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Assessment of physico – mechanical and durability characteristics of difficult soils improved by mixing with special lime-based hydraulic binders

Evaluation des propriétés physico – mécaniques et de durabilité des sols difficiles améliorés par malaxage avec des liants hydrauliques spéciaux à base de chaux

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ABSTRACT: Soils stabilized with hydraulic binders are more and more used for road works thanks to their good behaviour under traffic loads, climatic and hydrological factors. Site conditions or available materials in site vicinity are not always good for foundation or earthworks, so that it is required to build on or use difficult soils with low mechanical characteristics or with difficult behaviour, such as swelling soils, after their improvement. Hydraulic binders are used for soil stabilisation and improvement as they allow to use local soils in order to improve their geotechnical parameters, without bringing soils from quarries or other borrow pits. The increased complexity of works and site conditions have imposed to develop and use special hydraulic binders having improved properties in comparison with ordinary hydraulic ones. One of the most analysed aspect of soils improved by mixing with hydraulic binders is their durability. The paper approaches the study of behaviour during the time of a test field for a road earthwork stabilised with special lime-based hydraulic binder. The performed studies and researches emphasize the modification that the special lime-based hydraulic binder determine in the analysed soil, by quantitative and qualitative transformations due to changes in the intimate soil structure. As well, the factors offering work performance in terms of durability are identified. The main objective of the test field was to establish the durability performance through assessment of physical and mechanical properties in situ and by laboratory tests, before and after the improvement and after freeze/thaw cycles.

RÉSUMÉ: Les sols stabilisés avec des liants hydrauliques sont de plus en plus utilisés pour les travaux routiers grâce à leur bon comportement sous les charges apportées par le trafic ou en présence de facteurs climatiques et hydrologiques. Les conditions du site our les matériaux disponibles autour ne sont pas toujours bons pour les fondations ou les terrassements, donc il est nécessaire de construire sur ou d'utiliser des sols difficiles, ayant des pauvres caractéristiques mécaniques or manifestant un comportement difficile comme les sols gonflants, après leur amélioration. Les liants hydrauliques sont utilisés pour la stabilisation et amélioration des sols puisque cela permet d'utiliser les sols locaux pour améliorer leurs paramètres géotechniques, sans apport de matériaux de carrière. La complexité croissante des travaux et conditions des sites ont imposé de développer et d'utiliser des liants hydrauliques spéciaux, ayant des caractéristiques supérieures par rapports aux liants hydrauliques classiques. Un des aspects le plus étudié de sols améliorés par liants hydrauliques est leur durabilité. L'article traite le comportement dans le temps d'un plot d'essai sur un remblai routier stabilisé par liant hydraulique spécial à base de chaux. Les études et recherches réalisées mettent en évidence les modifications que les liants spéciaux à base de chaux produisent dans les sols analysés, par transformation quantitatives et qualitatives dues aux changements dans la structure intime. De même, sont identifiés les facteurs qui offrent de l'efficacité en termes de durabilité. L'objectif principal du plot expérimental est d'établir la performance de durabilité par l'évaluation des propriétés physiques et mécaniques in situ et par essais de laboratoire, avant et après l'amélioration et après des cycles de gel/dégel.

Keywords: binder; lime; improvement; difficult soils; durability

1 INTRODUCTION

Road earth embankments are often required to be built using local, marginal, even difficult soils that need to be improved prior to their use. Soft, clayey soils can be stabilised and improved by mixing with hydraulic binders, based on cement, lime, fly ash etc. As the work complexity is increasing, more results are expected from soils improved by mixing, therefore research is still ongoing (even if the technique is available since many years) for finding new special hydraulic binders and to assess their capabilities. Among the most studied aspects is the durability of the improved soil, especially to water and freeze/thaw cycles.

The paper approaches the study of the behaviour during time of a test field for a road embankment stabilised with special lime-based hydraulic binder. The performed studies and researches emphasize the modification that the special lime-based hydraulic binder determine in the analysed soil, by quantitative and qualitative transformations due to changes in the intimate soil structure.

