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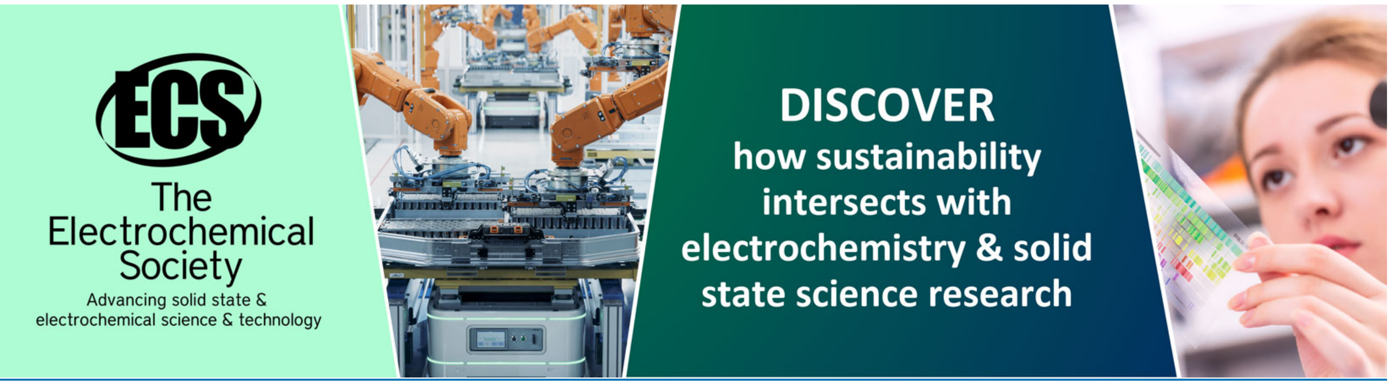
To cite this article: G Andries *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **664** 012091



IOP Conf. Series: Earth and Environmental Science **664** (2021) 012091 doi:10.1088/1755-1315/664/1/012091

Study of soil characteristics after treatment with lime-based hydraulic binder using the in situ "layer by layer" stabilization method

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Abstract. Paper presents the results obtained in situ and in laboratory for a test section where the soil has been improved by mixing with a lime-based hydraulic binder. The treatment has been applied in order to obtain a more uniform soil bearing capacity, thus reducing the differential settlement that could appear between adjacent foundations or under the same foundation. The test section has been performed by mixing the local cohesive soil (silty clay) with 4% special lime-based hydraulic binder, then compacted in 3 layers, 20 cm thick each after compaction, resulting a final compacted layer of 60 cm. For this treatment a laboratory study has been conducted in order to determine the optimum binder admixture. The physical and mechanical characteristics of the improved soil have been studied in laboratory and in situ for 3 curing times: 3, 7 and 28 days. In laboratory have been carried out tests for identification and classification, for determining the density and water content, followed by mechanical tests as oedometers and shear box tests, while in situ Lukas plate tests have been performed. Paper presents results of all tests, including analyses and interpretation.

1. Introduction
Fine-grained soils with low bearing capacity are a challenge on many sites. Clayey soils, especially when humid, create poor working conditions, as well as difficult access of construction equipment on the site. Also, such soil makes difficult to meet the bearing capacity and compaction degree design requirements. In absence of treatment or stabilization by mixing with hydraulic binders, soils with low mechanical strength and low bearing capacity lead to poor quality earthworks.

Soil stabilization with hydraulic binders can offer many benefits in construction projects, such as improving the soil bearing capacity, allowing the flow of construction operations to be carried out in a timely manner. Also, costs are reduced compared to other improvement solutions, such as extra excavation and replacement operations, where aggregates and geosynthetic materials (geogrid or geotextile) are used.

Paper presents a case study for which an experimental section has been built in order to assess the soil performances after stabilization by mixing with lime-based special binder.

2. Case study and aim of the research
The case study presented in this paper shows the results obtained on a trial section of the ground improvement works for "Ghencea Stadium". The request was to improve the foundation ground by

carrying out a 60 cm thick layer of local soil treated with 4% special lime-based binder. The goal was to obtain a more uniform bearing capacity, in order to reduce the differential settlements that could occur between adjacent foundations or under the footprint of the same foundation.

The trial section was built in a controlled manner, by mixing the local cohesive soil (silty clay) with 4% special lime-based binder and compacting thereof in 3 layers of 20 cm thickness each (after compaction), so it resulted a 60 cm thick cushion of improved soil.

