Mix-design, construction and controls of lime stabilized embankments

Projet, realisation et contrôles d'un remblai en sol stabilisé à la chaux

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ABSTRACT

A case history concerning mixture design, in-place mixing and compaction procedures, construction and controls of road embankments made of lime stabilized soil is described and discussed. The case history points out the importance of proper design and construction procedures, starting from laboratory testing, in situ test pad and construction quality control to assure the desired overall performance of lime-stabilised embankments. In this way it is also possible to remedy unavoidable defects and to optimise the construction practices in case of unexpected events, such as particular weather conditions, variation of soil type, or wrong procedures. The paper also shows that a test pad is absolutely necessary not only to set up proper construction procedures, but also to define the reference values of the parameters to control construction procedures.

RÉSUMÉ

Cet article présente le projet, la construction et les contrôles d'un remblai en sol stabilisé à la chaux. Cet exemple d'application démontre l'importance d'une attente contrôle de la qualité en phase d'exécution pour assicurer la performance désirée de ces ouvrages. De cette façon il est aussi possible de remédier défets et optimiser les phases de construction en présence de évents inattendus comme conditions atmosphériques adverses, variation du sol ou wrong procédures.

L'article met en lumière la nécessité d'un terrain d'essai pour mettre à point les procédures exécutives et pour définir les valeurs acceptable des paramètres utilisés pour le contrôle en course d'ouvre.

Keywords : soil stabilization, lime, test pad

1 INTRODUCTION

Structural embankments in roads construction generally require high shear strength and low deformability under static and dynamic loads (Chai and Miura, 2002). In these cases coarse grained materials are typically recommended but the availability of natural high-quality materials is nowadays more and more limited for environmental and economical reasons. Therefore the soil available from trenches along the route is often used after it is improved by adding lime (quick or hydrated), to obtain proper mechanical characteristics (Winterkorn and Pamukcu, 1991; Greaves, 1996).

Lime stabilization is not difficult to carry out, but construction procedures strongly affect the overall performance. The successful use of compacted fine soil-lime mixtures requires a careful testing on the soil to be used and, most of all, proper construction methods and effective controls must be set up in order to reach the desired performance. These aspects will be focused in the following with reference to a recent case history concerning road embankments built in a urban area in Ancona, Italy. About 1 km of road embankments (including a roundabout) had to be built, 15 m wide on average and maximum 5 m in height.

2 LABORATORY TESTS

Soil samples taken along the stretch of road on trenches (i.e. the soil to be used for embankments) were classified to verify soil uniformity. All the samples were found to have similar properties (Table 1) and resulted a fat clay, CH (on or slightly above the "A" line of the plasticity chart). The presence of organic matter resulted of 0.4% and the sulphates content was always less than 0.1%, thus allowing the use of lime as stabilizer. All the subsequent laboratory tests were carried out on a "representative" soil sample prepared by mixing all the collected samples.

Hydrated lime, $Ca(OH)_2$, was initially selected to stabilise the local soil instead of quick lime, CaO, as some of the embankments had to be built close to a hospital, to avoid any risk for people due to possible dispersion of lime by wind. Moreover, the natural water content of the soil to be stabilized (Table 1) was low enough to guarantee sufficient workability. Most of the laboratory investigations was done on soil-hydrated lime mixtures. However, a mixture of soil and quick lime was also investigated in view of possible high soil water contents due to rainy periods, for the embankments far from the hospital.

The minimum quantity of hydrated lime required for solidification of soil was found by the initial consumption of lime (ICL) test. The ICL value was found to be 2.7 % by dry mass of soil (Figure 1). On the basis of this value, soil-lime mixtures with 3% and 5% of hydrated lime and a mixture of soil-4% CaO were investigated by laboratory test on samples compacted according to the standard Proctor procedure.

As far as the hydraulic conductivity, k, is concerned, the lime addition was found to strongly increases the k value of the soil (Figure 2); according to the interaction mechanisms widely discussed in the literature (e.g. Boardman et al., 2001), this increase is due to an immediate modification reaction as a result of cation exchange (flocculation of clay particles), but also to a reduction in the water content and to the formation of calcium silicate hydrated, CSH, and calcium aluminate hydrated, CAH; both of them make the soil clods quite hard and not well bound after compaction, thus causing high hydraulic conductivity

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(Elsbury et al., 1990); indeed, macro-pores were evident among clods in the compacted soil-lime samples.

Table 2 and Figure 3 summarize results of direct shear tests and oedometer tests, respectively, performed on samples with 3% and 5% of hydrated lime at different curing times. The shear tests were performed on samples at the end of permeability tests (Figure 2) to assure saturation.

