
Microstructure of a Lime Stabilised Compacted Silt

Giacomo Russo, Sebastiana Dal Vecchio, and Giuseppe Mascolo

Facoltà di Ingegneria, Università di Cassino, Via G. Di Biasio 43, 03043 Cassino, Italy gjarusso@unicas.it, s.dalvecchio@unicas.it, mascolo@unicas.it

Summary. Lime stabilisation of fine-grained soils is a well tested technique, traditionally used to improve clay subgrades for road pavements. The lime treated soils show a deep modification of the physical and mechanical properties (e.g., grain size distribution, plasticity, compressibility, shear strength). A deeper insight into the above mentioned behaviour has been achieved by investigating the changes of microstructure taking place after the addition of lime. In the paper, results from Mercury Intrusion Porosimetry (MIP) on a lime stabilised dynamically compacted natural silty soil are reported. Those results highlight the time dependency of modifications induced by lime on the microstructure, which is strongly related to the initial moulding water content of the sample.

Key words: lime stabilisation, compaction, microstructure

1 Introduction

Lime stabilisation of fine grained soils is widely recognized as a suitable ground improvement technique, since it allows the reuse of soils normally inadequate to be involved in earthworks (Croce and Russo 2002).

The effectiveness of the improvement is mainly due to the mineralogical and physical properties of natural soil, but also the treatment procedures play an important role. Therefore the lime stabilisation practice is based on some laboratory analyses concerning relevant physical and chemical properties of the soil, such as grain size distribution, Atterberg limits, organic matter, sulphate content, in order to state the suitability of lime stabilisation, and others tests in order to set up the treatment procedure (lime percent by weight, initial water content, curing time, type and energy of compaction) in order to gain the expected mechanical properties of the improved soil.

When lime is added to soil, two main phenomena take place: the cation exchange and the pozzolanic reactions (Bell 1996). These two mechanisms, referred to as modification and stabilisation of treated soils respectively (Rogers and Glendinning 1996), develop at different interval on the time scale. The

cation exchange between calcium ions and clayey minerals takes place very rapidly inducing the flocculation of the fine-grained fraction. On a macroscopic scale, this structural modification results in a different grain size distribution of the treated soil, characterized by a reduction of the finer fraction. As a further consequence of the cation exchange, the plasticity index of the treated soil is considerably reduced. The development of the pozzolanic reactions, with the formation of stable compounds as hydrated calcium silicates and hydrated alumina silicates, is slower than the cation exchange on the time scale, and it is responsible for the improvement of the mechanical properties of the treated soil (Diamond and Kinter 1965, Sherwood 1993). The considerable increase of shear strength is strongly dependent on curing time (Bell 1996, Croce and Russo 2003a). Otherwise the reduction of the soil compressibility measured after the addition of lime seems to be less influenced by the curing time (Russo and Croce 2001).

The treated soil is compacted and stabilised and both the improvement techniques change the physical state of the natural soil and his mechanical behaviour. Furthermore, the unsaturated state of the treated soil plays a relevant role in affecting his mechanical behaviour. The time dependency of the mechanical improvement of lime stabilised soils represents an additive complexity in the analysis of the effectiveness of this technique. The time scale over which the reactions take place is not well established, and there is not a wide agreement about the exact sequence of the chemical reactions (Boardman et al. 2001). From the practical point of view, it is relevant to appreciate the longevity of lime stabilised soils with respect to the mineralogy of the soil and to the treatment parameters.

Microstructural investigations allow a deeper insight in the complex of phenomena taking place after the addition of lime, as already observed for soils stabilised by cement (Ye 2003). In this perspective, in this paper some results of an experimental analysis on remoulded natural and lime stabilised specimen of an alluvial silty soil are reported. In order to highlight the time-dependency of the microstructure of a lime treated soil, Mercury Intrusion Porosimetry (MIP) on both natural and lime stabilized samples compacted at different initial water content and cured at different times have been performed. Other relevant parameters influencing the effectiveness of lime stabilisation (e.g. type and percent by weight of lime, compaction energy) were fixed in order to reduce the complexity of the data analysis.