The trial section aimed to determine the compaction characteristics (thickness of the compaction layers and number of passes of the compaction equipment) in order to achieve the compaction degree and the bearing capacity required by the technical specifications (compaction degree of minimum 98%; deformation moduli E_{v1} > 35 MPa; E_{v2} > 60 MPa at the age of 3 days; E_{v1} > 45 MPa; E_{v2} > 75 MPa at the age of 7 days; $E_{v2}/E_{v1} < 2.5$).

3. Materials and testing methods

For the improvement of the foundation ground, local soil (resulted from the excavation works previously carried out on site) was used. The local soil is a silty clay of high plasticity (PI = 26.8%, LL = 42,6%), with a natural water content w = 23…27%, firm (CI = 0.68…0.71), with medium to high free swelling (FSI = 70%) and low content of organic matter (content of soluble humus 0…1 colourless).

The local soil was mixed with 4% special lime-based binder, compared to the dry mass of the soil. The binder is a hydraulic road binder, with a total amount of CaO+MgO higher than 60%, recommended for silty and sandy soils, in order to optimize and neutralize the clay content and to speed up working progress.

In order to establish the optimum binder addition, 3 percentages of special lime-based binder were analyzed: 3%, 4% and 5%. For each admixture the compaction characteristics (maximum dry density, ρ_{dmax} and optimum water content for compaction, w_{opt}, by modified Proctor test according to STAS 1913/13-83 [1]) and the mechanical ones (unconfined compressive strength) were determined on cylinder specimens of treated soil for curing times of: 3, 7, 14 and 28 days. The results are presented Tables 1 - 2 and Figure 1.

Table 1. Synthetic values for the 3 admixtures of silty clay and 3%, 4% and 5% lime-based binder, according to STAS 10473-2/86.

Binder percentage (%)	Binder quantity (kg/m^3)	Maximum density in dry state (g/cm^3) (Modified Proctor)	Optimum water content (%)
3.0	52	1.800	17.5
4.0	69	1.790	18.3
5.0	85	1.780	19.0

Table 2. Unconfined Compressive Strength of the soil (silty clay) after treatment with 3%, 4% and 5% lime-based binder, for various curing times, according to STAS 10473-2/86.

Binder percentage (%)	Unconfined Compressive Strength (N/mm^2) For curing times:			
	3 days	7 days	14 days	28 days
3.0	0.69	0.83	1.06	1.27
4.0	0.81	0.87	1.13	1.31
5.0	0.92	1.05	1.31	1.45

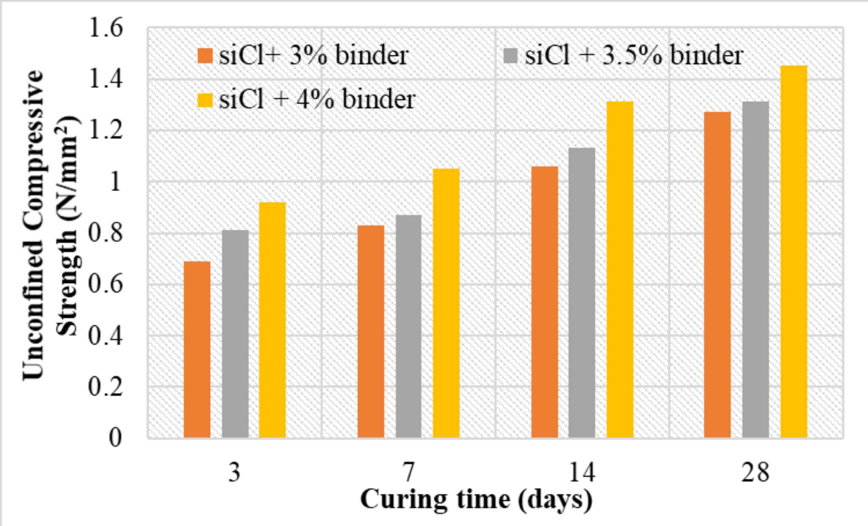

Figure 1. Variation of the Unconfined Compressive Strength for different binder percentages (3%, 4%, 5%) on samples prepared at Modified Proctor compaction energy (M.P.)

Note: The Romanian standard STAS 10473/2 (Road works. Road layers made of soils stabilised with cement. Testing methods) [2] imposes that for admixtures study a modified Proctor compaction should be used. As well, by using modified Proctor compaction energy on site it is possible to obtain high mechanical performances after short periods of time compared to normal Proctor energy.

