INNOVATION IN IN THE TREATMENT OF CLAYEY MATERIALS

L'INNOVATION DANS LE TRAITEMENT DE MATERIELS ARGILEUX

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ABSTRACT

The growing interest in cement and/or lime stabilizations is due to the possibility of re-use of poor-quality excavated materials in road constructions, with clear environmental benefits. In some situations, it appears more suitable the lime-cement treatment. In this case the lime stabilization is the first part of a two-section process using ordinary Portland cement, ground blast furnace cement, pulverised fuel ash, or some other hydraulic binding agent. However, in order to guarantee the required improvement of the mechanical properties during the time, it is important to accurately study the lime/cement addition by considering many factors such as soil gradation, type and amount of clay mineral content, organic matter, type and amount of lime/cement added, curing period and temperature. Rapid curing of the cement, actual clay minerals present in the raw material (necessity to perform X-Ray Diffractions -XRDs), activity of minerals (reactivity tests), insufficient density, Sulphate attack and ettringite formation, are recurring issues.
In the light of the abovementioned facts, the objectives and scopes of this paper were focused into the study of lime/cement treatments. Benefits and drawbacks associated to a case-history were described and discuss.

1. INTRODUCTION

Cement and/or lime treatment of clayey soil and sub-base is a widespread practice in road construction and rehabilitation due to the possibility to have poor-quality excavated materials capable of meeting the requirements of the specific engineering projects The reuse of these materials will produce environmental and economic benefits by reducing the impact of the works on the environment and reducing costs [1] – [6].

From a technical standpoint, it is well known that lime addition produces reactions, such as cationic exchange and flocculation, which lead to an immediate reduction in soil plasticity. On the contrary, the lime carbonation and, overall, the pozzolanic reactions are responsible for long-term increase in soil strength even many months after mixing and compaction. Improvements leading to longer life pavement are generally categorized as subgrade or base stabilization when, for example, a higher quantity of lime, typically 5-8% of the dry weight of the soil, is used. Lime stabilisation is particularly suited for stabilisation of subbases and subgrades in pavement construction. Pavements with lime-stabilization subgrades result in reduced deflections and improved critical pavement responses under applied wheel loading.

Cement treatments can be used for both modification and stabilization purposes. Cement can be applied to stabilize any type of soil, except those with organic content greater than

2% or having pH lower than 5.3 (granular soils and clayey materials with low plasticity index). Cement treatments can be used for both modification and stabilization purposes.

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Several advantages con be associated to the soil treatments (see Figures 1 and 2)

- Technical advantage. Treatments with lime and/or cement allow the production and laying of homogeneous, long-lasting and stable materials with mechanical characteristics comparable to those of graded aggregate with cementitious binders. In addition, these materials have great stiffness and excellent fatigue strength. They also show good performance in hot weather, with no deformation or rutting, and good performance on exposure to freeze-thaw cycles.

- Economic advantage. Field recycling is a significant savings factor since it reduces to a minimum, landfill, provision of aggregates and thus the cost of their transport. The absence of transport of aggregates and of cuts to the landfill contributes to preserve the road network in the vicinity of the building site. Also, these are very economical techniques, especially on account of the shorter duration of the works: compared to a conventional solution, the savings are around 30%.

- Ecological and environmental advantage. Cold treatment reduces pollution and discharge of fumes and gas into the atmosphere. Moreover this technique allows significant global energy savings by reducing the transport of materials, the quantity of materials for landfill (thus limiting indirect effects - nuisance to users and residents) (see Figure 2). Field recycling minimises exploitation of aggregates deposits (quarries and gravel pits), non-renewable natural resources.