It is evident a very low compressibility of the mixtures and a high shear resistance even for the lower content of hydrated lime. In particular, Table 2 shows that the lime increases both cohesion and peak angle. An increase in the cohesion with the lime content is also evident, whereas it does not seem to appreciably influence the mixture compressibility (Figure 3).

Based on these results and considering that the soil-lime mixed in situ is necessarily less uniform than that prepared in the laboratory, the percentage of 4% of hydrated lime (or quick lime when necessary for weather conditions) was selected for the embankments.

Of course, the good results from the laboratory tests had to be confirmed by tests performed on the soil-mixture compacted in situ. Therefore a test pad was built.

Table 1. Index properties of the soil to be stabilized with lime (w_n = natural water content; w_L = liquid limit; PI = plasticity index).

w_n (%)	w_L (%)	PI (%)	Fine (%)	Clay (%)
21-28	50-58	24-28	95-97	42-51

Table 2. Direct shear test results (vertical stress = 50, 100 and 200 kPa) on samples compacted at different lime contents and permeated.

lime	w_{opt} (%)	γ_d (kN/m^3)	w before k test (%)	w after k test (%)	curing time (days)	c' (kPa)	ϕ_p' (°)
0	22	15.8	22	n.d.	33	10	22
3% $Ca(OH)_2$	23	15.4	23	29	27	37	41
5% $Ca(OH)_2$	22	15.6	22	29	27	56	42
4% CaO	n.d.	15.5	22	27	21	51	43

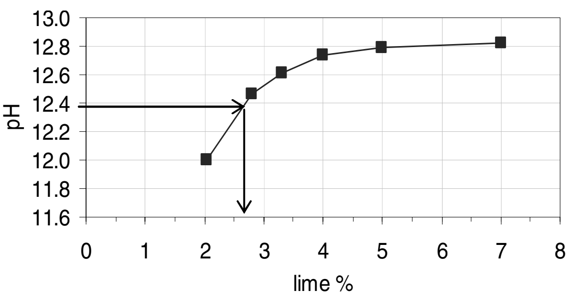

Figure 1. Results of the test to determine the initial consumption of lime, ICL.

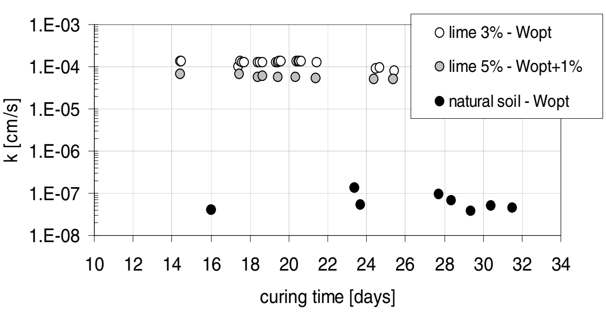

Figure 2. Hydraulic conductivity of soil-hydrated lime mixtures and of the natural soil, all compacted at the standard Proctor optimum water content, w_{opt} , and permeated with tap water.

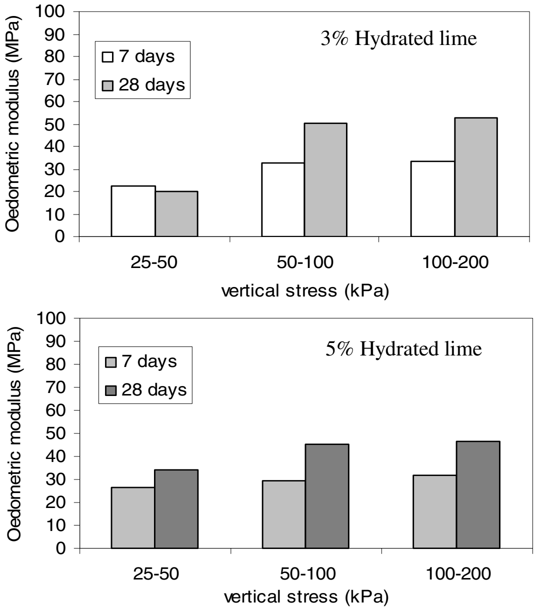

Figure 3. Results of oedometer tests on the soil-hydrated lime mixtures at different curing times (in the legend), all compacted at w_{opt} ± 2 %.