The obtained results have been compared to the allowable values given by the Romanian standards for quality conditions (STAS 10473/1-87 [3] – Layers of natural aggregates or soils stabilized with cement and STAS 12253-84 – Subgrade layers [4]) and it was concluded that the optimum percentage of binder for fulfilling the strength requirements is 4%. For this admixture the recorded unconfined compressive strength measured on cylinders of treated soil met the minimum requirement of 1 MPa, while the optimum compaction water content was around the natural one on site for the filling material (18 - 19%). The 3% binder percentage was considered too low for coping with adverse weather conditions (rainfall).

4. Laboratory and field results

4.1. Laboratory tests

Once the optimum binder percentage was determined, treated and untreated soil specimens were created in laboratory by compaction in order to determine the mechanical characteristics: compressibility in oedometer and consolidated-undrained (CU) shear strength. Sample have been prepared for a compaction degree of 98% compared to modified Proctor parameters. The tests were performed at various curing times: 3, 7 and 28 days. Similarly, same tests were performed on undisturbed specimens sampled taken from the trial section. The compaction on site had a compaction degree of at least 98%, compared to the modified Proctor test. The results obtained can be found in the Tables 3 – 4 and Figures 2 - 4 below:

Table 3. Compressibility characteristics for treated soil + 4% binder, for various curing times.

Binder percentage (%)	Curing time (days)	Oedometer modulus $E_{oed\ 200\text{-}300}$ (kPa) Specimen prepared in laboratory *Specimen sampled "in situ"*
0	-	10500
4%	3	16667
		16000
	7	20000
		19608
	28	*26152*
		25000

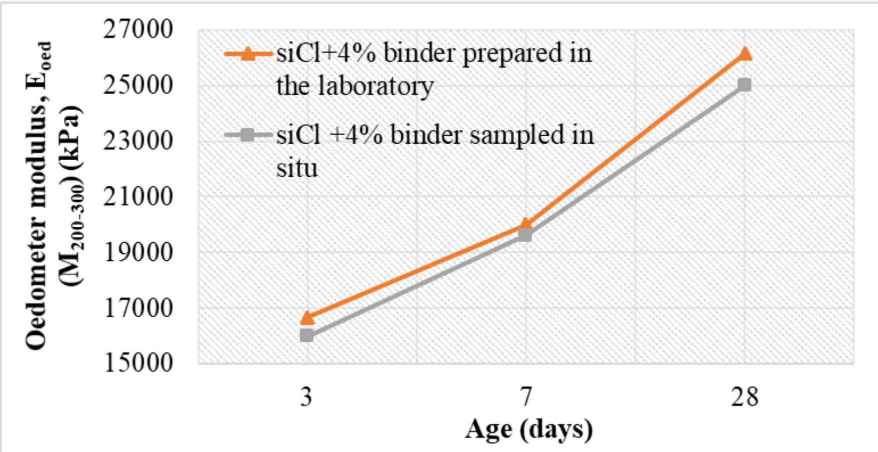

Figure 2. Oedometer modulus $E_{oed200\text{-}300}$ vs. curing times

Table 4. Shear strength parameters (CU) on samples of silty clay in natural state and after treatment with 4% binder, for various curing times.

Binder percentage (%)	Curing time (days)	Shear strength parameters CU Specimen prepared in laboratory *Specimen sampled "in situ"*	
		Internal friction angle, Φ (°)	Cohesion (kPa)
0	-	14	55
4%	3	26	68
		25	*65*
	7	31	83
		30	*80*
	28	33	85
		31	*81*