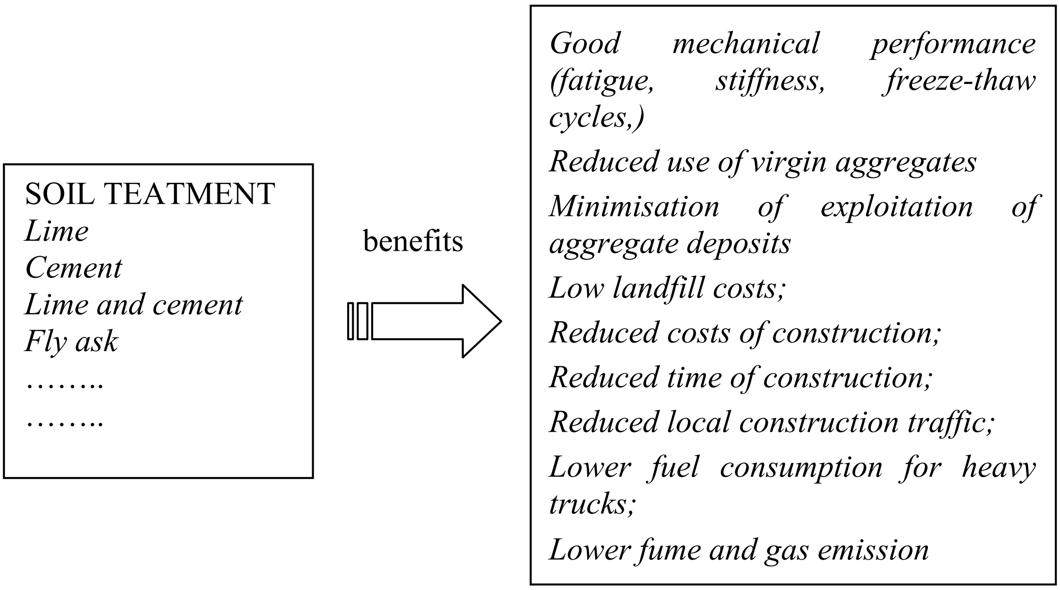


Figure 1 – Synopsis of benefits of soil treatments

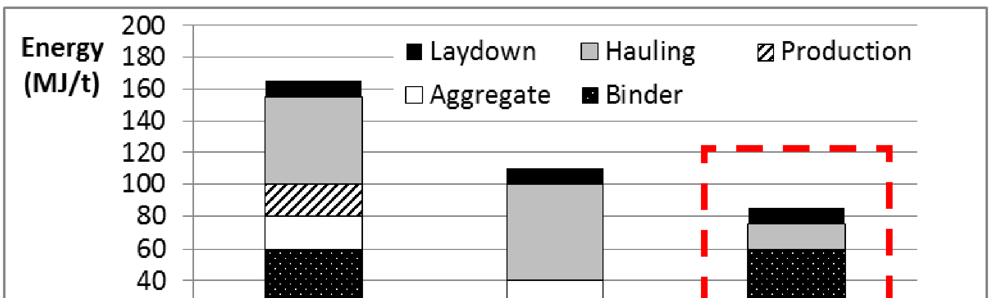


Figure 2 – Energy consumption (MJ/ton) for different solutions ([7], [8])

However, in order to achieve the quoted improvement of the mechanical properties during the time, it is important to accurately study the lime/cement addition by considering many factors such as soil gradation, type and amount of clay mineral content, organic matter, type and amount of lime/cement added, curing period, mellowing and temperature. Rapid curing of the cement, actual clay minerals present in the raw material (necessity to perform X-Ray Diffractions -XRDs), activity of minerals (reactivity tests), insufficient density, sulfate attack and ettringite formation, are recurring issues [9].

2. LIME-CEMENT TREATMENTS

Since 1960 in the U.S. and in some European countries several researches were carried out dealing with soils treated with lime and / or cement. The choice of lime and cement was usually carried out because both binders can have a very good action with soils. Soil stabilization using lime or cement has been used to improve the handling and mechanical characteristics of soils for civil engineering purposes [10].

Stabilization with lime is widely used to transform chemically unstable ground in stable structures. Soil stabilization using lime is known to be one of the methods to increase the shear strength of soils. There are two types of lime: CaO (quicklime or burnt lime or calce viva) and $Ca(OH)_2$ (slake or hydrated lime, calce spenta or calce idrata) [11].

This type of stabilization increases the resistance to cracking, fatigue and deformation. It also improves the properties and also reduces the damaging effects of moisture. The soil-lime reactions are chemically complex and depend on time and temperature.

The reaction (which is relatively slow) between calcium silicate and the soil (in an environment with high pH) is the key –factor in the stabilization of mixtures [12].