2 Experimental Procedures

Laboratory tests were performed on remoulded samples of an alluvial silty soil. The physical characteristics (grain size distribution, specific weight, plastic limit, liquid limit) of the natural soil were determined and standard Proctor tests were performed. Lime treated samples were prepared by hand mixing the oven dried soil with 3% quicklime powder and distilled water, allowing the

quicklime to hydrate for 24 hours. The selected percent by weight of quicklime allowed the development of pozzolanic reactions (Rogers et al. 1997). The samples were then compacted at three different water contents, namely dry of optimum (w_{dry}), optimum (w_{opt}) and wet of optimum (w_{wet}). The initial water contents for samples compacted dry and wet of optimum were selected in order to obtain very similar densities.

Samples were then dehydrated by freeze-drying (Delage and Pellerin 1984), that is rapid freezing in liquid nitrogen (boiling point -196°C) followed by sublimation in a true vacuum. Freezing was accelerated using small pieces of soil (1–2 g in weight). In such condition the 9% volume expansion of the water does not take place, preserving the microstructure of the soil.

The dehydrated lime stabilised samples were cured for fixed time intervals under controlled conditions before performing MIP tests. The repeatability of the procedure was carefully verified performing several MIP test on samples taken from the same specimen. The curing intervals of time selected were $t = 0, 7, 28$ days, traditionally considered in order to evaluate the effectiveness of stabilisation. Only for the optimum stabilised samples curing times of $t = 0, 7, 14, 21, 28$ days were considered. Since the duration of the freeze drying procedure takes about 24 hours, all the time intervals are nominal.

3 Results

3.1 Physical Properties

In Table 1 the main physical characteristics of both natural and lime treated samples are reported. The plasticity of lime stabilised sample has not been reported since the plasticity limit w_{p} was not determinable.

The grain size distribution of both natural and lime stabilised samples is reported in Fig. 1a. The addition of 3% of quicklime changes the grain size distribution, shifting and rotating the distribution towards an increase of the medium-grained fraction of the sample. This change takes place immediately after the addition of lime, as evidenced by the two distributions determined by dry sieving and sedimentation respectively after the addition of lime ($t = 0$ days) and after a curing time of 7 days. The compaction curves of lime-treated samples (Fig. 1b) are shifted with respect to those of natural samples, showing an increase of the optimum water content and a reduction of the

Table 1. Physical properties of the alluvial silty soil

	γ_s [kN/m ³]	w_L [%]	IP [%]	w_{opt} [%]	γ_{dmax} [kN/m ³]
natural	26.4	25.0	8.0	14.5	18.6
3% lime	26.1	24.0	—	17.5	17.3

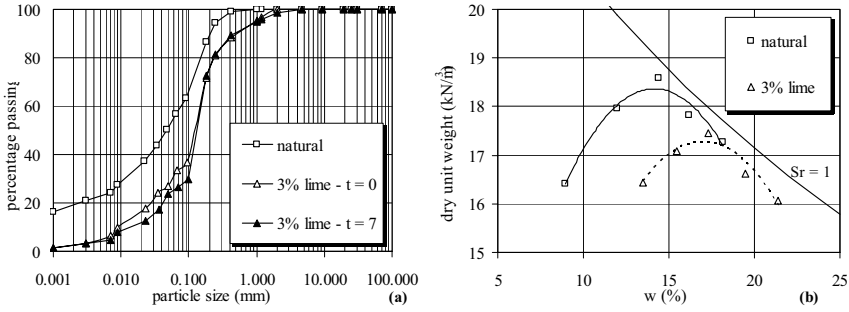


Fig. 1. Grain size distributions (a) and compaction characteristics (b) of natural and stabilized samples

maximum dry weight. The shape of the curve remains unchanged. Stabilised samples show an increase of the optimum water content w_{opt} restricted to 3% with respect to natural samples, while the reduction of maximum dry density is about $1.0 \div 1.3 \text{ kN/m}^3$ after the addition of lime. The latter results are in good agreement with those reported in literature for other fine-grained soils (Croce and Russo 2003b).