3 TEST PAD

Since the in situ mixing and compaction conditions significantly differ from the highly controlled laboratory conditions, the feasibility of the design concept was verified through a full scale trial pad, which allowed also to set up the construction procedures, in particular:
- thickness of the lifts,
- lime spreading and mixing with soil,
- addition of water if necessary,
- number of passes of the tilling equipment and compactor.

The trial pad was prepared using both hydrated and quick lime. The amount of lime corresponding to 4% by dry mass of soil was calculated on the basis of the soil moisture content and lift thickness, and spread on the soil lift. Several trials were done (different lift thicknesses, number of passes, etc.) until a visibly uniform soil crumbling and mixing between soil and lime were reached (Figure 4). Finally, two lifts were compacted with a foot roller compactor of a weight of 20.8 t, passing three times each area. Undisturbed samples of the in situ compacted soil-lime mixture were taken from the trial pad for laboratory testing and the in situ dry density was measured by the sand cone tests (ASTM D1556-90).

Referring to compaction energy, Figures 5 shows that the soil-lime mixture resulted well compacted, with a dry density always higher that that of the samples compacted in the laboratory with the standard Proctor procedure, which is considered as a mean compaction effort. For three samples taken from the test pad the quick lime content was measured (ASTM D3155-83) and it resulted 3.5%, 4.0% and 3.9%.

Figure 6 compares the shear strength envelopes of the samples from the test pad with those of the samples compacted in the laboratory. Both for hydrated and quick lime mixtures, a good agreement was found in terms of cohesion (47-65 kPa), whereas lower values of the shear strength angle (34°-38°) resulted in comparison with the laboratory compacted sample (Table 1). A lot of factors can explain this difference: in situ sampling and laboratory trimming, non homogeneity of the in situ samples due to the mixing procedures, variation in the water content and curing times, curing conditions, etc. However, the results of the samples taken from the test pad can be considered as good in the sense that they demonstrate the possibility to built a material with good shear strength. The stability analyses were done and the embankments slopes were designed considering, as characteristic shear strength parameters, the lower values of c' and ϕ' measured on the samples from the test pad.

The same comparison was made in terms of compressibility with reference to the results of oedometer tests performed on the samples compacted in the laboratory and those taken from the test pad. As shown in Figure 7, a quite good agreement is confirmed as far as compressibility is concerned. Considering the design load levels, the embankment resulted to be practically uncompressible.

All these results confirmed the good quality and effectiveness of the selected mixing and compaction procedure.

Finally, 4 plate load tests, PLT (ASTM D1194-94), were performed on the test pad after few days of curing. Very similar values of the modulus of elasticity (78-85 N/mm^2) were measured at the pressure interval of 150-250 kN/m^2; they were considered as the reference value, together with the water content and lime content, for the construction quality controls.

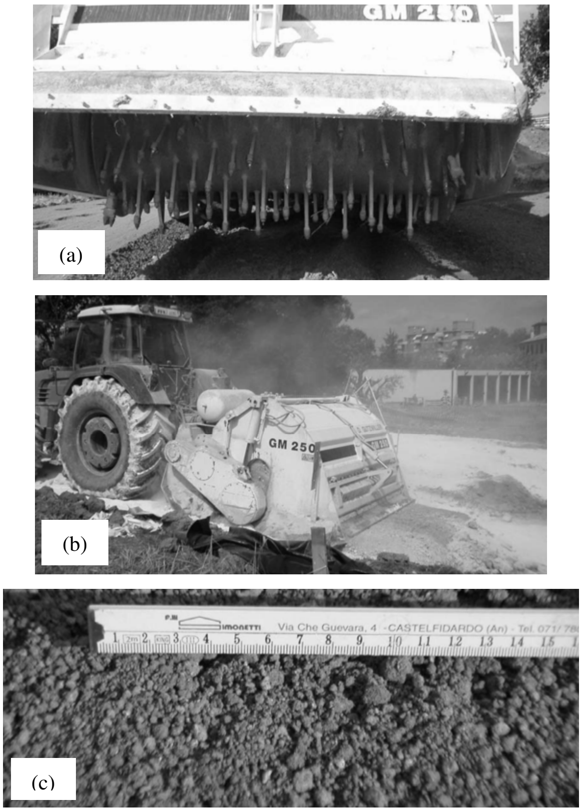

Figure 4. Soil-lime mixture test pad: tilling equipment (a), spreading of lime on the surface of a 35-40 cm thick lift and first mixing (b), soil-lime mixture after 3 passes of tiller.