For some types of soil, a certain period of time is needed (mellowing) to allow for chemical reactions between lime and soil. Usually this time is approximately 24 hours [12].

In the Short Term, the following main effects can be listed [9]:

- Atterberg limits change (the plastic limit increases while the liquid limit decreases and subsequently the plasticity index deacreases);
- size distribution changes;
- density decreases.

In the Long Term, the following main effects can be listed [9]:

- shear strength increases (especially in terms of cohesion);
- modulus and fatigue resistance increase;
- the durability under the action of water and frost is improved.

Lime stabilization can be described in terms of short term and long term reactions.

In the Short-term, there is an effect of Drying, resulting in an increase of temperature which is generated by the following reaction:
CaO + H2O = Ca (OH) 2 +64900 J / mole
where 64900 J / mole is the energy which is generated.

Another important reaction is the flocculation, due to the exchange of free ions in solution Ca + + and cations Na +, K +, etc., which allows the formation at the earliest hours of ties between the dispersed particles of clay that are agglomerated facilitating the operations of mixing and compaction [9].
In the Long term, the typical reactions between lime and clay soils are the following [9]:

$$Ca(OH)_2 = Ca^{+++}{}_2[OH]^-$$
$$Ca^{+++}{}_2[OH]^- + SiO_2 \text{ (silica clay)} = CxSyHz$$
$$Ca^{+++}{}_2[OH]^- + Al_2O_3 \text{ (alumina clay)} = Cx'Ay'Hz'$$

in which the various indices vary depending on the type of clay that we consider.
As for cement stabilization, it is well known that cement is a mixture of calcium silicates and calcium aluminates which bind efficiently with lime. The technique of stabilization with cement is often used to improve the bearing capacity of foundations with a road compromised stability due to deformation of the deep pavement [12]. The main thing to consider is the speed with the cement reacts with water. In fact, this aspect can positively influence the benefit potential of such use. We must consider that because of its nature of powder, such as lime, Portland cement can be considered as a stabilizer in the case of granular soils. The result is a moisture-resistant material that is highly durable and resistant to long term. It should be emphasized that the use of a technique (lime or cement) does not exclude the other. If a material to be stabilized with cement has a certain amount of silt-clay particles it can be useful to combine the action of cement with lime [12].
Soil stabilization with lime and /or cement requires a preliminary study in the laboratory in order the optimal quantity of lime and / or cement be defined. Furthermore, the optimum moisture content to be added in mixing has to be assessed.
The use of lime in addition to cement, it is necessary in cases where the material to be stabilized ha index plasticity IP> 0. [12]

Many authors [13] suggest to determine stabilizer by referring to percent passing at the 0.075mm sieve (P200) and plasticity index (PI) (see figure 3).

In more detail, for intermediate PI (10-25 or 10-30), both for high P200 (>25%) and for low P200 (<25%), quicklime & cement blends are suggested. Particularly, if P200 >25%, a 3% quicklime+Portland cement stabilizer is suggested. On the contrary if P200<25%, a 2% quicklime+Portland cement stabilizer is suggested.

On the contrary, in the case of high PI (>25) and high P200 (>25%), quicklime stabilization is suggested (more than 90% of CaO or 55-60 CaO+ 35-40% MgO).
Finally, for low PI (<10) and low P200 (<25%), Portland cement is suggested as stabilizer (Cao 61-67% and SiO2 19-23%).

It is noted that [13]:

- The higher the quicklime and or cement percentage, the higher the 7-days UCS (unconfined compressive strength,(ASTM D2166-06 and ASTM D4609-08), the lower the permeability.
- The lower the PI, the lower the durability and the lower the expansion for lime-stabilized soils.
- The higher the PI, the lower the strength for cement-treated soils.
- For intermediate values of PI (10-25), and for 2% of lime + cement stabilizers, the higher the cement percentage, the higher the strength.
- For intermediate values of PI (10-25), and for 3% of lime + cement stabilizers, the lower the cement percentage, the lower the expansion.

Mellowing depends on the treatment that we consider, as the reaction time varies depending on the cement or lime content (see table 1, [13]).

