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Effects of stabilization on the behaviour of Finnish sensitive soils

Effets de la stabilisation sur le comportement des sols sensibles Finlandais

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ABSTRACT: The proposed note presents the results of an experimental activity aiming at studying the hydraulic and mechanical behaviour of a Finnish sensitive soil treated by fly ash and lime. A laboratory testing program was carried out both on treated and untreated soil; soil-binders samples were prepared by wet mixing of the components and by Standard Proctor compaction. Hydraulic conductivity tests were carried out in flexible wall permeameters; the compressibility was studied by incremental load oedometric tests. The results have shown a general increase of the hydraulic conductivity and a significant reduction in compressibility after binders addition; the extent of modification of soil properties was observed to depend upon the compaction water content of the soil. The soil treatment is generally economically convenient if compared to disposal in waste landfills, which would represent the only alternative for the soil type of concern. In addition, if a by-product such as fly-ash is able to act as effective binder in the mixture, this surely constitutes a promising perspective in terms of sustainability in the field of earthen structures.

RÉSUMÉ: La note proposée présente les résultats d'une activité expérimentale visant à étudier le comportement hydraulique et mécanique d'un sol finlandais sensible traité aux cendres volantes et à la chaux. Un programme d'essais en laboratoire a été réalisé sur du sol traité et non traité. Les échantillons de sol modifié aux liants ont été préparés par mélange humide des composants et compactage Standard Proctor. Les tests de conductivité hydraulique ont été réalisés avec des perméamètres à parois flexibles; la compressibilité a été étudiée par des essais oedométriques à charges incrémentales. Les résultats ont montré une augmentation générale de la conductivité hydraulique et une réduction significative de la compressibilité après l'ajout de liants; les degré de modification des propriétés du sol a été différent en fonction de la teneur initiale en eau du sol. Généralement, le traitement du sol est économiquement avantageux par rapport à la mise en décharge, qui représenterait la seule solution alternative pour le type de sol concerné. De plus, si un sous-produit tel que la cendre volante est capable d'agir comme liant efficace dans le mélange, cela constitue sûrement une perspective prometteuse en termes de soutenabilité dans le domaine des constructions en terre.

Keywords: Soil reuse; sensitive soils; stabilization.

1 INTRODUCTION

Fostered by the objectives of the recent European Green Deal, global societies share the target of implementing reuse practices and search for innovative technical solutions to reduce overall waste generation thus limiting landfilling and carbon emissions. Environmental geotechnics, in particular the field of ground improvement techniques, can surely contribute to reach these goals allowing for the reuse of treated excavated soils in earthen structures.

Several studies (e.g. Blengini et al., 2010) indicate that the re-use of excavated soils and rocks saves up to 14 kg CO_2 per ton and 250 MJ/ton of non-renewable energy as transport, landfilling and collection from quarries are reduced. Soil stabilization allows for the reuse of excavated soil by treating it with different additives. If the binder used in the mixture is a by-product from industrial processes, this will additionally contribute to the sustainability goal.

1.1 Soil stabilization by lime

Lime is nowadays commonly used as binder for clayey soil stabilization. In addition to the need of extracting limestone for lime production, the process itself causes the emission of 1006.5 kg CO_2/ton of lime (Zhang et al., 2019). On the other hand, its potentiality is well known and testing standards and construction procedures have been fully finalized (e.g., Di Sante et al., 2014; Beetham et al., 2014).

When treating a clayey soil with lime, cation exchange reaction firstly develops (and consequent aggregation of clayey particles) and then lime reacts with silica and alumina producing long-term pozzolanic products (reaction fostered by high pH environment).

The treatment improves the mechanical characteristics of a soil (increase in strength and reduction in compressibility), whereas, hydraulic conductivity usually increases taking into account the compaction water content effect (Bhattacharia et al, 2003; Bellezza et al.,2006; Di Sante et al., 2016).

1.2 By-products for soil stabilization

Developing a strategy to employ production scraps as binding agents for soil stabilization unquestionably constitutes a significant stride within the context of sustainable methodologies. By-products currently studied for soil stabilization include rice husk ash, mushroom waste, wet olive pomace, marble powder, ground granulated blast furnace slag or fly ash (Devi et al., 2020). The latter develops cementitious products if alkali activated with hydroxides acting as strong bases in the soil-binders-water system (Costa et al., 2023). The high alkaline environment fosters the dissolution of silicates and aluminates coming both from the ash and from the clay fraction of the soil, thus cementation reactions.

