Abstract

As detailed in Part 1, the most common Italian Technical Specifications refer to different design methodologies for design of lime-soil mixtures, some being quite different from those internationally adopted. Therefore, it seemed appropriate to the Authors to compare these methodologies, via a wide experimental program.

It is shown that the Italian methodology of the National Road Agency is different not only from those used in Italy, but also from the main international standards. The experimental results highlight that a revision of that methodology is needed in order to bring it into line with what is prescribed by the European standard.

© 2012 The Authors. Published by Elsevier Ltd. Selection and/or peer-review under responsibility of SIIV2012 Scientific Committee

Keywords: soil stabilization, lime, mechanical performances, laboratory testing

1. Background

Based on the findings detailed in Part 1 [1] in order to evaluate the level of agreement (or disagreement) between the different design methods and specifications [2] [3] [4] [5] [6], a specific experimental program was defined, based on compaction studies of mixtures at different energy levels, with different lime contents, and for different curing time (in air and soaking), as detailed the following sections.

* Corresponding author. Tel.: +39 091 238 99716; fax: +39 091 487068.
E-mail address: clara.celauro@unipa.it
Nomenclature

PL Plastic limit, in %
LL Liquid limit, in %
PI Plasticity Index
IBI Immediate Bearing Index, in %
CBR California Bearing Ratio, in %
Gv Volumetric Swelling, in %
OMC Optimum Moisture Content, in %
MDD Maximum Dry Density, in kN/m³

1.1. Experimental program

For the production and testing of the soil-lime mixture, five lime contents are selected, as summarized in Table 1

Table 1 Lime contents used in the experimental program

| Dosage levels | c1 | c2 | c3 | c4 | c5 |
|---------------|----|----|----|----|----|
| Lime content CaO (%) | 0  | 1.5| 2  | 3  | 6  |

In particular, the chosen dosages are such that:

- the nil one (CaO = 0%) is necessary for comparison with the non-treated soil;
- the average dosages (CaO = 1.5 – 2.0 – 3.0%) are representative of typical lime contents used for stabilized soils in embankments. They are also useful for simulating cases of underdosage with respect to the expected lime content;
- the highest dosage (CaO = 6%) is representative of lime stabilized soils optimized for use in capping layers.

As far as the soil is concerned, the range of studied moisture contents was set between \( w_{\text{MIN}} = 12\% \) and \( w_{\text{MAX}} = 32 \% \), as given in Table 2. It should be noticed that the soil plastic limit (PL = 27.3%) falls within the chosen range.

Table 2 Initial moisture content, \( w \), used for production of the soil-lime mixtures

| CaO (%) | Initial moisture content of the soil, \( w \) (%) |
|---------|-----------------------------------------------|
| 0       | 12 15 19 22 25 29 |
| 1.5     | 15 19 22 25 29 -   |
| 2.0     | 15 19 22 25 29 -   |
| 3.0     | 15 19 22 25 29 32  |
| 6.0     | 15 19 22 25 29 32  |
With regards to the compaction and curing procedures, Table 3 summarizes the experimental conditions considered for the bearing capacity of laboratory-compacted specimens [7] [8].

| Table 3 Experimental conditions for the Proctor compaction and for the CBR tests |
|----------------------------------|---------------------------------|-----------------|-----------------|
| Compaction energy               | standard effort [9]             | standard effort [9] | modified effort [10] |
| Curing in air (days)            | 0                               | 0                | 7               |
| Curing in water at T = 22 ± 2°C (days) | 0                               | 4                | 4               |
| Total curing time (days)        | 0                               | 4                | 7 + 4           |
| Identification of the test      | IBI                             | cbr(4i)          | CBR(7+4i)       |

The testing temperature, irrespective of the curing procedure (in air or in water), was kept constant, in the range T = 22 ± 2°C.

For those specimens that were cured in water, namely cbr(4i) and CBR(7+4i) series, swelling measurements in CBR mould (linear swelling) were also taken, during their soaking time. This was done in order to evaluate the effect of the lime content, of the density of the mixture and also of the curing procedure on the swelling behavior of the different mixtures.