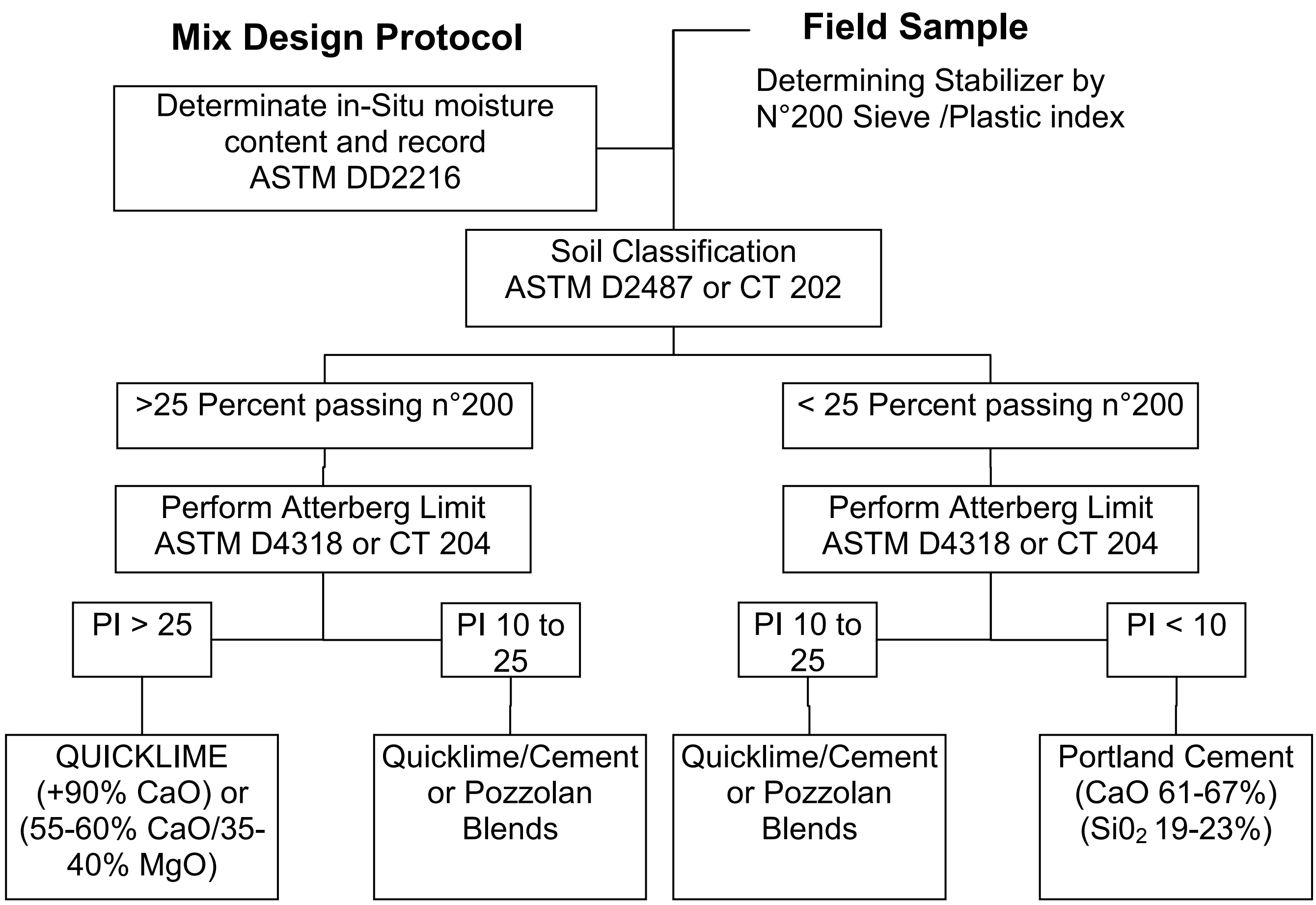


Figure 3 - Mix design protocol

Table 1 - Mellowing/slaking period

Reagent	Percentage of Reagent	Rate of initial Hydratation - Mellowing/Slaking Period
Portland Cement	2%-5%	2 hours
	5%-10%	3 hours
	+10%	+-3 hours
Quicklime	2%-4%	18 hours
	5%-6%	36 hours
	7%-10%	+54 hours

3. EXPERIMENTS AND DISCUSSION

This section illustrates the design of experiments and the results obtained. Different lime/cement treatments of a clayey soil were performed.