1.3 Soft sensitive soils

Soft sensitive clays can be found in the coastal areas of Scandinavia, as well as in some part of North America and Asia. The high compressibility, low undrained shear strength and high sensitivity shown by these soils make the geotechnical design often rather challenging. The degree of sensitivity is expressed by the ratio between the undrained shear strength of an undisturbed specimen and the strength of the same specimen at the same water content but in a remoulded condition (Torrance, 1974; Rosenqvuist, 1953; Bjerrum, 1954). The essential factors for development of high sensitivities can be divided into depositional and post-depositional factors (Torrance 1974). Of depositional factors most important is inter-particle flocculation, which is necessary to create open structure high water content sediments. Most of these clays are deposited in marine to brackish environment, where the ions in salty water reduce the repulsive forces between the soil particles allowing flocculation. In fresh water similar response may be due to sufficiently high concentrates of calcium. Out of post depositional factors the one having most impact is leaching. When the salinity decreases the open structure remains, but repulsive forces between the soil particles increase, reducing the liquid limit and remolded shear strength. Such high sensitivity clays with a remoulded shear strength below 0.5 kPa are often classified as quick clays.

Soft sensitive clay deposits are mainly located along the coastal regions of southern Finland. Inland, various local conditions manifest, such as the presence of intermediate soils like clayey silt or silt. While these soils might arise from similar geological processes, they exhibit distinct mechanical behaviors and mineral compositions.

In the present note, experimental results on soil-lime-fly ash mixtures are presented, focusing on hydraulic conductivity and compressibility. Results are discussed also in comparison with those of the untreated compacted soil. The present work is the result of an established research cooperation between Università Politecnica delle Marche, Ancona – Italy and Tampere University, Tampere – Finland.

2 MATERIALS AND TEST METHODS

2.1 Materials

The studied soil is a clayey silt of low plasticity, characterized by a medium-high sensitivity (Sensitivity index=31.4 - Rankka et al., 2004) taken from the Kouvola site in the southern part of Finland, 135 km east of Helsinki. It is worth highlighting that the remoulded strength of the soil is equal to5 kPa, higher than the usual values registered for sensitive clays (<1 kPa). Soil characteristics are summarized in Table 1.

Table 1. Soil properties(ICL=Initial Consumption of ime).

Property	Value	STANDARD
sand (%)	22	ASTM D422-63(07)
fine (%)	78	ASTM D422-63(07)
clay (<2μm,%)	24	ASTM D422-63(07)
Liquid Limit (%)	28	CEN ISO/TS17892-12
Plasticity Index (%)	16	ASTM D4318-05
ICL - %CaO	3	ASTM C977-00
CEC (meq/100g)	8.6	CUR n.33 EUBA2002
Specific surf. (m^2/g)	77	CUR n.33 EUBA2002

The X-Ray diffraction spectrum (Philips diffractometer, PW1730 X-ray generator, PW 1050/70 goniometer and CuK radiation) is displayed in Figure 1: the main mineralogical components include Quartz, Albite, Muscovite, Chlinochlore (chlorite group), Amphibole and Sanidine (potassium Feldspar).