The main objective of the test field was to establish the durability performance through assessment of physical and mechanical properties in situ and by laboratory tests, before and after the improvement and after frost/thaw cycles.

2 THEORETIC PRINCIPLES

Lime-based hydraulic binders are generally used for stabilising soils with plasticity index higher than 10%, while for lower values a treatment with cement-based binders is recommended (CRR, 2004).

Soil stabilisation with lime-based binders is obtained due to short term reactions (lime hydration, cation exchange, flocculation) and to long term reactions of puzzolanic type. The first category reactions are inducing plasticity decrease and texture change, while the second category ones are responsible for the strength and durability increase (LCPC, 2000).

After treatment of clayey soils with lime-based hydraulic binders the following improvements are obtained (LCPC, 2000):

- Modification of soil structure (flocculation or granulation) due to bonds created by $Ca(OH)_2$ or $CaOH^+$ between the clay platelets, producing plasticity limit (w_P) increase, plasticity index (I_P) decrease, modification of the compaction curve (Proctor) and increase of mechanical and durability characteristics.

- Soil desiccation: decrease of soil water content due to lime reaction and to mixing procedure.

The current state of the art demonstrates that lime migration may instigate diffuse cementation throughout larger clods of clay soil. Of a most importance is the fact that the optimal combination of binders and different soil type is not known, acknowledging the absence of a unique approach and the importance of based upon suitability to achieve the required engineering performance (Lutenegger, 2012).

3 EXPERIMENTAL STUDIES

3.1 Description of experimental plot, materials and studies

The chosen site was one on which a road was to be built on a ground composed of a fat clay, classified as bad for earthworks. A stabilisation with lime-based binder has been considered, for which the optimum recipe has been studied first in laboratory, where 3 admixtures have been considered: 3%, 3.5% and 4%.

The binder that has been used is a high lime-content hydraulic road binder, with a total amount of CaO+MgO higher than 60%. It contains cement in order to increase the bearing capacity at short term.

After determining the optimum dosage of binder, an experimental plot of 200 m long has been built on site, for which were performed in situ and laboratory tests.

The experimental plot consisted in the construction of the base layer by using the natural clay in place mixed on site with the special lime-based hydraulic binder. After topsoil removal on 30 – 40 cm, the existing soil in place was stabilised by mixing on 50 cm depth with the optimum percentage of binder.

The binder has been spread using a mechanical equipment with volumetric dosing, then mixed with the soil by milling. After the first passage of the milling equipment the grind degree was of 70 % (passing on 4mm – diameter sieve). After the second passage the grind degree was of 85%, considered to be satisfying. After levelling, the layer has been compacted using a 20 to sheepfoot roller for 5 passages, than with a 20 to smooth roller for 4 passages. The required compaction degree was 98%.

3.2 Initial laboratory studies

3.2.1 Physical properties

The soil on site was a fat, black clay, with 51% clay fraction, 42% silt and 7 % sand, with 2% organic matter, very high free swell (120 %) and very high plasticity (I_P = 40 %). The natural water content of the soil was of 22 – 25%, not requiring water to be added.

The objective was to follow the texture and properties modification after treatment, especially the percentage of colloidal clay (<2μ) and the swelling potential, after different times of curing: 3, 7, 14 and 28 days.

Figure 1 presents the grain size distribution curves for all samples, showing that the clay fraction decreased from 51% to 20%, 17% and 14% for lime-based binder percetange of 3%, 3.5% and 4%, respectively. Also, it can be seen that the clay fraction decreases during the time, for example for 3% addition from 51% to 47 % after 3 days, 39% after 7 days, 29% after 14 days and 20% after 28 days of curing, proving the modification of the soils structure due to lime reactions.

Plasticity properties have also been modified as follows: the plasticity index (Figure 2) has decreased from 44.8% to 23.2%, 19.6% and 17.4% for 3%, 3.5%, 4% binder, respectively; the plasticity limit (w_P) has increased from 20.5% to 31.4%, 32.7% and 33.4%, respectively; the liquid limit (w_L) has decreased from 65.3% to 54.6%, 52.3 and 50.8 %, respectively. Figure 3 shows the evolution of the free swell, from 120% for the untreated soil to 65%, 60% and 55% for 3%, 3.5% and 4% addition, respectively.

