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Effects of variation in compaction water content on geotechnical properties of lime-treated clayey soil

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Abstract

The note presents the results of an experimental research study on the behaviour of a clayey soil of high plasticity treated with 3% quicklime for the stabilization of the foundation soil of a plant to be constructed along a slope. The aim of the study is to investigate the effect of a wide range of water content and of curing time on the mechanical and hydraulic characteristics of the treated soil. Soil-lime samples were prepared by wet mixing and Standard Proctor compaction. The development of chemical reactions in the compacted soil-lime mixtures were monitored by measuring the pH values of the soaking water with curing time. In the long term, a reduction of three orders of magnitude in permeability values was observed by comparing optimum and 5% wet of optimum conditions. Also compressibility was affected by variations in the compaction water content. The shear strength was not significantly affected by water content varying in the considered range.

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Keywords: lime, stabilization, microstructure, hydraulic conductivity, compressibility, strength

1. Introduction

Construction design practice along slopes requires high shear strength parameters and low deformability of the foundation soil. In these cases, deep foundations (i.e. piles) are preferable. If the sloping soil is clayey and a cut-and-fill method is adopted, a possible option is lime stabilization in order to achieve its mechanical and hydraulic

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improvement [1,2] and, if possible, to design shallow foundation. The successful use of compacted fine soil-lime mixtures requires a careful testing program both on the soil to be used and on the proposed soil-lime mixture. In particular, the overall performance of the mixture must be studied by means of laboratory tests in order to identify the best soil-lime proportion. Several water contents and different curing periods have to be considered in the laboratory study to properly take into account weather conditions during the construction phase.

These aspects will be focused in the following with reference to a recent case study concerning a plant for anaerobic digestion system to be constructed along a slope and located near to a non-hazardous waste landfill area in the Marche Region, in central Italy.

Quicklime addition to wet clayey soils gives rise to a sequence of reactions that includes (e.g.[3]): (1) lime hydration; (2) cation exchange in which calcium ions replace existing monovalent ions on the surface of clayey particles; (3) pozzolanic reactions with silica and alumina of soil to form calcium silicate and aluminate hydrates. Timing of reactions varies as a function of soil type and of lime type and amount [4] and is significantly affected by temperature [5,6]. As a consequence of soil-lime reactions, an improvement in workability occurs due to both drying and reduction of the plasticity index caused by cation exchange; water affinity and swelling potential decrease [7] and hydraulic conductivity increases [8]. Pozzolanic reactions produce improvements in strength and compressibility (e.g. [9,10]). The aim of the present study is to outline the advantages offered by lime treatment and to assess the effect of the variation in compaction water content on soil-lime characteristics.

2. Materials

Taking into account the depth of excavation during construction, the soil to be reused is that located between 0 and 5 m from ground surface, described as “clayey silt” and “silty clay” in boring logs. It is classified in laboratory as a clayey soil (CH in the plasticity chart) and its physical characteristics are summarized in Table 1. The amounts of sulphate and organic matter are 0.39% and 2.70% by dry mass of soil, respectively. The lime used in this research is a fine calcic quicklime, classified as CL80-Q (UNI EN 459-01). The amount of lime added to the soil was 3% by dry mass of soil. This amount is higher than the initial consumption of lime (ICL, Table 1), that represents the minimum lime content to start pozzolanic reactions.

Table 1. Soil characteristics (ICL =Initial Consumption of Lime).

Property	Value	Standard	Property	Value	Standard
sand (%)	3	ASTM D422-63(07)	Liquid Limit (%)	57	ASTM D4318-05
fine (%)	97	ASTM D422-63(07)	Plasticity Index (%)	33	ASTM D4318-05
clay (<2μm,%)	52	ASTM D422-63(07)	ICL * - %CaO	1.5	ASTM C977-00

3. Test Methods

All the specimens were prepared by crumbling the air dried soil, adding the amount of water necessary to reach the desired moisture content, then mixing lime and soil at the wet state (as usually done in the field, e.g. [11]) until a uniform distribution was achieved. The soil mixture was then compacted according to the Standard Proctor procedure (ASTM D698-12) both in three layers and in one layer, obtaining specimens of 101 mm in diameter and 116.5 mm and 40 mm in height, respectively. These specimens were cured for 7 days of curing in unsaturated conditions in sealed containers at a temperature ranging from 20 to 25°C.