1.2. Laboratory qualification of the lime used

The lime used for the laboratory tests is a commercial quicklime, certified as CL 80-Q according to the EN 459-1 Standard [11] Results from preliminary chemical and physical characterization [12] of the lime used in this study are given in Table 4.

| Table 4 Results of the chemical and gradation tests performed on the lime used |
|----------------------------------|------------------------|-----------------|
| Detected compound               | %                      | CL 80-Q Requirements |
| H₂O (from Portlandite Ca(OH)₂)  | 3.2                    | ≤ 2             |
| CO₂                              | 7.2                    | ≤ 7             |
| CaO                              | 86.6                   |                 |
| MgO                              | 0.6                    | ≤ 5             |
| Free oxides (CaO + MgO)          | 87.2                   | ≥ 80            |
| NA not analyzable               | 2.4                    | --              |
| Passing to 5 mm                  | 100                    | 100             |
| Passing to 2 mm                  | 99                     | ≥ 95            |
| Passing to 0.18 mm               | 51                     | ≥ 70            |
| Passing to 0.075 mm              | 31                     | ≥ 50            |
| Reactivity test (°C)            | 53.4                   | ≥ 60            |
1.3. Laboratory qualification of the soil used

Gradation curve of the reference soil used for this study, as determined via both dry and wet sieving, is depicted in Figure 1.

![Gradation of the soil studied](image)

Fig. 1. Gradation of the soil studied

Consistency limit tests - both liquid and plastic limit - were conducted at room temperature. Results are given in Table 5:

| Liquid Limit LL (%) | Plastic Limit PL (%) | Plasticity Index PI (%) |
|---------------------|----------------------|-------------------------|
| 51.5                | 27.3                 | 24.2                    |

Based on the previous results, the soils can be classified as belonging to subclass A7-5 (with a group index GI = 16) of the AASHTO Soil Classification System [13]. For both its gradation and plasticity, this soil complies with the requirements for lime stabilization for mixtures to be used for capping layers and improved subgrade, without the need to use any other hydraulic binder.

Thermal analysis and ion chromatography were conducted in order to verify the presence of harmful substances. The results obtained, as shown in Table 6, comply with the soil requirements for lime stabilization.

| Organic Matter (%) | Cl⁻ (%) | NO₃⁻ (%) | SO₄²⁻ (%) | CO₂⁻ (%) |
|--------------------|---------|----------|-----------|----------|
| absent             | 0.069   | 0.021    | 0.17      | 12.4     |

1.4. Determination of the minimum lime content

First, determination of the minimum lime content according to the Eades & Grim test described in the ASTM D6276 Standard [14] was performed by pH measurements on five mixtures, with different lime contents as
specified in the Standard itself, as well as on a saturated water solution of calcium hydroxide. The results are shown in Figure 2a. According to the ASTM Standard, the minimum lime content is the one needed in order to achieve a pH = 12.4 in the lime-soil mixture. In this case, this minimum is equal to 3%.

Secondly, according to the Swiss Standard SNV 640 503a [15] the minimum lime content was determined, based on the variation in the soil consistency limits. In this case, this minimum is defined as the one needed for modifying the plasticity of the soil. A further increase in the lime content beyond this value does not affect the soil plasticity in a noticeable way. Consistency results depicted in Figure 2b show that lime content higher than 2% does not provide any further modification to the consistency of the mixtures.

Comparing the results of the two different standards applied for determination of the minimum lime content to be added to the mixture, a disagreement was found. The results found in accordance to the Swiss standard, for practical application in field, are preferable, since they provide an overall view of the expected variation of the consistency limits and, above all, of the widening of the solid state range (PL) of the treated soil.

2. Results

In the following sections, the effect of lime and water content, as well as of the curing time and conditions on the compaction properties and bearing capacity of the lime-stabilized mixtures are presented. The findings of the experimental tests are discussed, also with a view to revision of the Italian design methodology considered by the National Road Agency (ANAS).

2.1. Proctor compaction tests

Figure 3 depicts the compaction test results as obtained for the 5 lime contents introduced in the mixture, for both compaction energies (standard and modified effort). For both, the dry density of the mixture is given in function of the water content. It is clearly observed that, as a consequence of the modification of the compaction
characteristics of the soil, the increase in the lime content reduces the maximum value of the dry density of that may be reached and increases the corresponding optimum water content at which this maximum density may be achieved.