The following tests were performed on soil (see figure 4):

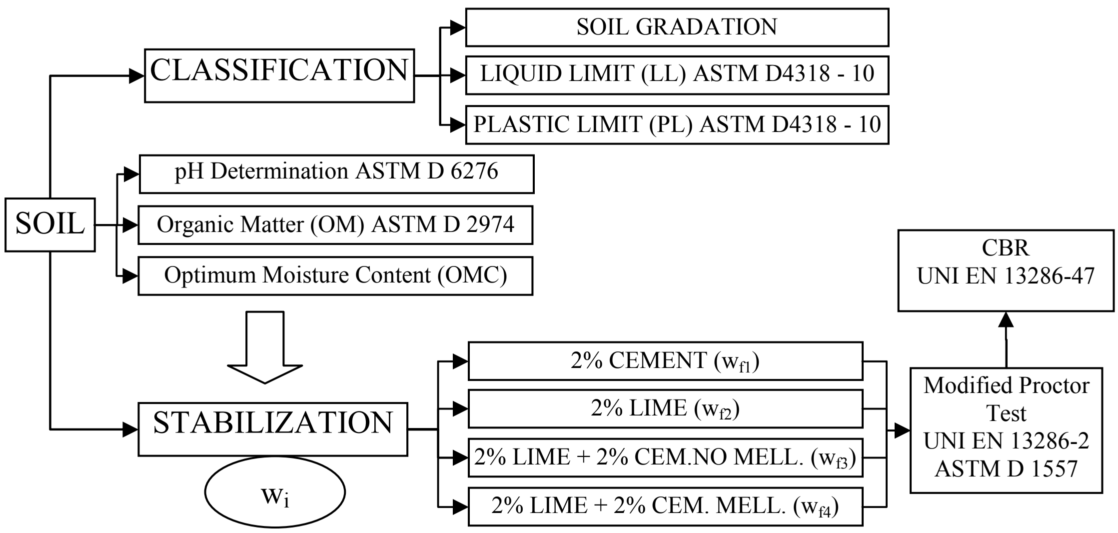
- soil classification (by performing soil gradation and Atterberg Limits tests);

- pH determination for minimum lime content for soil stabilization;
- organic matter (OM) determination;
- Modified Proctor Tests (compaction curve - relationship between water content and dry unit weight of the soil - and the Optimum Moisture Content (OMC).

The following four different lime/cement treatments were carried out:

i) 2% cement (of the dry weight of the soil);
ii) 2% lime (of the dry weight of the soil);
iii) 2% lime + 2% cement NO MELL. (without mellowing time);
iv) 2% lime + 2% cement MELL (with mellowing time).

California bearing ratio, CBR, tests were performed on stabilised soils.



Symbols. w_i: initial water content; w_{f1}-w_{f4}: final water content

Figure 4 - Main phases of the lime/cement treatment

Figure 5 and table 2 show the results we obtained for soil gradation and Atterberg Limits tests.