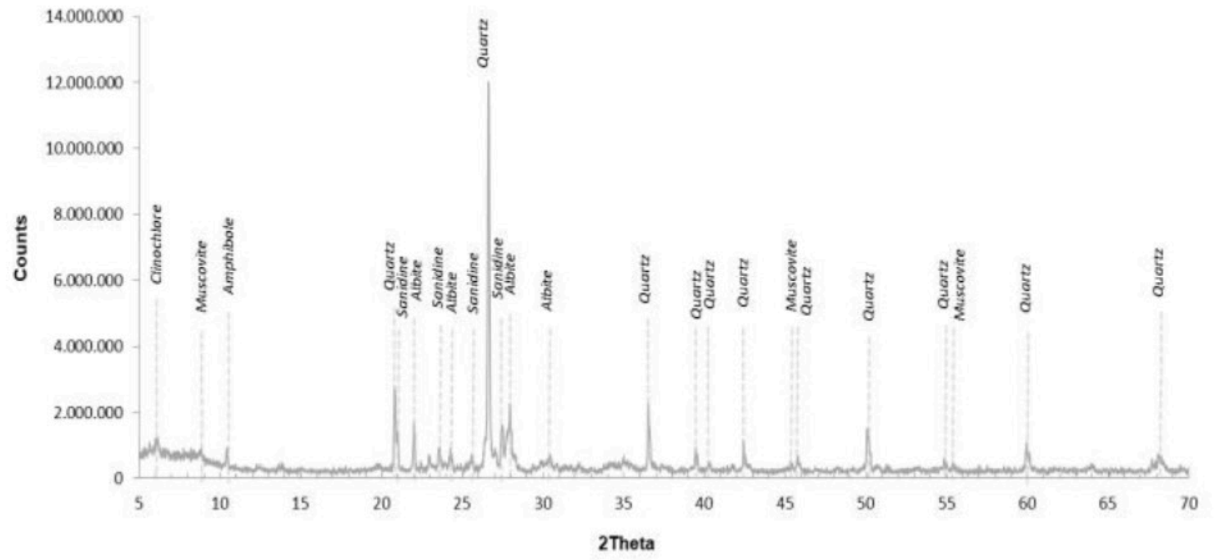

Figure 1. X-Ray diffraction spectrum of the soil.

The amounts of sulphate and organic matter are 0.01% and 1.31% by dry mass of soil, respectively. The studied soil fully matches the requirements for the suitability for lime treatment.

The lime used (QL) is a fine calcic quicklime, classified as CL80-Q dp (UNI EN 459-1).

The Fly Ash (FA) is a high pozzolanic fly ash (supplied by General Admixtures SpA). Its unit weight is 2200 kg/m^3. Microstructural and chemical investigation was performed on the FA by means of SEM observations and Energy Dispersive X-Ray Spectroscopy, EDS (FESEMSUPRA40–ZEISS), after air dewatering of samples and their gilding (by an Emitech K550 sputter coater). SEM image of spheroidal particles of the FA is displayed in Figure 2. EDS highlighted the presence of 45% Silicon, 23% Aluminum, 10% Iron, 10% Calcium, 4% Potassium and 7% other components (% by weight, excluding Oxygen).

The X-Ray diffraction spectrum highlights the presence of silicon dioxide (quartz), calcium oxide and mullite ($Al_{4.56}\,Si_{1.44}\,O_{9.72}$) as main components.