![Proctor compaction at different lime content](image)

The abscissa of the graphs depicted in Figure 3 is the initial water content of the soil, prior to lime addition: this results in a useful information for adjustment of the lime content during the construction phase, once in situ, as a function of the natural moisture content of the soil to be treated. Figure 4 depicts the results obtained from the Proctor compaction with normal effort, after complete extinction of the lime (after an elapsed time of at least 60 minutes). The dry density is given as a function of the final water content of the mixture since this variable allows one to evaluate the optimum moisture content, OMC, to be compared with the minimum water content, \( w_{\text{MIN}} \); necessary for allowing the pozzolanic reactions to develop and required by the French methodology as in Part 1 [1] [6].

Table 7 summarizes, for both compaction energies, the OMC, in terms of initial water content in the soil, as well as the related Maximum Dry Density, MDD, as determined by the compaction curves depicted in Figure 3 a and b. It can be noticed that, for the same lime content, the OMCs found for standard compaction energy are always higher than those obtained with modified compaction energy.

The minimum final water content (\( w_{\text{MIN}} \) of the soil = 0,9 OMC of the mixture), as deduced from Figure 4 and prescribed by the French methodology for production of the mixture, is also given in Table 7. It can be observed that, for the soil studied and for each lime content in the mixture, the OMC deduced from the Proctor test with modified effort is always lower than the minimum needed for ensuring the development of the long-term performances and, therefore, it cannot be used as a reference for prescribing the moisture conditions to be reached during the construction phase.
Fig. 4. Proctor compaction with standard effort, as a function of the final water content in the mixture

Table 7 OMC and MMD from Proctor tests, standard and modified compaction effort

| Lime content | Standard Effort | Modified Effort | Difference |
|--------------|----------------|----------------|------------|
| CaO (%)      | OMC (%)        | MDD (kN/m³)    | w_MIN (%)  | OMC (%) | MDD (kN/m³) | ΔOMC |
| 0            | 16.00          | 16.40          | - -        | 13.00    | 18.10       | 3.00 |
| 1.5          | 17.30          | 16.00          | 15.20      | 14.00    | 17.90       | 3.30 |
| 2            | 20.00          | 15.50          | 17.10      | 16.90    | 17.40       | 3.10 |
| 3            | 21.60          | 15.40          | 18.90      | 17.20    | 17.20       | 4.40 |
| 6            | 22.20          | 15.20          | 19.30      | 17.70    | 16.80       | 4.50 |

2.2. CBR tests

Measurements of the load-bearing capacity of the soil-lime mixtures were taken, via CBR testing, on specimens produced according to the variables defined for this experimental program in Table 3. Then specimens compacted with standard or modified effort were tested for CBR evaluation:

- immediately after production, for IBI testing;
- after 4 days of soaking in water at 20°C, also indicated with cbr(4i);
- after 7 days of curing in air, followed by 4 days of soaking, indicated with CBR(7+4i), only for specimens compacted with modified effort, as prescribed by the ANAS design method.

The test results are depicted in Figures 5, from a to d.
Figure 5 Results of the CBR-tests, for different lime contents: (a) IBI; (b) cbr (4i); (c) CBR(7+4i); (d) comparison IBI and cbr(4i)
From results in Figure 5c, an optimum moisture content for this bearing capacity can be identified. Typically, this optimum content increases with the lime content and, for the conditions studied, it falls within the range 20 - 25% i.e. in the “wet” side of the Proctor curve ($w > OMC$). Furthermore, for each lime content, the optimum moisture content with respect to the mechanical performance is, on average, equal to 1.35 OMC, and therefore, rather higher than the OMC (modified effort) given in Table 7. This result discriminates the soil-lime mixtures behavior from that of natural soils, both granular and fine-grained. As concerns the minimum requirements for the bearing capacity as defined in the ANAS Specifications, they appear to be fulfilled in a wide range of moisture contents, as detailed in Table 8 for different lime contents. In this connection, in Figure 6c, for easier reading, the minimum levels required for use in embankments (CBR = 30 MPa) or in capping layers (CBR = 60 MPa) are depicted. The results show that all are satisfactory, even in the case of underdosage of lime, that is CaO = 1.5%.