In order to investigate the development of soil-lime reactions, a sample was compacted (in one layer) close to the optimum water content and was submerged in distilled water, resting on its lateral surface to maximize the contact area with water. The development of soil-lime reactions was investigated by measuring the pH values of the soaking water until the 40th day from the compaction. Cations concentration was also periodically measured by ionic chromatography on water samples, according to the methodology proposed and validated by [4].

Permeability tests (ASTM D5084-10) and one-dimensional incremental load consolidation tests (ASTM D24345-11) were performed on samples compacted at different water contents. Permeability tests were carried out in flexible walls permeameter at 35 kPa effective confining stress with tap water as permeant.

Unconfined compression tests were carried out with a deformation rate of 1.3% per min (ASTM D5102-09) on trimmed specimen of 35mm in diameter and 70 mm in height.

In order to determine the shear strength parameters, direct shear tests and isotropic consolidated undrained triaxial tests were performed according to ASTM D3080-11 and UNI CEN ISO/TS17892-9, respectively.

For direct shear tests, drained conditions were ensured by applying very low displacement rate (0.0014 mm/min) and the applied vertical effective stresses were 50, 100 and 200 kPa. The range of effective confining isotropic pressure applied in the consolidated triaxial tests was 50-150 kPa.

4. Results and discussion

Compaction curves of the treated and untreated soil are shown in Figure 1a. Separate curves are drawn for samples compacted in one and three layers. Lime addition slightly reduces the maximum dry unit weight, γ_d max, that results equal to 1.58 g/cm^3 for 3 layers curve and 1.6 g/cm^3 for the 1 layer curve. Optimum water content ranges between 22% and 23%. In Figure 2 it is possible to identify in 20-28% the range of water content (3 layers curve) able to guarantee a sufficiently high dry unit weight (set equal to 95% of the γ_d max, as most of technical specifications for construction works). It is important to underline that lime addition also causes a reduction in the water content achieved by the soil after treatment and compaction. A reduction of 2-3 per cent was observed registered for 80% of the samples (see Fig. 1b). This reduction has to be considered when monitoring the water content of the soil to be treated during field controls. All the soil-lime samples compacted wet of optimum show a degree of saturation (Sr) greater than 90%.

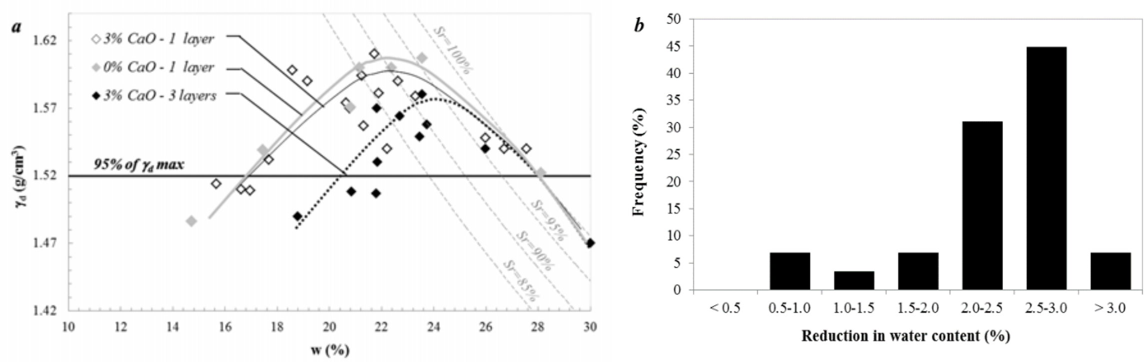

Fig. 1. (a) Standard Proctor compaction curves of treated and untreated soil; (b) Frequencies of reduction in water content due to lime addition.