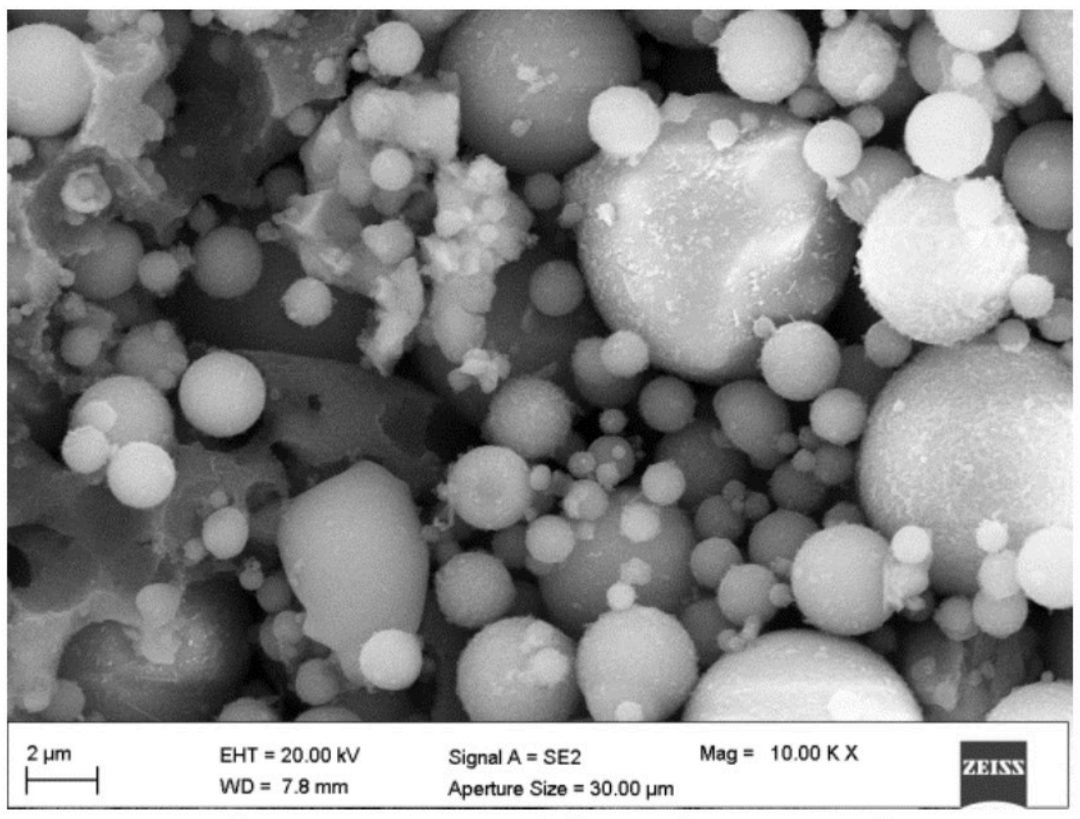

Figure 2. SEM images of the FA (Magnification:2000x).

2.2 Test methods

All the specimens for the laboratory geotechnical tests were prepared by crumbling the air dried soil (to 2 mm in size), adding the amount of water necessary to reach the desired moisture content, then mixing binders and soil at the wet state (as usually done in the field) until a uniform distribution was achieved. The only exception was done for the soil at w_{Nat}, for which lime was added "as is". The soil mixtures was then compacted according to the Standard Proctor procedure (ASTM D698-12) in one layer, obtaining samples of 101 mm in diameter and 40 mm in height. The samples were then cured in sealed plastic containers at a temperature of 20±1°C.

One-dimensional incremental load consolidation tests (ASTM D24345-11) were performed on specimens after 7 days of curing.

Permeability tests (ASTM D5084-10) were carried out in flexible walls permeameters at 35 kPa of effective confining stress with tap water as permeant. The tests on the treated specimens were carried out for 20 days of curing.

Also pH trend with time is monitored by daily measuring pH in the slurry of the mixture of concern (20g of dry soil+2%FA+2%QL+100ml of distilled water).

3 RESULTS AND DISCUSSION

In order to set the mix design for the experimental program, being the ICL value equal to 3% by dry weight of soil (Table 1) and given that ICL+1-2% is usually the promising value to be tested in lab phase of lime stabilization studies, a total amount of 4% of binders was fixed. Aim of the present research work is to test the efficacy of the use of by products as binders for soil stabilization. For this reason soil was treated with 2% of FA combined with 2% of QL. The latter has the double function of acting both as a stabilizer and as activator of the FA.

The first important experimental results is that the soil lost its sensitive behaviour once treated.

3.1 Compaction

Compaction curves of the untreated soil and of soil treated with binders are shown in Figure 3.

Binders addition slightly reduces the optimum water content from 20% to 19%. In Figure 3 it is possible to identify in 14-23% the range of water contents able to guarantee a sufficiently high dry unit weight (considered higher than 95% of the γ_{dmax}, as reported in most of technical specifications for construction works).