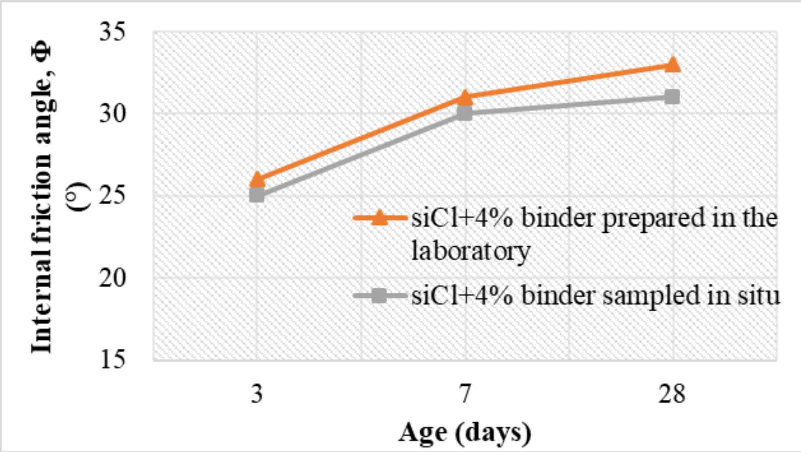

Figure 3. Internal friction angle versus curing time

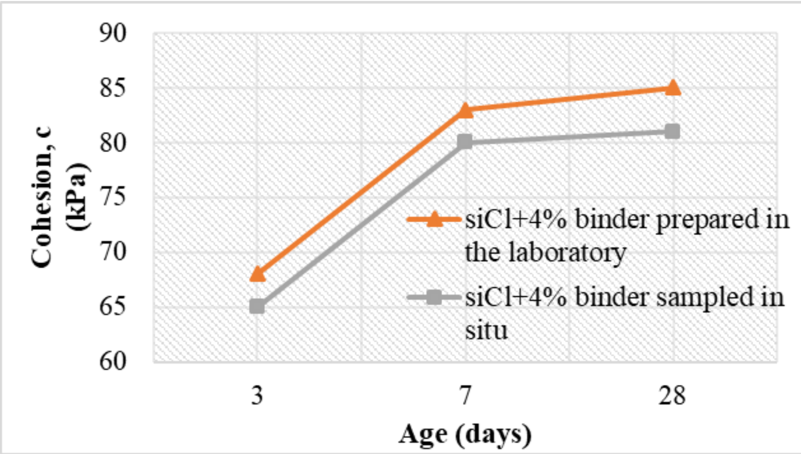

Figure 4. Cohesion versus curing time

4.2. Experimental section – "in situ" tests

The experimental section was built using a "layer by layer" in situ stabilization process, being comprised of 3 layers (20 cm thickness each) of cohesive material improved by 4% special lime-based binder.

The 3 layers were built during the same day, consecutively and by overlapping, creating a system with 3 stairs (with withdrawals). Thus, 3 distinct sections have resulted, having the following thicknesses: 20 cm – Layer 1; 40 cm – Layer 1 + Layer 2; 60 cm – Layer 1 + Layer 2 + Layer 3. This construction procedure allowed to perform the bearing capacity measurements on the top of each layer at the same time.

The in situ bearing capacity was determined using the Lukas plate by determining E_{v1} – for the first loading-unloading cycle and E_{v2} – for the second loading-unloading cycle moduli carried out at 3 days and 7 days of curing for each layer. The obtained results can be found in Table 5 - 6 and Figure 5.

The number of passes of the compaction equipment, necessary to achieve a degree of compaction of more than 98% at the top of each layer, was 3 passes with a cam roller and 2 passes with a smooth roller.

Table 5. Results of Lukas plate tests for 3 days curing time.

Layer 1		Layer 2		Layer 3	
E_{v1} (MPa)	E_{v2} (MPa)	E_{v1} (MPa)	E_{v2} (MPa)	E_{v1} (MPa)	E_{v2} (MPa)
46.6	100.6	52.2	129.1	69.4	139.5
E_{v2}/E_{v1} = 2.16		E_{v2}/E_{v1} = 2.47		E_{v2}/E_{v1} = 2.01	

Table 6. Results of Lukas plate tests for 3 days curing time.

Layer 1		Layer 2		Layer 3	
E_{v1} (MPa)	E_{v2} (MPa)	E_{v1} (MPa)	E_{v2} (MPa)	E_{v1} (MPa)	E_{v2} (MPa)
79.1	133.2	76.4	157.8	74.8	182.6
E_{v2}/E_{v1} = 1.69		E_{v2}/E_{v1} = 2.07		E_{v2}/E_{v1} = 2.44	

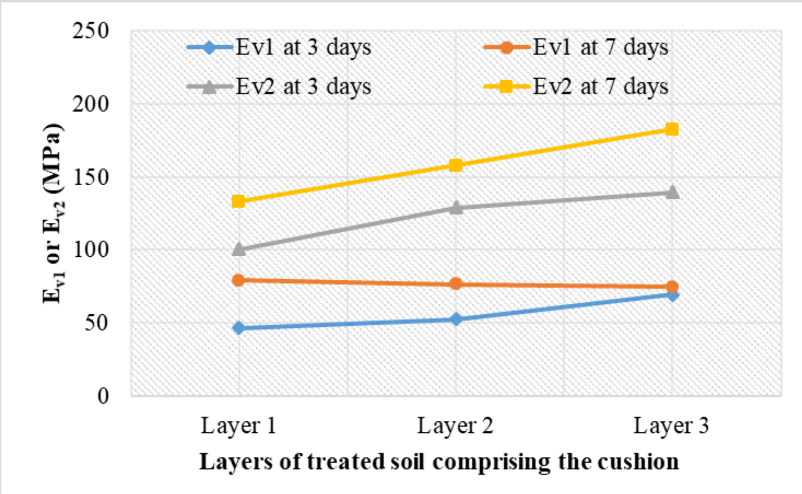

Figure 5. Deformation moduli E_{v1} and E_{v2} at the top of the layers 1, 2, 3, for 3-days and 7-days curing time

Lukas plate tests were performed also for the compacted, unimproved soil, for comparison purposes, the results being the following: E_{v1} = 27.8 MPa; E_{v2} = 56.4 MPa; E_{v2}/E_{v1} = 2.03.