4.1. Soil-lime reaction development

The pH values and cation concentrations of immersion water are plotted in Figure 2 against curing time. Within the first 20 hours of immersion the pH raises to the maximum value of 12.7 and calcium concentration (Fig.2b) reaches its maximum value of 400 mg/l after almost 4 hours. Since Na^+ concentration starts to increase just after 10 min from immersion (Fig. 2c), it is possible to state that cation exchange immediately starts in the mixture.

It is also possible to state that ion exchange reaction lasts for the first two days of curing because, during this time, pH holds steady (about 12.5) and sodium and potassium concentrations (Fig.2d) significantly increase, reaching their maximum at 2 days of curing (Na^+:110-120 mg/l and K^+:6-8 mg/l) and remain constant thereafter. After the first 2 days pH starts to decrease reaching the value of 10.7 after about 1 month and then remains almost steady. Ca^{++} concentration significantly decreases (with variable rate) during the first 2–3 weeks of curing. Given that, it is possible to identify the time interval for the development of most of pozzolanic reactions approximately between 2 and 30 days of curing.

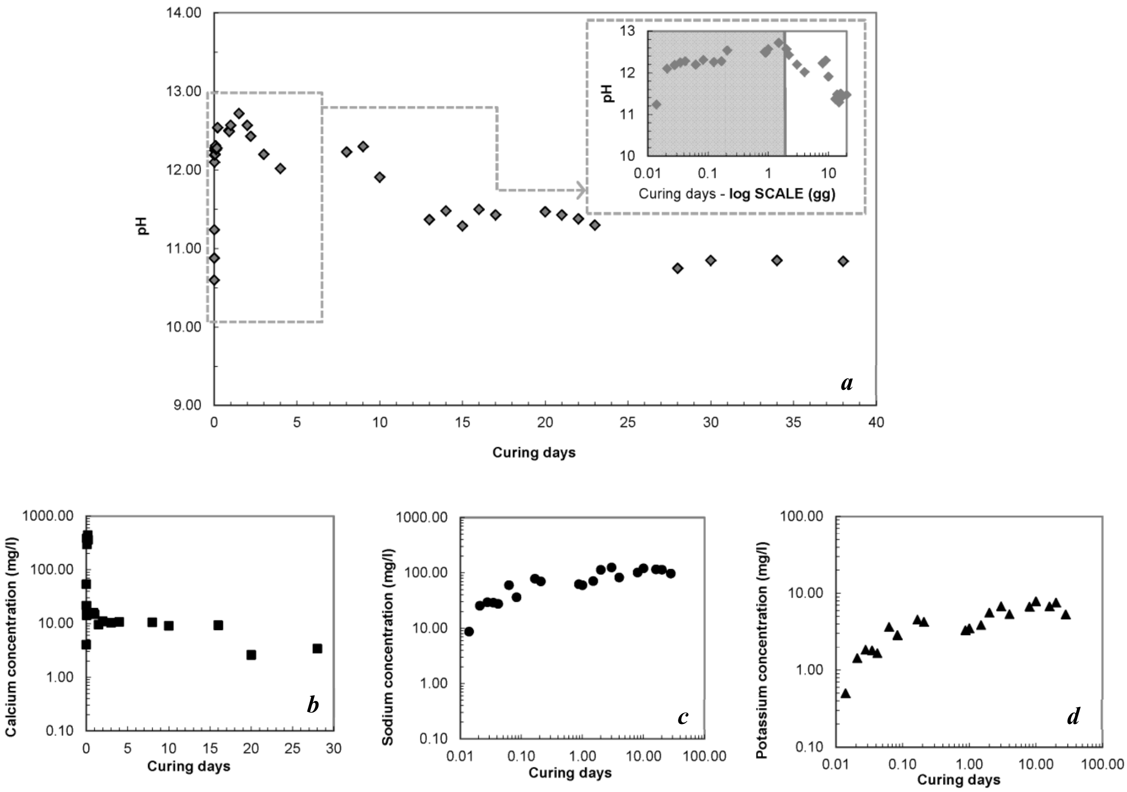

Fig. 2. pH (a) and cations concentration variations (b, c, d) in the immersion water with time.