The immediate bearing results depicted in Figure 5a provide IBI values that gradually decrease when the moisture content of the soil to be treated increases. By contrast, the test results after 4 days of soaking (cbr(4i), depicted in Figure 5b), show a similar trend to that of the series CBR(7+4i), whose optimum bearing capacity is reached for moisture contents falling within the range 22 ÷ 25%, again in the “wet” side of the compaction curve. It should be noticed that in this case the mechanical response of the mixtures is less sensitive to the variation in the initial moisture content in the soil, since the curves found are more flattened than those typical of mixtures compacted at higher energy. Again, the optimum - initial – water content with respect to the bearing capacity CBR increases with a higher lime content and is always higher than the optimum content for compaction, though less noticeably than what is found for the analogous optimum values from testing with modified effort. In fact, in this case, the optimum water content for bearing capacity ranges from 1.1 to 1.3 times the OMC for compaction.

The results obtained with respect to the French methodology described in Part 1 (see Table 2 of Part 1) [1], the following conclusions may be drawn for the soil studied:

- the minimum requirements for use in embankments are fulfilled for lime contents not lower than 2%;
- the minimum requirements for use in embankment layers less than 2 m from the formation level are fulfilled only for the lime content of 6%;
- in none of the cases, the minimum requirements for use in capping layers are satisfied. Indeed, the IBI results are always lower than the minimum required with respect to the soil plasticity (in this case, the minimum is IBI = 15%).

### Table 8 Moisture range that, for different lime contents, fulfills the minimum ANAS requirement for bearing capacity

| Lime content CaO (%) | w @ CBR(7+4i)$_{MAX}$ (%) | Allowable range of water content for fulfillment of the ANAS requirements |
|----------------------|-----------------------------|---------------------------------------------------------------|
|                      |                             | Embankment (CBR $\geq$ 30MPa) | Capping layers (CBR $\geq$ 60MPa) |
|                      |                             | $w_{MIN} - w_{MAX}$ (%)    | $w_{MIN} - w_{MAX}$ (%)    |
| 0                    | --                          | never                       | never                       |
| 1.5                  | 21.90                       | 17 - 25                     | never                       |
| 2                    | 20.00                       | 17 - 24                     | 19 - 21                     |
| 3                    | 22.00                       | always                      | 18 - 23.5                   |
| 6                    | 24.70                       | always                      | 19 - 26.5                   |
2.3. CBR swelling in water

During the 4 days of soaking of the specimens of the series cbr(4i) and CBR(7+4i) to be tested for bearing capacity, swelling measurements were taken in order to evaluate the sensitivity of this feature, as a function of the mixture composition, as well as of the different experimental conditions (compaction energy, time and modes of curing). It should be noticed that this swelling is different from that necessary for identification of the swelling class LS (linear swelling) as defined in the Standard EN 14227-11 [16], for evaluation of soil lime mixtures, since the latter has to be monitored 28 days on specimens compacted with normal effort only. Figures 6a and 6b depict the typical trend for swelling for soil lime mixtures during the four days of soaking, for different initial water contents.

As can be seen from Figure 6a, for specimens compacted at a low energy and soaked without prior curing in air, the observed swelling is not stable but it increases with time, in a significant way. Additionally, it is evident that the measured swelling is reduced with an increase in initial water content in the soil. On the other hand, from Figure 6b it can be noticed that a 7-day curing time in air, in protected conditions, implies swelling measurements that are totally negligible and that are constant with time (always lower than 0.1%). This result should be related with the higher density reached for the specimens tested in the CBR(7+4i) series. From Figure 7, it can also be observed that 7 days of curing in air, apart from the higher density achieved, makes the mixtures CBR(7+4i) insensitive to swelling, independently of the lime content studied.

Therefore, evaluation of this characteristic based on CBR(7+4i) specimens leads one to formulate judgments that are not correct with respect to the swelling potential of the mixtures.
3. Conclusions