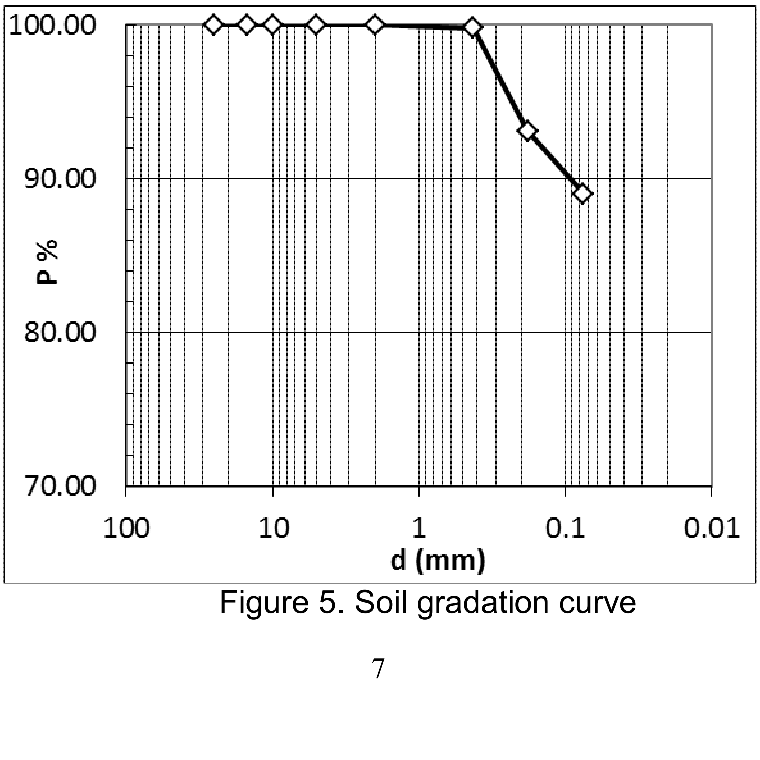


Figure 5. Soil gradation curve

Table 2 - Atterberg Limits of the tested soil

LL	PL	PI
45	26	19
LEGEND LL = LIQUID LIMIT ; PL = PLASTIC LIMIT; PI = PLASTICITY INDEX		

Figure 6 refers to pH tests, while Table 3 summarizes the results of the organic matter tests, which were performed on three soil specimens. The percentage of organic matter (ASTM 2974-07a) ranged from 1.43 to 2.40 % with a mean of 1.85%.

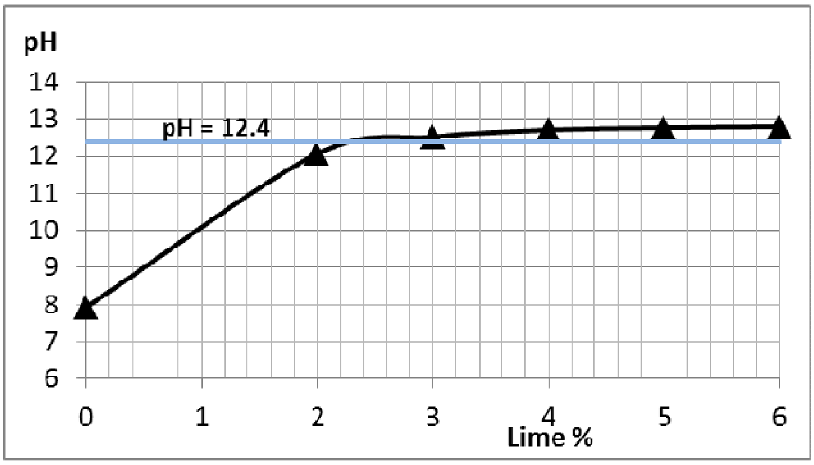


Figure 6 - pH test

Table 3

Soil specimen	1	2	3	Specification limit
OM = Organic matter (%)	1.71	1.43	2.40	1% - 2 %
Note. Soil with organics content above 1-2% by weight as determined by ASTM D 2974 may be incapable of achieving the desired unconfined compressive strength for lime stabilized soil [14]. Sulfate content must be tested separately [15].				

Figure 7 illustrates the Modified Proctor compaction curve for the soil, while table 4 summarises the physical properties of the soil before the stabilization. Figure 8 refers to California bearing ratio (CBR) test. Finally figures 9 and 10 refer to soil performance before and after the stabilization.