4.2. Compressibility

With reference to Fig. 3, the significant reduction in compressibility caused by lime addition (in black and dark grey) to the natural soil (in white and light gray) can be immediately noticed.

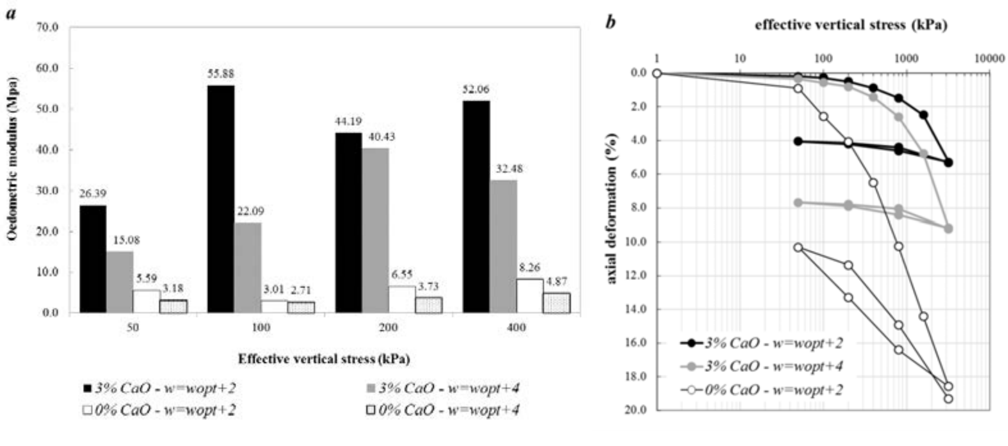

Fig. 3. (a) Oedometric moduli and (b) compressibility curves of specimens tested after 7 days of curing

An increase of 2 percent in water content causes a reduction of the oedometric modulus; in any case, the moduli are higher than 15MPa for every pressure applied and for every moisture condition studied, meaning very low compressibility of the lime stabilized soil. By comparing 2% and 4% wet of optimum conditions (Fig. 3b) differences in compressibility are detected at vertical effective stresses greater than 800kPa. In particular, at 3200 kPa, axial deformation of 4% wet of optimum specimen (in grey) doubled that of the 2% wet of optimum one (in black).

4.3. Hydraulic conductivity

In Figure 4a it is possible to observe a reduction in permeability, k, of 1order of magnitude with curing time (from $4 \cdot 10^{-7}$cm/s at 7 day of curing to $4 \cdot 10^{-8}$ cm/s after 3 weeks) for a lime-treated specimen compacted in wet of optimum conditions. This decrease in the long term is due to the growth of pozzolanic products (see section 4.1 and Fig. 2) capable to partially fill the inter-aggregate porosity [12]. In the long term (i.e. more than 20 days of curing) permeability values remain steady. By comparing this long term permeability coefficient with the one registered for a sample compacted at the optimum water content (Fig. 4b) it is possible to state that for the compacted soil-lime mixture of concern, an increase in the moulding water content causes a significant reduction (3 orders of magnitude) in hydraulic conductivity. As for untreated compacted clayey soils [13], the permeability coefficient strongly decreases with increasing the moulding water content.