3.2 Pore Size Distributions

The influence of initial water content of the natural samples has been firstly investigated. As expected, the cumulative intruded volume of mercury is lower for the optimum water content sample, characterized by the highest density (Fig. 2a). The percent porosity of the sample is about 21.4%. The other two samples show a similar porosity after compaction. The higher frequency of pore size of the sample compacted at optimum water content take place around an average entry values of $1 \mu\text{m}$ (Fig. 2b). The pore size distribution is unimodal. Both dry and wet samples are characterized by higher frequency

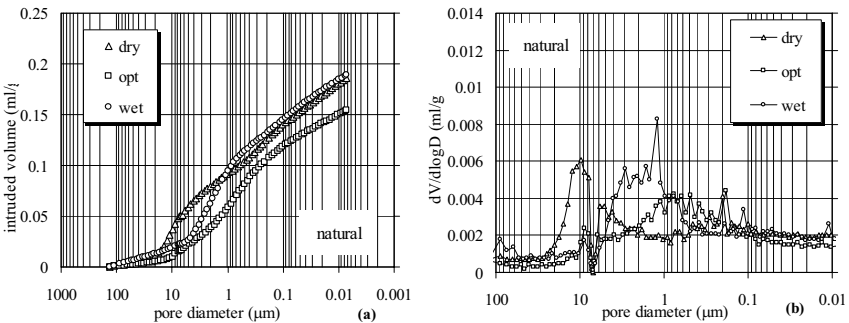


Fig. 2. Cumulative volume intruded (a) and pore size distribution (b) of natural samples

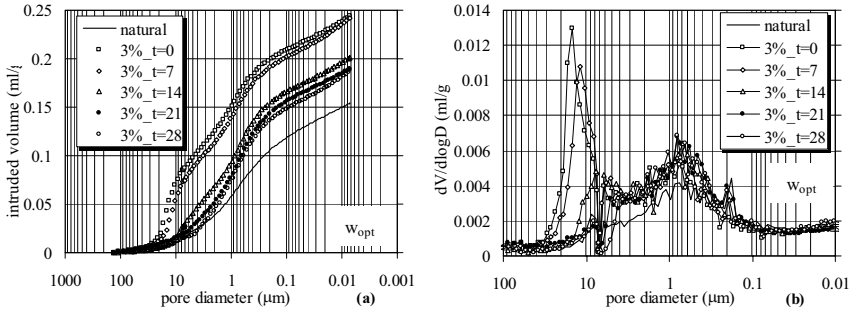


Fig. 3. Cumulative volume intruded (a) and pore size distribution (b) of optimum stabilised samples

of larger pores than the optimum sample. The dry sample show a pore size distribution slightly bimodal. The curves are qualitatively similar to those obtained by Delage et al. (1996) on different soils.

In Figure 3a the cumulative volumes of mercury intruded for the stabilised optimum samples are reported. Each curve corresponds to different curing time of the sample. A relevant increase of the intrusion is shown by the $t = 0$ days stabilised sample, corresponding to an increase of 33% of the natural sample percent porosity. This result is in agreement with the change of the grain size distribution and the shift of the Proctor curve induced by lime. The increase of porosity diminishes gradually for longer curing time, and the sample cured for 28 day shows only a porosity raise of 7% with respect to natural sample. At curing time of $t = 0$ days, the pore size distribution (Fig. 3b) shows a new peak not present in the natural sample curve around average entry values of 15 μm and a slight increase of the porosity contained between 6 and 0.3 μm. This peak disappear at curing time higher than 21 days, while the increase of porosity around 1 μm becomes stable and the curve unimodal again. The intra-aggregate porosity (average entrance entry values smaller than 0.3 μm) seems to be not affected by the addition of lime.

The behaviour shown by the wet stabilised samples is similar to the optimum stabilised samples. The percent porosity at curing time of $t = 0$ is 16% higher than the natural wet sample porosity, and it reduces for longer curing time (Fig. 4a). The pore size distribution becomes bimodal after the addition of lime ($t = 0$), but the new peak detected around 10 μm disappears after a curing time of 7 days, and the curve becomes unimodal again (Fig. 4b). The samples show a distribution characterised by higher frequency of pores contained between 3 μm and 0.3 μm.