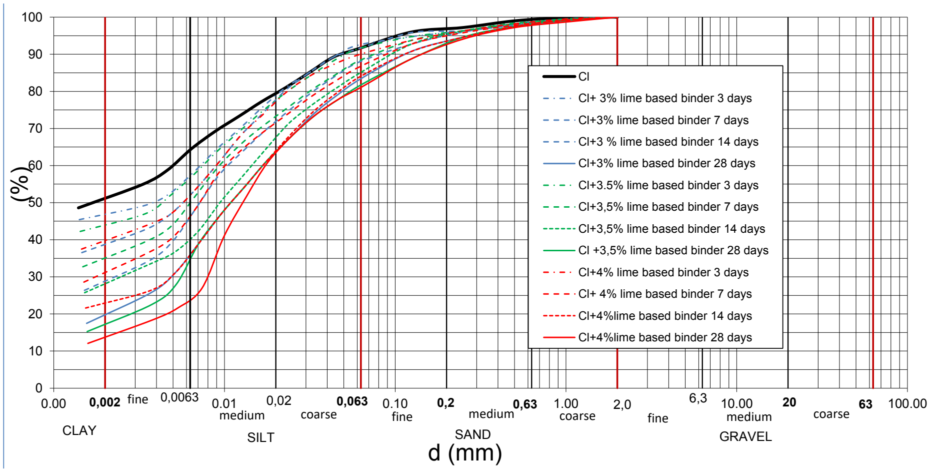

Figure 1. Grain size distribution for untreated and treated samples, for 3 admixtures of lime-base binder and 4 curing times

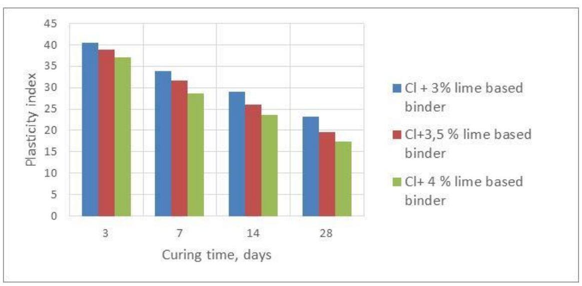

Figure 2. Evolution of plasticity index vs lime-base binder addition and curing time

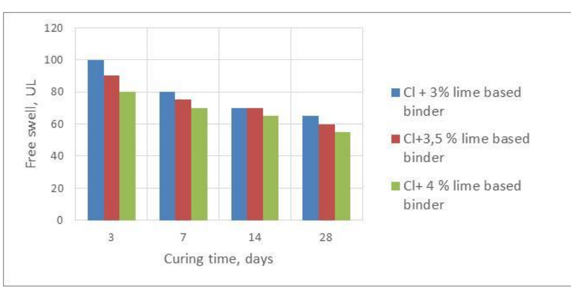

Figure 3. Free swell vs lime-base binder addition and curing time

Also in this case one can note the evolution of the free swell decrease with the curing time.

Figure 4 is presenting the Proctor curves for each admixture and for the untreated soil. The compaction tests have been performed using Proctor modified energy (2.7 J/cm^3). One can note that as the binder addition increases, the optimum water content also increases, while the maximum dry density decreases, therefore the curves for treated soils are below and on the "wet" side of the untreated soil curve. The increase in the optimum water content is obvious due to lime hydration.

The curves are also flattened showing that the relative compaction state (ρ_d/ρ_{dmax}) of the treated soils is improved. Similar findings are reported in the literature (e.g. Abbasi et al, 2012).