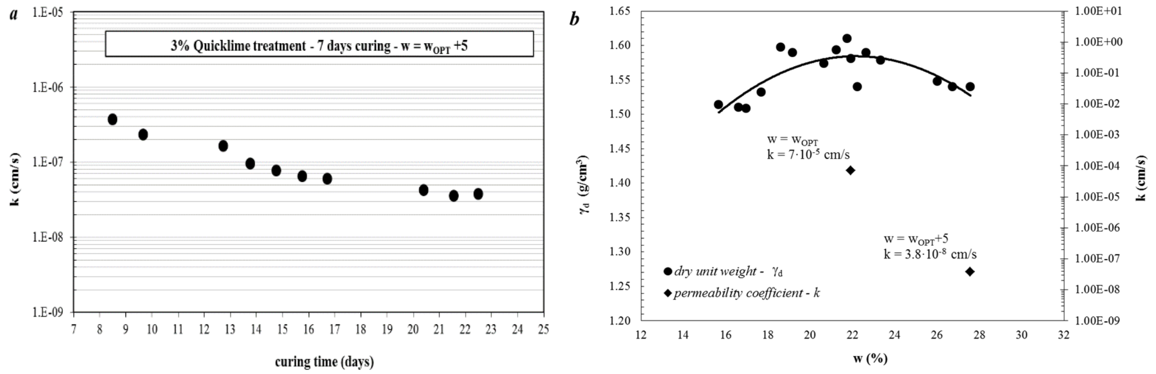

Fig. 4. (a) permeability trend with curing time of specimen compacted at wOPT+5; (b) long term permeability values related to the moulding water content of the specimens.

4.4. Compression and shear strength

The unconfined compressive strength, determined for three specimens, compacted at optimum and wet of optimum conditions, does not show a defined trend with water content (Fig. 5). Values vary in the range of 600-1000 kPa. All measured strength values are higher than the reference minimum values specified for road embankments at 7days of curing (300 kPa for subbase and 500 kPa for the body).

In Table 2 shear strength parameters (peak envelopes) for treated (7 days of curing) and untreated soil are listed. The results of triaxial and direct shear tests show the improvement due to the lime addition. It is important to underline that the stress-strain relationship is also modified by lime: the compacted untreated specimen show a trend typical of normal-consolidated soils while lime-treated specimens behave as over-consolidated soils showing a well identifiable peak strength. The drained cohesion intercept increases from 15 kPa (untreated soil) up to a maximum value equal to 100 kPa and peak angle increases of at least 7 degree. It is evident that 2 per cent variation in water content does not significantly affect the shear resistance.

These high strength values, determined after 7 days after compaction, are expected to increase with longer curing [1].

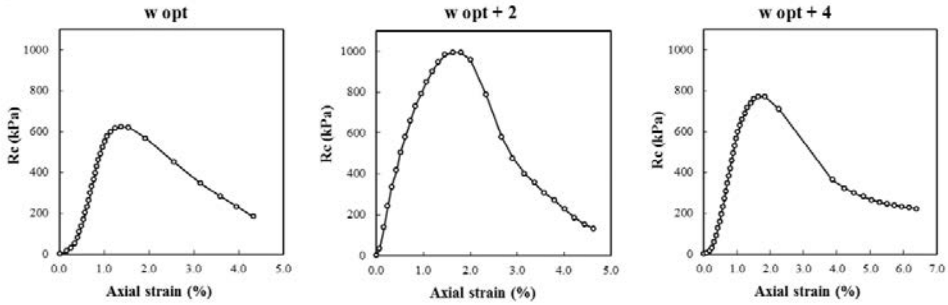

Fig. 5. Unconfined compression strength, determined for 3% lime treated specimens at 7 day of curing, for different moisture conditions.

Table 2. Shear strength parameters. * DS = Direct Shear test; TX = Triaxial test

CaO (%)	CURING (days)	w	γ_d (g/cm^3)	c' (kPa)	Φ'p (°)	Test*
0	-	wopt	1.60	15	21	DS
3	7	wopt	1.59	76	36	DS
3	7	wopt+2	1.59	77	34	DS
3	7	wopt	1.58	88	28	TX
3	7	wopt+2	1.54	101	30	TX

5. Conclusion

For the considered soil-lime mixture (3%CaO), cation exchange immediately starts and lasts for 2 days after mixing, most of pozzolanic reactions develop in the first 2-3 weeks of curing. A reduction of 2-3 per cent in water content after mixing and compaction needs to be considered when performing field controls. For the tested mix, the hydraulic conductivity is very sensitive to variations in water content: a reduction of 3 orders of magnitude in permeability values is obtained by comparing optimum and 5% wet of optimum conditions. Compressibility is also affected by the compaction water content, particularly at high values of the applied pressure (>400 kPa). Strength does not seem to significantly vary in the considered range of water content.

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