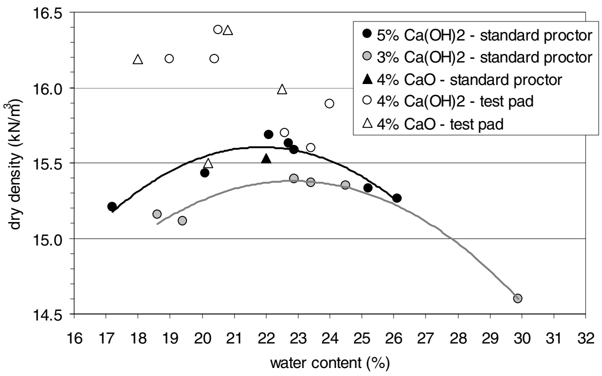

Figure 5. Comparison between the dry density of the soil-lime mixtures compacted in the laboratory and of that of the test pad.

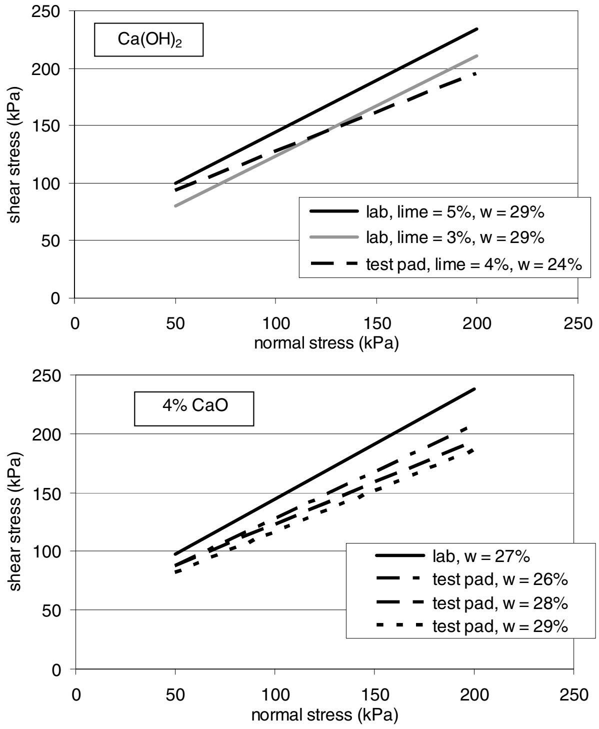

Figure 6. Comparison between the shear strength of the soil-lime mixtures compacted in the laboratory and in the test pad (curing times: 27 days for laboratory samples, 25-33 days for the test pad samples).

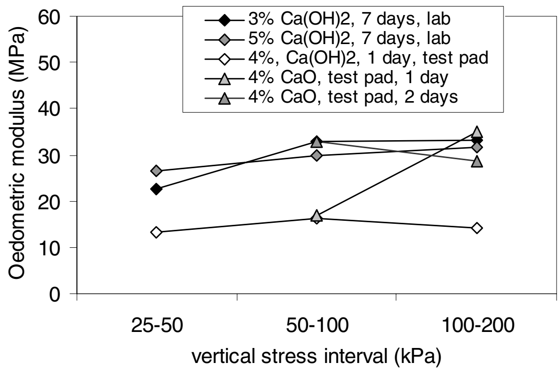

Figure 7. Oedometer modulus measured on samples compacted in the laboratory and taken from the test pad (curing times in the legend).

4 CONSTRUCTION AND CONTROLS

The embankments were built according to the procedures set up by the test pad and the materials and all the construction phases were controlled by means of constant supervision. In particular, the soil-lime mixture was always compacted no later than few hours from mixing.

On the basis of the results from the laboratory tests and test pad, a water content between 18% and 28% and a minimum soil-lime modulus of 80 MPa by PLT were defined as acceptable values for construction quality control. Controls on the dry density were also done.

As far as controls on the natural soil are concerned, the fine content (< 75 μm) and Atterberg limits were determined with a frequency of about one test each 2,000 m^3, whereas a higher frequency (500 m^3) was chosen for the measurements of water content. In situ dry density measurements were performed within few days after compaction; a plate loading test approximately each 10,000 m^2 of compacted mixture was done after 1-3 weeks from compaction.

Figure 8 shows the values of the dry density and water content measured during construction of the embankments, compared with those from the test pad: a good compaction in terms of specific energy was always obtained as the dry density resulted in the range of the values of the test pad. The lime content measured on some samples taken from the soil-quick lime mixtures resulted always greater than 3.5 % (Figure 9) thus demonstrating the effectiveness of lime spreading and mixing procedures.