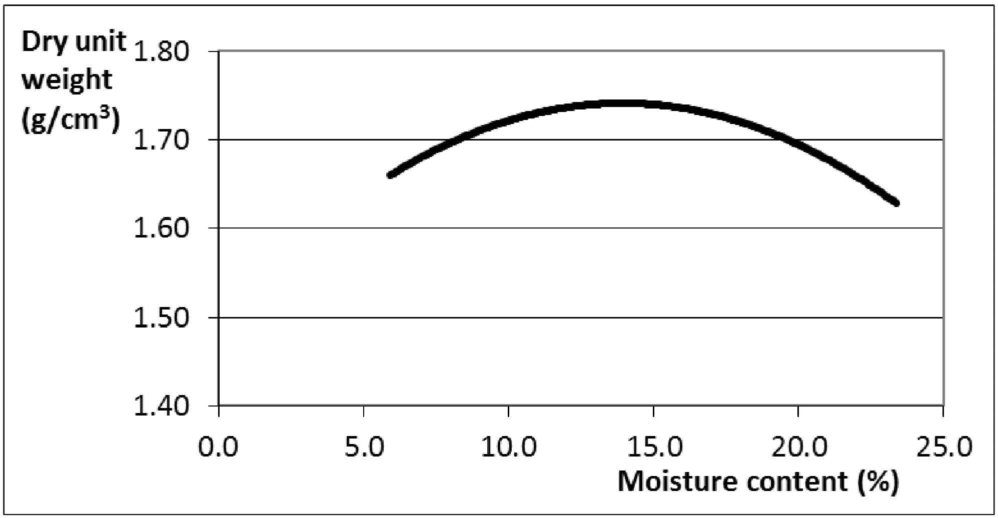


Figure 7 - Modified Proctor compaction curve

Table 4: Physical soil properties

% passing No. 200	89	UNI EN 933-1:2009
LL, Liquid Limit (%)	45	ASTM D4318 - 10
PL, Plastic Limit (%)	26	ASTM D4318 - 10
PI, Plasticity Index (%)	19	ASTM D4318 - 10
OC, Organic Content (%)	1.85	ASTM D 2974
VB "Value of blue"	45g/Kg	UNI EN 933-9:2000
OMC, Optimum moisture content (%)	13.5	UNI EN 13286-2 ASTM D 1557
MDD, Maximum dry density (g/cm^3)	1.735	UNI EN 13286-2 ASTM D 1557
HRB-AASHTO classification	A_{7-6}	CNR-UNI 10006
Initial Consumption of Lime ICL (%)	2.2	ASTM D 6276
Water content (%)	18.0	UNI CEN ISO/TS 17892-1:2005