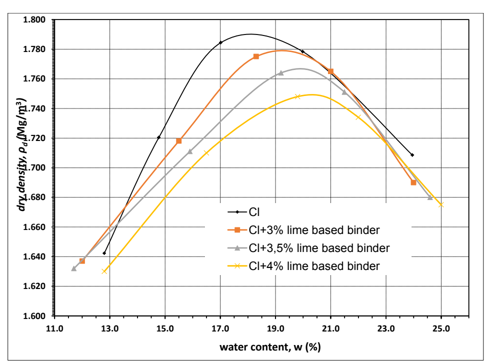

Figure 4. Compaction curves for treated and un-treated soil

3.2.2 Mechanical properties

The mechanical behaviour has been assessed through unconfined compression tests on compacted samples, whose results are shown Figure 5. As expected, the compression strength increased from 0.65 N/mm^2 for the initial soil to 1.46, 1.56 and 1.68 N/mm^2, for 3%, 3.5% and 4% addition, respectively.

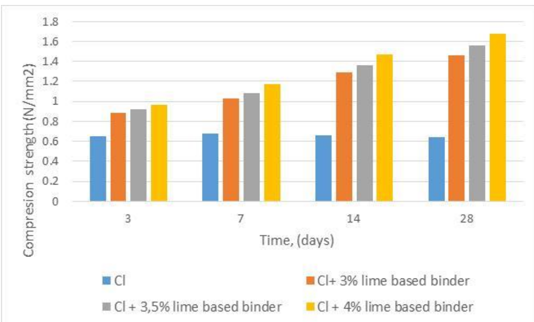

Figure 5. Compression strength vs lime-base binder addition and curing time

3.2.3 Durability properties

The durability has been assessed through tests for stability to water imersion and to freeze/thaw cycles.

The stability to water has been assessed by determining the change of the compression strength (according to EN 14227-15:2016), volumetric swelling (according to EN 13286-49:2004) and water absorption (according to STAS 10473-2:1986) of samples soaked in water for 7 days determined according to eq. (1) – (3).

$$I_r = \frac{R_{c7+7im}}{R_{c14}} \quad (1)$$

Where I_r is the change of compression strength after immersion, expressed as ratio, R_{c14} is the compression strength after 14 days and R_{c7+7im} is the compression strength after 7 days curing plus 7 days of imerstion in water.

$$G_v = \frac{V_{7+7im} - V_7}{V_7} x100 \quad (2)$$

Where G_v is the volumetric swelling of samples, V_{7+7im} is the volume of samples after 7 days of curing and 7 days immersion in water and V_7 is the volume of the sample after 7 days of curing.

$$A_i = \frac{m_{7+7im} - m_7}{m_7} x100 \quad (3)$$

Where A_i is the water absorption, m_7 is the mass of samples after 7 days of curing and m_{7+7im} is the mass of the samples after 7 days of curing and 7 days of imersion in water.

The obtained results are shown Figures 6 – 8.

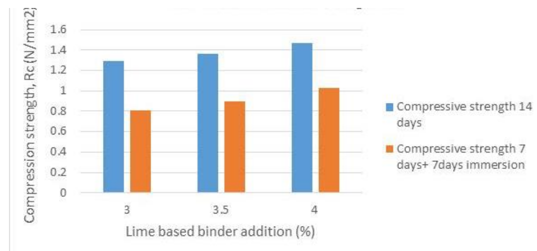

Figure 6. Compression strength after water immersion vs lime-base binder addition and curing time

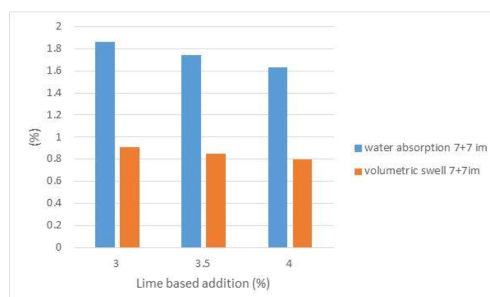

Figure 7. Volumetric swelling and water absorption after immersion in water vs lime-base binder addition and curing time

The change of the compression strength after immersion in water (I_r) was of 0.63, 0.66 and 0.70 for binder addition of 3%, 3.5% and 4%, respectively, category $I_{0.6}$ according to EN 14227-15:2016.

The volumetric swelling, G_v is comprised between 0.80% and 0.91 %, the condition imposed by EN 13286-49:2004 being to be less than 5%.