5. Analysis and interpretation of the results

5.1. Interpretation of the laboratory tests

Based on the results obtained in laboratory, we can conclude that after treating the soil by mixing with 4% special lime-based binder, its deformability decreased and, implicitly, its bearing capacity increased. Obviously, an increased curing time leads to an increase of the bearing capacity. The value of the oedometer modulus for the samples treated with 4% binder at the age of 3 days increases by about 50% compared to the unimproved soil and doubled its values after 7 days.

It was also aimed to determine at what extent the stabilization with 4% special lime-based binder also improves the shear strength. It was observed that the internal friction angle increases from its initial value of 14° to 31° at the age of 7 days. Similarly, the cohesion increased from its initial value of 55 kPa, to 85 kPa at 28 days. As shown in Figure 3 and Figure 4, the increase of both shear strength parameters, internal friction angle and cohesion, is more important in the first 7 days (approximately 20%), whereas between the age of 7 days and the age of 28 days, the rate of increase is lower (an approximate average of 5%). An explanation may be the short-term reactions as lime hydration for quick lime, cation exchange and flocculation. This modification of the soil structure is due to bonds created by $Ca(OH)_2$ or $CaOH^+$ between the clay platelets, which increases the soil aptitude to compaction and the mechanical characteristics (bearing capacity, shear strength) [5].

The results obtained in the laboratory were confirmed by the values obtained on undisturbed specimens sampled from the experimental section, therefore one can conclude that its execution was performed in a controlled manner, with adequate means to achieve the required physical and mechanical performances. The differences between the two types of samples are ranged in the interval 3…6% for the shear strength parameters and 1…5% for the oedometer modulus.

5.2. Interpretation of the field tests

The main aim of the experimental section was to evaluate the benefits of the "layer-by-layer" execution method and to monitor the bearing capacity of each layer for various curing times, on the zone of influence. According to the literature [6], it is considered that the active zone for which records are obtained for static plate tests reaches (1.5-2) times the plate diameter. In this case, the tests were performed using a 30 cm diameter plate, therefore at the top of the cushion (layer 3), the pressure is considered to be completely taken over by the improved soil cushion, considering as negligible the contribution of the natural soil.

From the interpretation of the measurements carried out on site (graphically represented in the Figure 5) it is observed, as expected, an increase of the bearing capacity over time, for the moduli E_{v1} and E_{v2}. In the case of E_{v1} modulus, the increase is progressive, according to layers sequence, for the tests carried out at 3 days, after which it starts to stabilize around 80 MPa, according to the results obtained at 7 days. For E_{v2} modulus, there is a progressive increase of about 40% for layer 3 compared to layer 1, for each age of testing, which leads to the idea that the resistance will increase in time, fact confirmed by the unconfined compressive strength results obtained in the laboratory (Tables 5 and 6). At 3 days curing, E_{v2} modulus for layer 2 recorded an increase of approximately 30% compared to the value obtained for layer 1 and approximately 8% lower than the value obtained on top of layer 3. The comparative values obtained for layers 2 and 3 show a uniform compaction and that the natural ground beneath the cushion is not interfering significantly on the bearing capacity. This leads to the idea that, for improved layers less than 20 cm in thickness the natural ground has a significant weight (at least 30%) in the results of in situ static plate tests.

6. Conclusions

The paper shows the results obtained on a trial section performed in order to carry out the ground improvement works for "Ghencea Stadium" consisting in stabilisation by mixing with lime-based special binder. The experimental section was built using a "layer by layer" in situ stabilization process, being comprised of 3 layers (20 cm thickness each) of silty clay material improved by 4% special lime-based binder.

The results clearly showed that by mixing the soil with 4% special lime-based binder, its deformability is decreased and implicitly its bearing capacity is increased, as well as its shear strength parameters. The experimental section was carried out in a controlled manner, achieving the required performances in terms of physical and mechanical characteristics, as the values of the tested parameters were lower with less than 6% compared to the parameters obtained on samples created in the laboratory. The required mechanical characteristics can be obtained after short curing times (7 days), being improved with lower rates over longer time periods.

Obtained results are in line with other researchers' findings [5], [7], [8].

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