following an experimental polygon. For each layer of material applied, compaction is carried out by sectors and samples are taken to determine the density (degree of compaction) at the top, middle and bottom of each layer, for each compacted sector. Based on the values obtained, graphs are drawn in order to see the variation of the degree of compaction depending on the number of passes of the compaction machine (Figure 9). The optimal solution for the construction of the compacted cushion is established depending on the optimal compaction characteristics resulting in the laboratory and the optimal degree of compaction obtained in the experimental polygons.

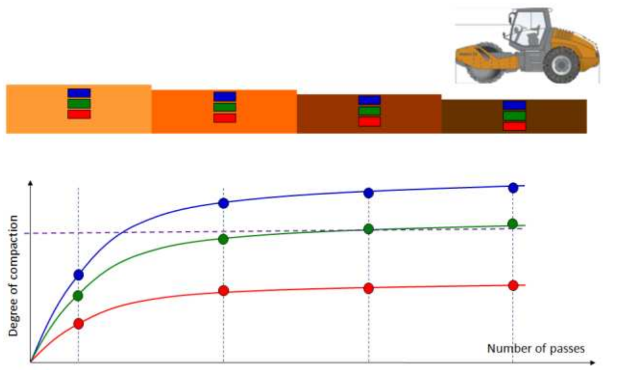


Figure 9. Variation of the degree of compaction depending on the number of passes of the compaction machine

3. CONCLUSIONS

In several projects applied in Romania, the improvement of the foundation soil was performed based on complex field and laboratory tests which established the optimal percentage of filler material so that the mixture obtained has optimum physical and mechanical parameters for the project. At the same time, for each optimal dosage, the variation of the physical and mechanical parameters of the mixture was followed depending on the difference compared to the optimal compaction moisture content, especially in the +/- 3% range which is recommended for compaction, in the current practice. It was found that, compared to compaction at optimum moisture content, the samples compacted at a lower moisture content, still retain an activity in relation to water.

The improvement of cohesive soils by mixing with granular material (physical mixture), leads to maximum dry densities higher than the natural sample. The improvement effect is visible for percentages of granular filler material that varies in the range of 20… 50%. In the case of soils active in relatio to water (fat clays) it may happen that for small percentages of granular filler material the activity in relation to water is even higher (higher swelling and swelling pressure) because the effect of soil compaction is higher. than reducing the amount of active material.

The improvement of cohesive soils by mixing with hidaulic binders (chemical mixture), leads to maximum dry densities lower than the natural sample. The optimal percentage of hydraulic binder varies in the range of 1… 5%. High percentages of hydraulic binder lead to obtaining a mixture with very good mechanical compressibility and mechanical shear strength characteristics, but with a brittle behavior which, after yielding, creates preferential water infiltration pathways, with a negative effect on the behavior of the work over time.

According to our own tests, it has been confirmed that there is no single recipe for soil improvement, and the establishment of an optimal solution must be based on laboratory tests and confirmed by experimental test pads. In this direction, in Figure 10, the stages of carrying out such research were synthesized.

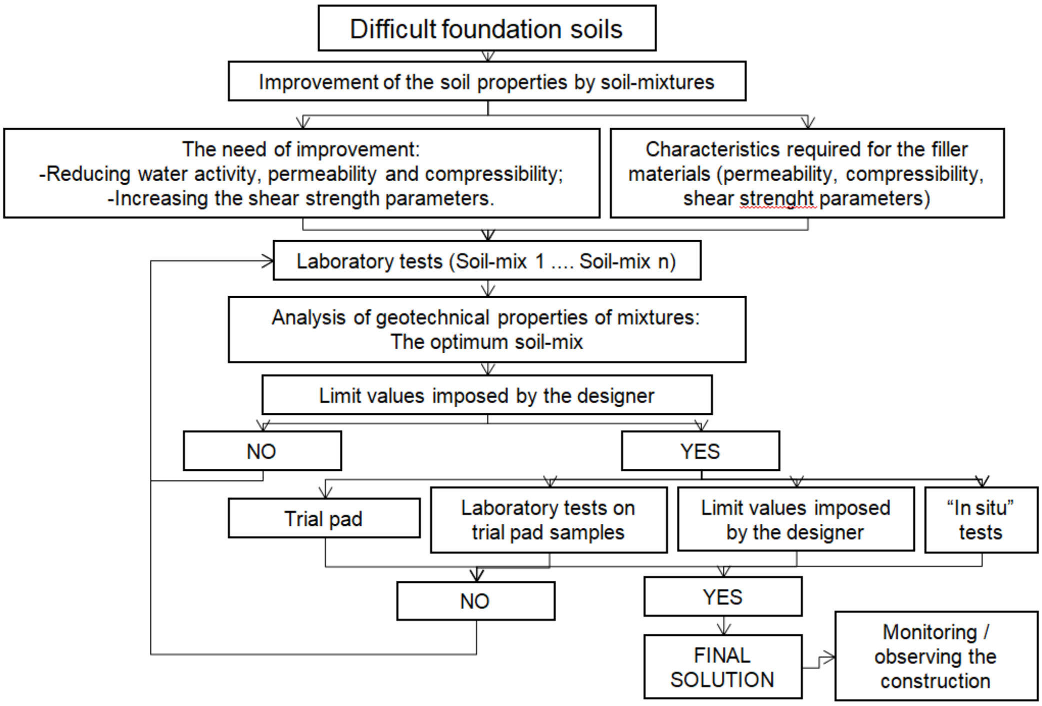


Figure 10. The stages of the improvement by soil-mixture

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