Water absorption was comprised between 1.63 % and 1.66%.

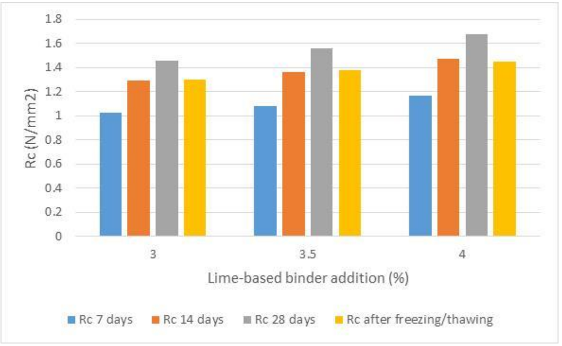

Figure 8. Compression strength after 12 freeze/thaw cycles vs lime-base binder addition and curing time

The stability to freeze/thaw cycles has been performed using a specific procedure as per ASTM D560, but adapted to the specific conditions on site. Therefore, the curing time was of 7 days and the temperatures -8°C and +20ºC. Samples were not soaked in water, but placed on water saturated felt pads according to ASTM D560, simulating a situation that can happen during autumn – spring season when unexpected negative temperature can appear during the night. 12 freeze/thaw cycles have been applied and the results are expressed in terms of compression strength (Figure 8).

To be noted that, when submitted to freeze (curing time: 7 days) the compression strength of the samples was lower then the one recorded after 12 freeze/thaw cycles.

Final values have been approx. 30% higher (as the total curing time was now higher, of 31 days, counting that each cycle last 2 days), but 10 – 15 % lower then values at 28 days of curing time. This means that the increase of strength is due to the binder that, even in presence of freeze/thaw cycles, continues to establish a long term puzzolanic reaction.

According to EN 14227-15:2016, for cylinders of slenderness ratio 1, the R_c category for freeze/thaw is $C_{0.8/1}$, the R_c values being comprised between 1.3 and 1.45 MPa.

After the 12 freeze/thaw cycles the loss of mass has also been determined according to the following formula, according to STAS 10473-2:1986):

$$\Delta m_{12ft} = \frac{m_7 - m_{12ft}}{m_7} x100 \quad (4)$$

Where Δm_{12ft} is the loss of mass after 12 freeze/thaw cycles, m_7 is the initial mass for 7 days curing time and m_{12ft} the mass after 12 freeze/thaw cycles.

The values of the mass loss were: 6.7%, 6% and 5.5% for 3%, 3.5% and 4% binder addition, respectively.

3.2.4 Conclusion of initial laboratory tests

Analysing all results presented above, in terms of physical, mechanical and durability properties it has been concluded that the optimum admixture is with 4% of lime-based special hydraulic binder.

Compared with the initial values of untreated soil, by adding 4% of lime-based special hydraulic binder the clay content is decreasing by 72%, the plasticity index by 61%, the free swell by 54%. The workability and the aptitude for compaction is improved: the optimum water content increased from 18% to 20%, thus the execution being easier. The compression strength increased by 62%.

The initial category of the clayey soil on site, according to Romanian technical norm (AND 530) was bad for earthworks (4d), while after improvement it is considered to be mediocre (4b), which allows to be used for this category of road.

The durability to water and freeze/thaw cycles proved also to be good for 4% addition of binder. This has been studied due to the fact that the final road will have only 15 cm of crushed stone above the stabilised soil, therefore being exposed to freeze/thaw.

Therefore, this admixture with 4% binder was further used for the experimental plot.

Some comments should be made regarding the procedures that have been used:

- whenever possible the procedures where applied according to European standards;
- for water absorbtion there was no European standard for stabilised soils indicating such procedure, therefore a Romanian standard has been applied;
- for freeze/thaw resistance the European standard EN 14227-15:2016 is providing that "if employed as curing regime, freeze thaw cycling of specimens shall be carried out in accordance with regulations at the place of use." And also: "There is currently insufficient experience to define a method of freeze thaw conditioning that can be used in all parts of Europe." This, combined with the lack of national specific regulation led us to modify the testing procedure as described here above.