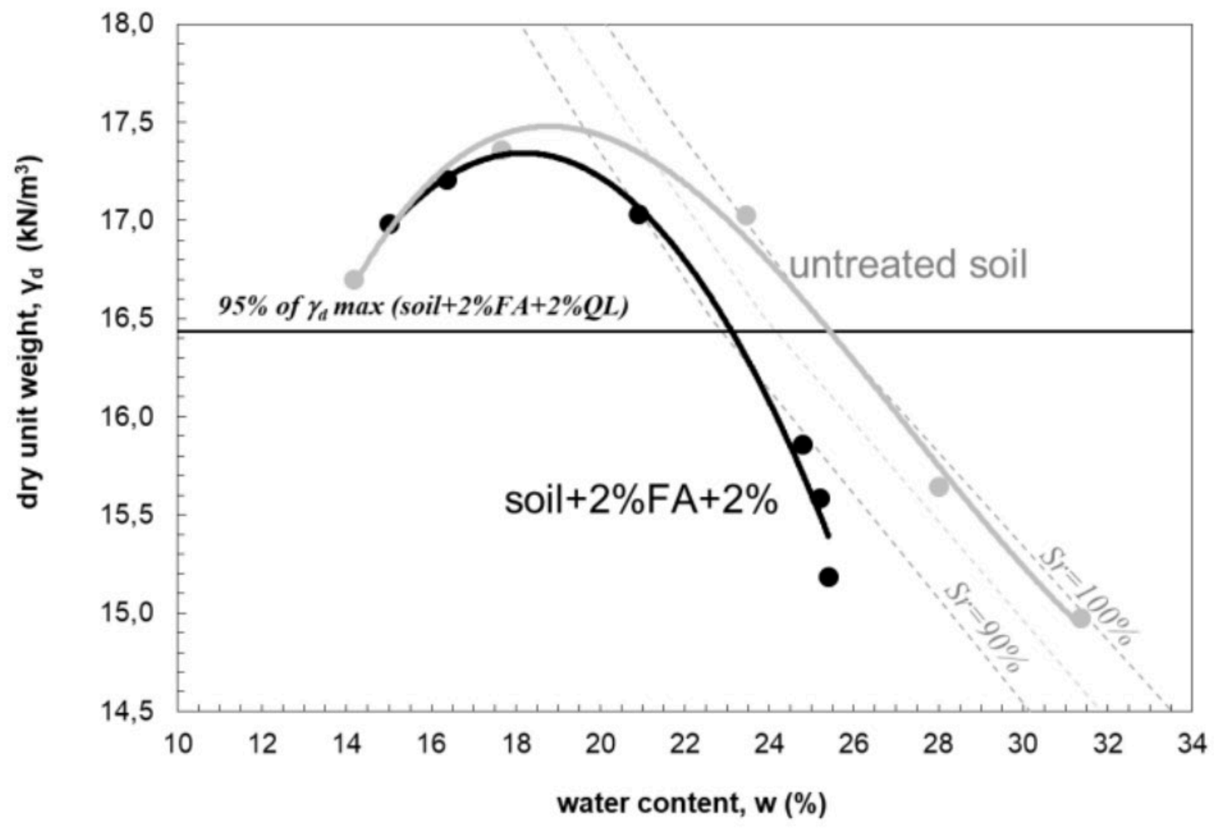

Figure 3. Proctor compaction curves of treated and untreated soil.

It is worth noticing that binder addition systematically reduces of 2-4 percent points the water content mainly due to CaO hydration process (oxide coming from both QL and FA).

3.2 Compressibility

Figure 4 shows the results of the one-dimensional compression tests performed starting from 7 days of curing on specimens of soil-FA-QL mixtures and of untreated soil, both compacted at w_{Nat}.