Slight differences in cumulative volume of mercury intruded are shown by dry stabilised samples cured for different times (Fig. 5a). Negligible variations of percent porosity are detected in function of the curing time. Dry stabilised samples show a bimodal distribution also after the addition of lime with a reduction in the average entry values from 10 to 3 μm (Fig. 5b). Samples

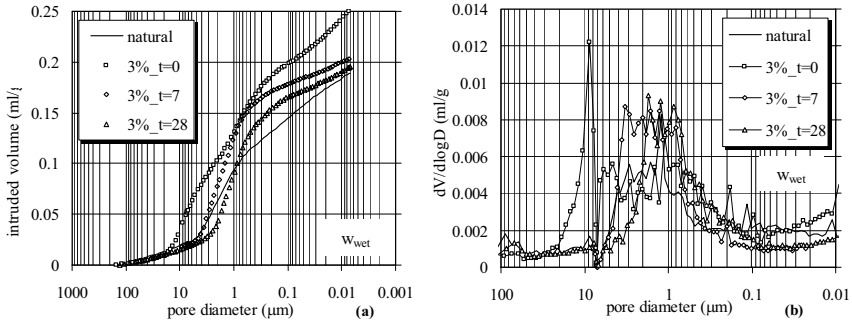


Fig. 4. Cumulative volume intruded (a) and pore size distribution (b) of wet stabilised samples

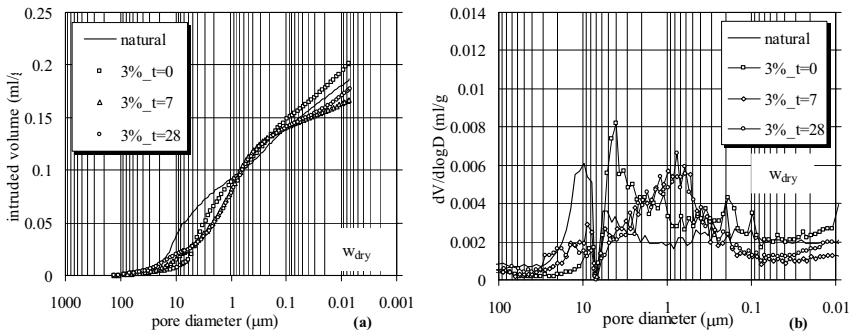


Fig. 5. Cumulative volume intruded (a) and pore size distribution (b) of dry stabilised samples

cured 7 days and more are characterised by a unimodal distribution, with a marked increase of diameters contained between 3 and 0.3 μm .

Variations in porosity induced by lime addition depend on the initial water contents of samples. In order to highlight the time-dependency of this variations, in Fig. 6 the curves representing cumulative volumes of mercury intruded in stabilised samples at different initial water content and equal curing time ($t = 0, 28$) are reported. It can be seen that lime affects the microstructure of the soil immediately after his addition. The more relevant effects are mainly detected in stabilised optimum samples, that show an increase of porosity (Fig. 6a) and, differently from the natural samples, a bimodal distribution of pore sizes (Fig. 6b). The less effective changes, at the same curing time, pertain to dry stabilised samples. Representing the intruded volume of all the three samples (namely dry, optimum and wet) cured for 28 days, a very slight difference in percent porosity (Fig. 6c) and a quite similar distribution of pore sizes (Fig. 6d) can be noted.

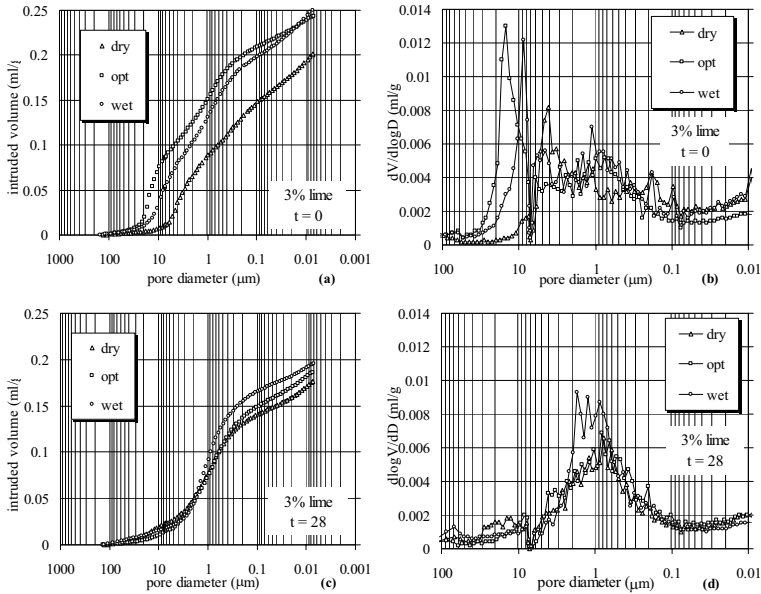


Fig. 6. Cumulative volume intruded (a) and pore size distribution (b) of stabilised samples cured for $t = 0$ and cumulative volume intruded (c) and pore size distribution (d) of stabilised samples cured for $t = 28$

4 Conclusions

A study of the microstructure induced by compaction and lime stabilisation on an alluvial silt was carried out by means of mercury intrusion porosimetry on freeze-dried samples.