3.3 In situ tests

On the experimental plot built using 4% addition of special lime-based hydraulic binder, were performed CBR and Lukas plate tests, after different periods of time after the compaction. Compaction of the experimental plot was performed according to the compaction parameters determined previously in laboratory for this admixture.

The monitoring has been performed with traffic on the experimental plot as after 7 days it has been put in service. Above the base layer stabilised by mixing with 4% binder was laid a 15 cm crushed stone layer (0 – 63 mm).

3.3.1 Lukas plate tests

Tests have been performed on 2 locations of the experimental plot at 1, 7, 14 and 28 days after compaction, according to DIN 18134:2012.

The results, expressed in terms of E_{v1} and E_{v2} moduli are presented Figure 9. The reference values, determined for untreated soil are: E_{v1} = 18.77 MPa, E_{v2} = 26.92 MPa.

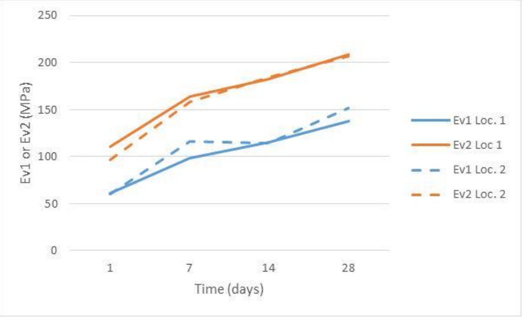

Figure 9. Results of Lukas plate tests on site

The value of E_{v1} and E_{v2} increased 3 times after only 1 day and 7 – 8 times after 28 days compared to the natural, untreated, uncompacted soil. According to the technical specifications of the project, E_{v2} should be higher than 80 Mpa, value which was reach after only 1 day.

3.3.2 CBR tests

Tests have been performed on 2 locations of the experimental plot at 1, 7, 14 and 28 days after compaction, according to EN 13286- 47:2012.

The reference value for untreated, uncompacted soil is $CBR_{2.5}$ = 4,87 %.

Figure 10 shows all values determined on the experimental plot.

CBR values are much higher then ones for untreated (natural, uncompacted) soil, meaning 8 times higher after only 1 day and up to 20 times higher after 28 days.

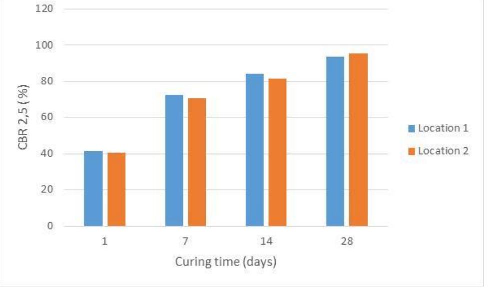

Figure 10. Results of CBR tests on site

3.3.3 Conclusions about the in situ tests

The in situ tests meant at determining the bearing capacity of the improved clayey soil after being mixed with 4% of lime-based special hydraulic binder, for various time of curing and in service.

The monitoring is still ongoing at the time of the redaction of the paper.

4 CONCLUSIONS

The presented study aimed at analysing the properties of a clayey soil, classified as bad for earhworks, before and after treatment with lime-based special hydraulic binder, through laboratory and in situ tests. The obtained results emphasized the modifications that the binder determined on the clayey soil, due to changes in the intimate structure of the soil. Also, the factors offering durability performances have been identified.

The study allowed to assess different working procedures for some of the laboratory tests, according to European and Romanian standards. Monitoring on site is still ongoing and will allow a better assessment of the durability properties in real conditions, a very important aspect to consider.

The final conclusion is that clay treatment with lime-based hydraulic binder is beneficial for earthworks use of this type of soils.

5 ACKNOWLEDGEMENTS

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STAS 10473-2:1986 *Lucrări de drumuri. Straturi rutiere din agregate naturale sau pământuri stabilizate cu lianți hidraulici sau puzzolanice. Metode de determinare și încercare (Road works. Road layers of natural aggreggates or soil stabilsed with hydraulic or puzzolanic binders. Methods of determination and testing)*