Before CBR


CBR test


After CBR

Figure 8 - California bearing ratio (CBR) test

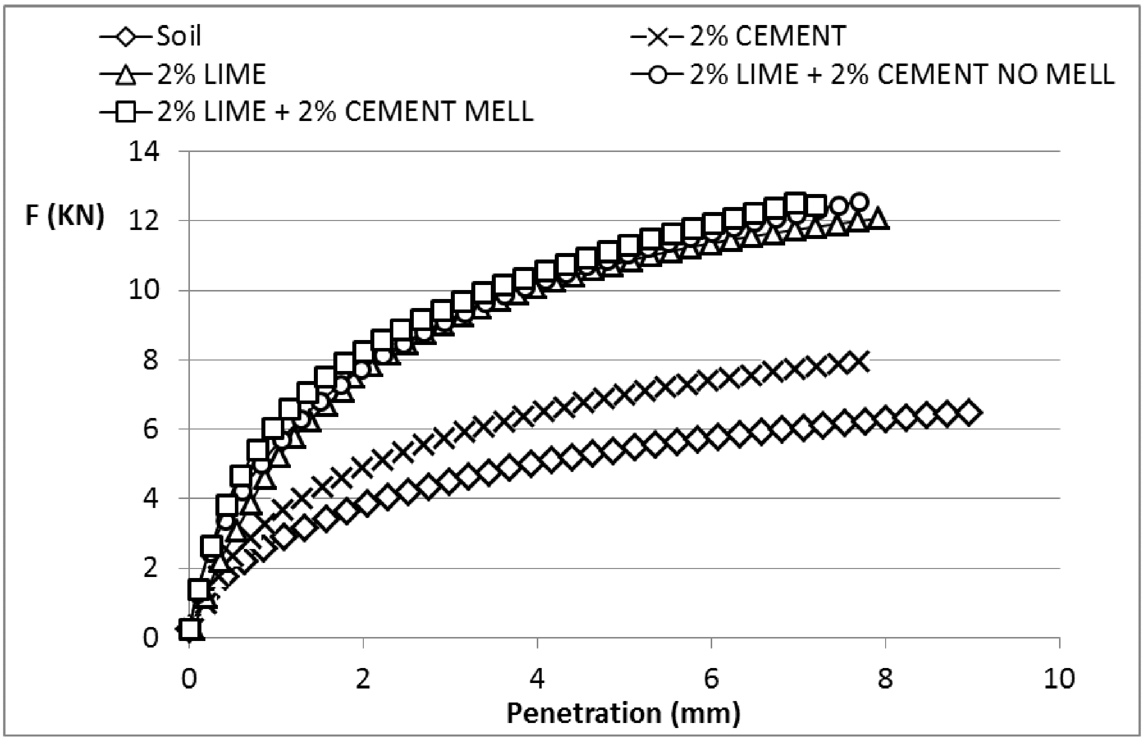


Figure 9 - CBR tests and results

Figure 9 shows the CBR values of the different stabilized mixtures. It is possible to note the strong benefits in terms of increase of mechanical properties due to stabilization treatments. Lime and lime-cement treatments performed quite the same. Mellowing did not cause an appreciable increase of performance.
It is worthwhile to remark that cement stabilization caused an improvement of CBR around 12 %, while lime stabilization resulted in a higher CBR (+35%). Importantly as for lime-cement stabilization, mellowing (18 hours) caused an improvement of CBR around 3 %.

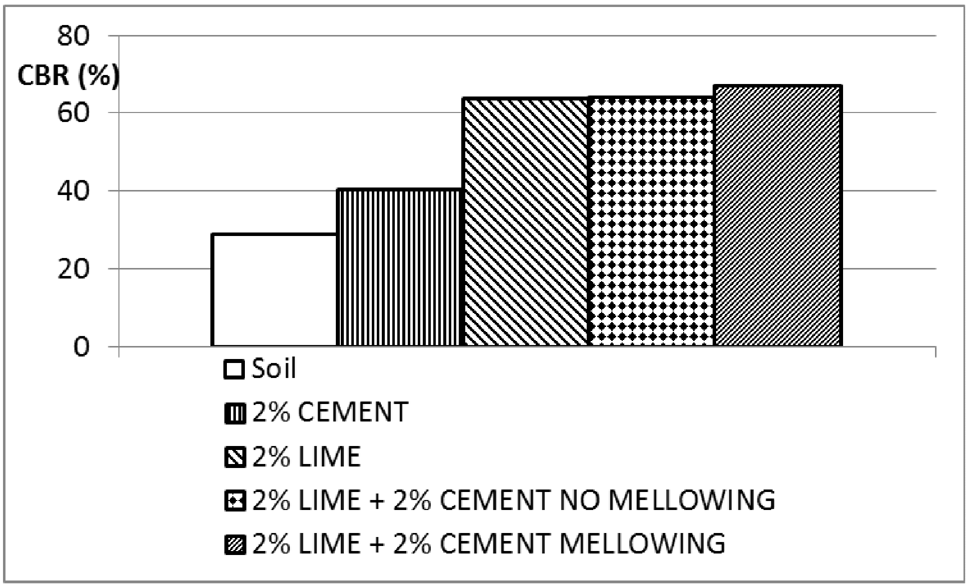


Figure 10 - CBR (averages)

CONCLUSIONS

Lime and/or cement stabilization can improve the engineering properties of soft, fine-grained soils significantly through chemical reactions. This fact influences the behaviour of pavements constructed on stabilized subgrades.

Although this paper presents only the first results obtained from of a lime/cement treatment, results allow for a better understanding of the effect of this treatment on the bearing capacity of the subgrade and on the subsequent cost of life cycle of the pavement (construction, maintenance rehabilitation).

From the experimental program of the effect of combined lime and cement treatment on subgrades, the following conclusions have been drawn:

- combined lime modification and cement stabilization enhanced the strength.
- by referring to the case study here considered, although cement stabilization caused an increase of the CBR, lime and lime/cement stabilizations performed better and CBR resulted strongly improved (+100% c.a);
- mellowing did not cause an appreciable increase of performance.

Future research will aim at gaining a better understanding of traffic and road type importance on net present values.

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