The results of an experimental plan for evaluating the level of agreement of the different lime-soil mixture design methods and specifications have been presented, based on compaction studies of mixtures at different energy levels, with different lime contents, and for different curing times (in air and soaking). Specifically, it has been shown that the Italian methodology of the National Road Agency – which represents the main Technical Specification for road construction in Italy – proves to be very different not only from those commonly used in Italy, but also from the main international standards, apart from not allowing the use of the requirements defined in the harmonized European Standard EN 14277-11 for qualification purposes of soil-lime mixtures. It has been proved that the optimum moisture content as found via Proctor tests with modified effort (even not considering the corresponding maximum density, which should not be used as a target for the compaction control in situ, since it is unrealistic if compared with what may be occur in the field) is inadequate and misleading with regards to the decision to be made in field. In fact, it corresponds to a water content lower than the minimum needed within the soil in order to assure, first, high-pH ionization so that the clay can be solubilised and, secondly, hydration of the chemical compounds which causes agglomeration of the particles.
Further, with regards to the mechanical requirements for soil-lime mixture, as a function of their intended use, it has been proved that the ANAS design method is based on a wrongly optimistic value, in contrast to what derived from the French and Belgian method, also taken into account in Italy by the National Railways Agency. Therefore, also considering the wide diffusion for road construction of the ANAS specifications, the results presented in this paper highlight that a prompt revision of that methodology is needed in order to align with the prescription of the European Standard 14277-11 for this kind of mixtures.

References

[1] Celauro B., Bevilacqua A., Lo Bosco D. Celauro C. (2012). Design procedures for soil-lime stabilization for road and railway embankments. Part 1 - review of design methods. 5th SIIV International Congress in Procedia - Social and Behavioral Sciences. Paper accepted for publication.
[2] ANAS (2006) Capitolato Speciale d’Appalto. Norme Tecniche – Opere Civili. ANAS Ente Nazionale per le Strade, Rome, Italy. In Italian.
[3] CRR (2010) Code de bonne pratique pour le traitement des sols à la chaux et/ou aux liants hydrauliques Recommandations. CRR R81/10, Centre de Recherches Routières, Bruxelles. In French.
[4] RFI (1999) Specifica Tecnica. Trattamento delle Terre con calce. Norma Interna. Divisione Infrastrutture FS, Rome, Italy. In Italian.
[5] SETRA (2000) Traitement des sols à la chaux et/ou aux liants hydrauliques. Application à la réalisation des remblais et des couches de forme. Guide Technique, Service d'Etudes Techniques des Routes et Autoroutes, Bagneux Cedex, France. In French.
[6] SETRA (2007) Traitement des sols à la chaux et/ou aux liants hydrauliques - Application à la réalisation des assises de chaussées. Guide Technique, Service d'Etudes Techniques des Routes et Autoroutes, Bagneux Cedex, France. In French.
[7] ASTM (1994) Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils Designation D1883-94. Annual Book of ASTM Standards. ASTM American Society for Testing and Materials, West Conshohocken, PA, US.
[8] CEN (2004) EN 13286-47. Unbound and hydraulically bound mixtures — Part 47: Test method for the determination of the California bearing Ratio, Immediate Bearing Index and linear swelling”. European Standards (EN) CEN European Committee for Standardization, Brussels, Belgium.
[9] ASTM (2000) Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft), Designation D698. Annual Book of ASTM Standards, ASTM American Society for Testing and Materials, West Conshohocken, PA, US.
[10] ASTM (2007) Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lb/ft) (Modified Proctor) Designation D1557. Annual Book of ASTM Standards, ASTM American Society for Testing and Materials, West Conshohocken, PA, US.
[11] CEN (2001) EN 459-1. Building lime - Definitions, specifications and conformity criteria. European Standards (EN) CEN - European Committee for Standardization, Brussels, Belgium.
[12] CEN (2001) EN 459-2. Building lime. Test methods. European Standards (EN) CEN European Committee for Standardization, Brussels, Belgium.
[13] AASHTO (2004) Classification of Soil and Soil-Aggregate Mixtures For Highway Construction Purposes. AASHTO M-145-82, Standard Specifications for Transportation Materials and Methods of Sampling and Testing. AASHTO American Association of State Highway and Transportation Officials. Washington, DC, US.
[14] ASTM (2006) Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization. Designation ASTM D6276. Annual Book of ASTM Standards, American Society for Testing and Materials, West Conshohocken, PA, US.
[15] VSS (1987) SN 640 503a, Stabilisation: Stabilisation à la chaux aérienne. Union des professionnels suisses de la route (VSS), Association Suisse de Normalisation, Zurich. In French.
[16] CEN (2006) EN 14227-11. Hydraulically bound mixtures — Specifications — Part 11: Soil treated by lime. European Standards (EN) CEN European Committee for Standardization, Brussels, Belgium.