The most reliable controls were found to be the PLTs. During construction of the portions of embankments far from the hospital in a humid period, the contractor decided to use quick lime but in percentage lower than 4%, considering that good results had been always obtained with 4% of hydrated lime. CaO in percentage of about 2.2 % was uses. The soil-lime mixture modulus, M_d, measured by PLT on those portions of embankments resulted significantly lower than the values required (Figure 10). Since no measurements could be done to check the lime content (samples must be tested within 8 hours after completing mixing), PLT results a very effective control tool, considering that both the water content and dry density resulted always in the range required. The lifts that did not give the required PLT results were, of course, rebuilt.

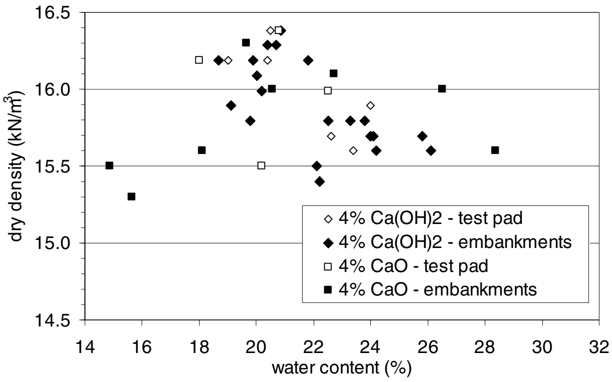

Figure 8. Dry density of the soil-lime mixtures during construction compared with the dry density of the samples from the test pad.

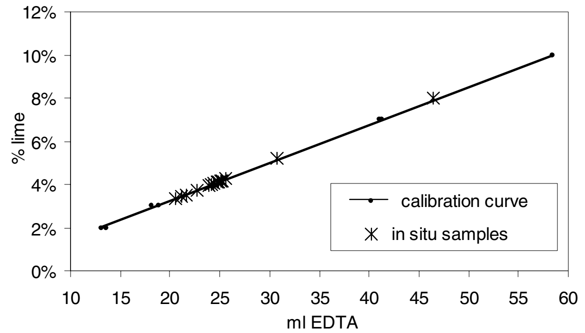

Figure 9. Measurement of the lime percentage (CaO) of in situ samples (ASTM D3155-83; EDTA = ethylenediaminetetraacetic acid).

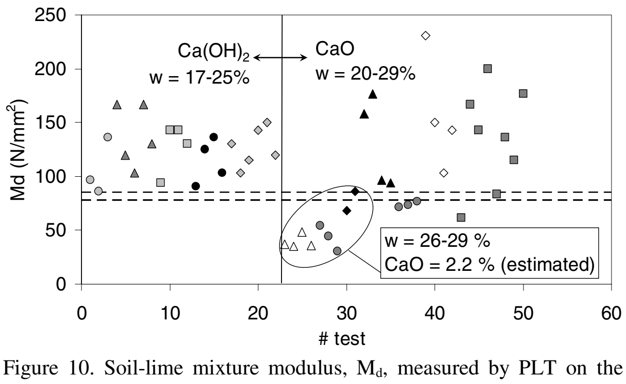

Figure 10. Soil-lime mixture modulus, M_d, measured by PLT on the embankments during construction (curing times: 1-3 weeks; pressure: 150-250 kN/m^2). The sequence of tests follows the construction sequence (symbols mark different embankments portions).

5 CONCLUDING REMARKS

The case history presented in the paper points out the importance of all the different steps necessary to assure the desired overall performance for lime-stabilised embankments: (a) laboratory testing on different soil-lime mixtures; (b) test pad and (c) controls during construction. In particular, the paper shows that a test pad is necessary not only to set up proper construction procedures, but also to define the reference values of the parameters both to design a soil-lime embankment and to control construction procedures. To this regard, in order to avoid disputes, the design should not only prescribe the required performance of the embankments, but also it should specify the tests and correlations to be used to evaluate it.

As far as controls during construction are concerned, a detailed and careful construction quality control is fundamental to remedy unavoidable defects and to optimise the construction practices in case of unexpected events, such as particular weather conditions, significant variation of soil type, wrong or not allowed decisions by contractor, that strongly influence the soil-lime compacted mixture performance. In particular, during construction phase, control tests that give results within times compatible with construction schedules have to be used, in order to immediately detect zones of inadequate properties. To this regard, plate load tests, which are cheap and fast, were found to be very effective in checking compliance with specifications. Frequent measurements of the lime content of mixtures sampled from projects under construction can be also useful, even if samples have to be brought to the laboratory and tested within 8 hours after mixing.

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