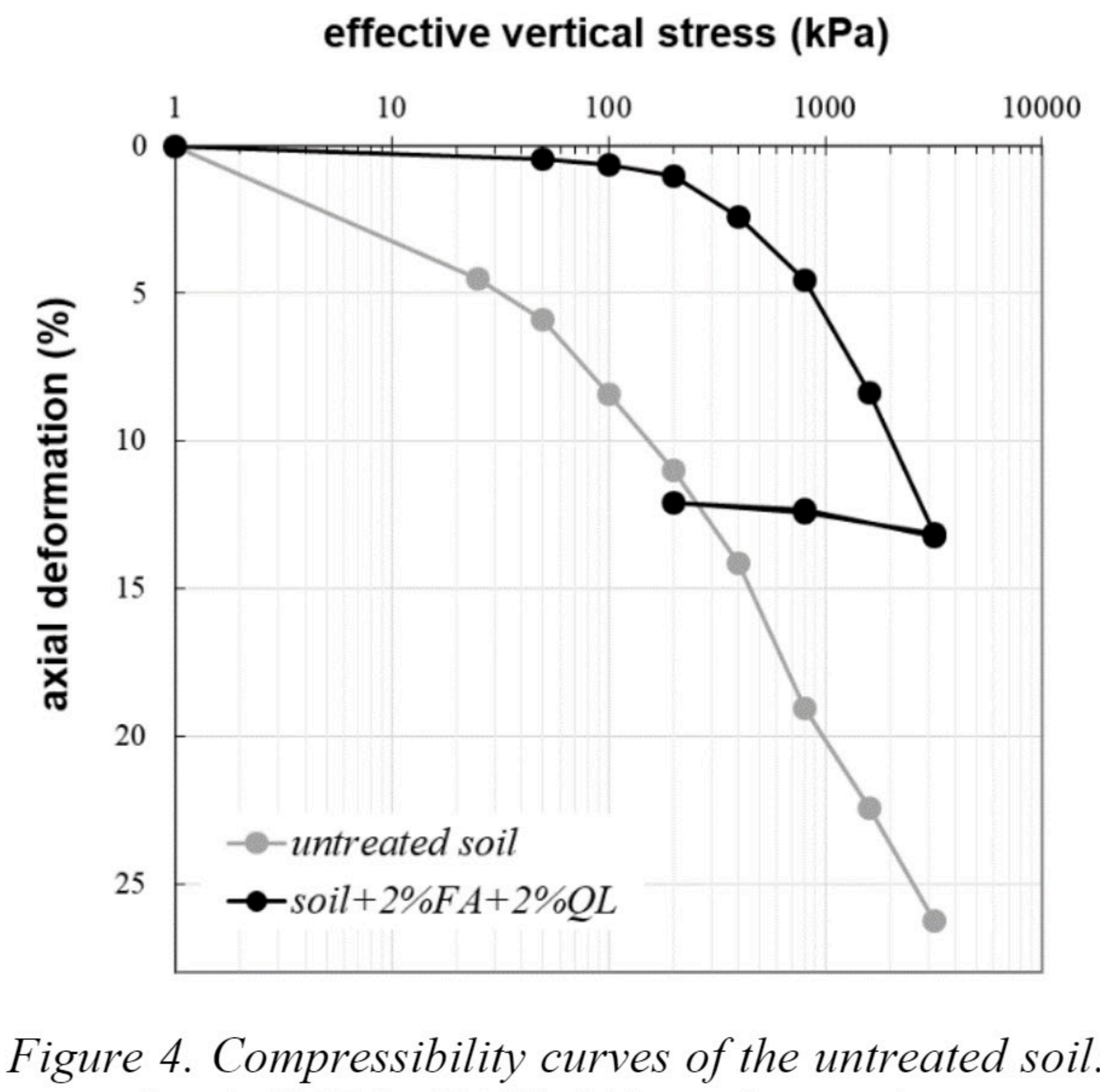

Figure 4. Compressibility curves of the untreated soil: and treated with 2%FA+2%QL (7days of curing).

The significant reduction in compressibility caused by binders addition is evident. In particular, at the range of 50-100 kPa of effective vertical stress (typical values for designing of earthworks, e.g. road embankments) axial deformation of the treated specimen is almost 10 times lower than that of the untreated compacted soil (8% deformation at 100kPa). When the vertical confining stress is increased, the untreated soil showed a maximum axial deformation of 26% that is reduced to 13% after FA+QL addition. The yield stress of the treated soil is 200 kPa while it is not possible to identify any yeld stress for the untreated compacted soil.

3.3 Hydraulic conductivity

Hydraulic conductivity values, k, are shown in Figure 5 as a function of the curing time. An increase in k values due to binders addition is evident when comparing data for treated and untreated soil compacted at w_{Nat} (grey and black circles in Figure 5). This increase is probably due to the aggregation of clay particles after cation exchange reaction. For the sample compacted at w=18% (w=15% after binder addition) k values (blak diamonds in Figure 5) are 2 order of magnitude higher than those of the treated sample compacted at w_{Nat}.