The moulding water content plays a relevant role on the microstructure of compacted natural samples. The lesser porosity pertains to samples compacted at optimum water content, in agreement with results reported in literature (Delage et al. 1996) on different soils.

The time-dependency of the stabilised samples microstructure was clearly detected by means of MIP results. Addition of lime mainly affects the inter-aggregate porosity. A relevant modification of porosity for samples stabilised at 3% by weight and compacted at optimum water content of quicklime takes place immediately after the addition of lime. In particular, an increase of pores of relatively large diameter is detected. A subsequent reduction of this effect occurs for longer curing time of the stabilised samples, bringing back the pore size distribution towards the distribution of the natural samples. Similar behaviour is shown by the wet stabilised samples, while the microstructure of dry samples is less affected by the addition of lime. After a curing time of 28 days the stabilised samples show a very similar porosity and pore size distribution, irrespective of the moulding water content.

Cation exchange induced by lime takes place immediately after the addition of lime, producing the flocculation of grains and increasing the porosity of the stabilised sample. This effect is relevant for optimum and wet moulding water contents but decays for longer curing time, probably due to changes of the pH of pore water (Eades and Grim 1966). The similarity of pore size distribution of samples compacted at different water content and cured for 28 days may suggest that the development of pozzolanic reactions and the consequent cementation of the aggregates contributes to reduce porosity induced by flocculation and increases the frequency of pores of small diameters. In the long term, this effect may be more valuable on the microstructure than the moulding water content.

References

- Bell FG (1996) Lime stabilization of clay minerals and soils, *Engineering Geology* 42:223–237
- Boardman DI, Glendinning S, Rogers CDF (2001) Development of stabilisation and solidification in lime-clay mixes, *Géotechnique* 50:533–543
- Croce P, Russo G (2002) Reimpiego dei terreni di scavo mediante stabilizzazione a calce. In: XXI Convegno Nazionale di Geotecnica, L'Aquila, Patron Editore, pp 11–216
- Croce P, Russo G (2003a) Experimental investigation on lime stabilized soils. In: Proc XIII European Conference of Soil Mechanics and Geotechnical Engineering, Prague
- Croce P, Russo G (2003b) Soil-water characteristic curves of lime stabilised soil. In: Vermeer, Schweiger, Karstunen, Cudny (eds) Proc Int Workshop on Geotechnics of Soft Soils – Theory and Practice. Noordwijkerhout
- Delage P, Audiguier M, Cui YJ, Howat MD (1996) Microstructure of a compacted silt, *Canadian Geotechnical Journal* 33:150–158
- Delage P, Pellerin FM (1984) Influence de la lyophilisation sur la structure d'une argile sensible du Québec, *Clay Minerals* 19:151–160
- Diamond S, Kinter EB (1965) Mechanisms of soil-lime stabilization: an interpretative review, *Highway Research Record* 92:83–96
- Eades JL, Grim RE (1966) A quick test to determine lime requirements of lime stabilization, *Highway Research Record* 139:61–72
- Rogers CDF, Glendinning S (1996) Modification of clay soils using lime. In: Rogers CDF, Glendinning S, Dixon N (eds) Lime Stabilisation, Thomas Telford, London, pp 99–114
- Rogers CDF, Glendinning S, Roff TEJ (1997) Modification of clay soils for construction expediency, *Geotechnical Engineering* 125:1–8
- Russo G, Croce P (2001) Indagini sperimentali sui terreni stabilizzati a calce. In: Incontro Annuale dei Ricercatori di Geotecnica – IARG 2001, Milano
- Sherwood PT (1993) Soil stabilization with Cement and Lime: State-of-Art Review. HMSO, London
- Ye G (2003) Experimental study and numerical simulation of the development of the microstructure and permeability of cementitious materials. Ph.D. thesis, Delft University