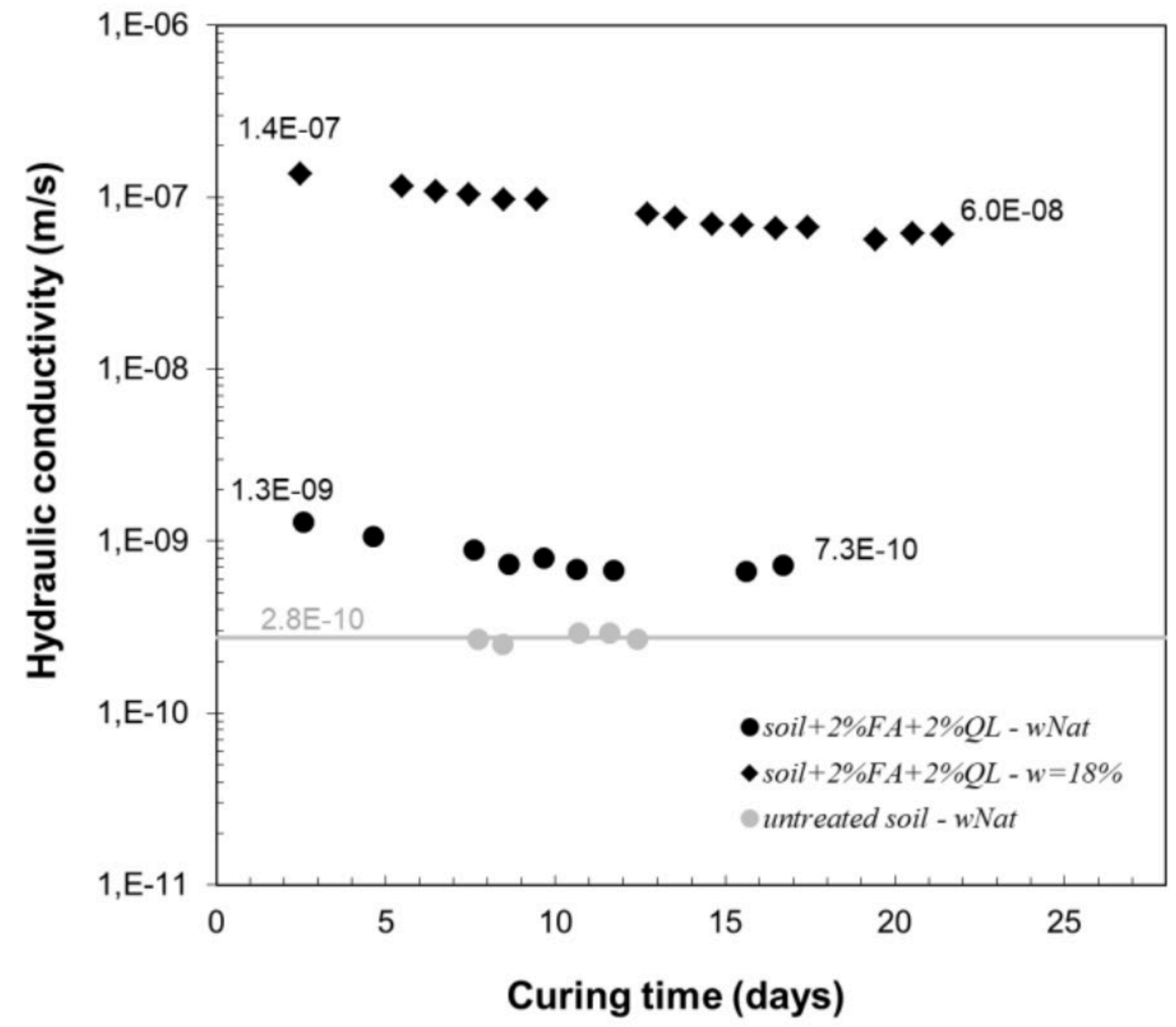

Figure 5. Hydraulic conductivity of treated and untreated compacted samples.

In addition, the treated samples show significant decreasing trend with curing (k values attained after 14 days of curing is half of the initial k). This trend is typically caused by gel form of pozzolanic products that partially fill the inter-aggregate porosity resulting from cation exchange (Beetham et al., 2014). Pozzolanic products are formed due to both hydration of fly ash and reaction of calcium ions supplied by lime and silicates and aluminates from clay fraction of the soil.

Measurements of pH of slurry of the mixture soil+2%FA+2%QL (Figure 6) corroborates this findings showing a continuously decreasing trend. In fact, in pozzolanic reactions, each calcium ion reacting with SiO_2 links 2 hydroxil ions thus causing the decrease in pH values.

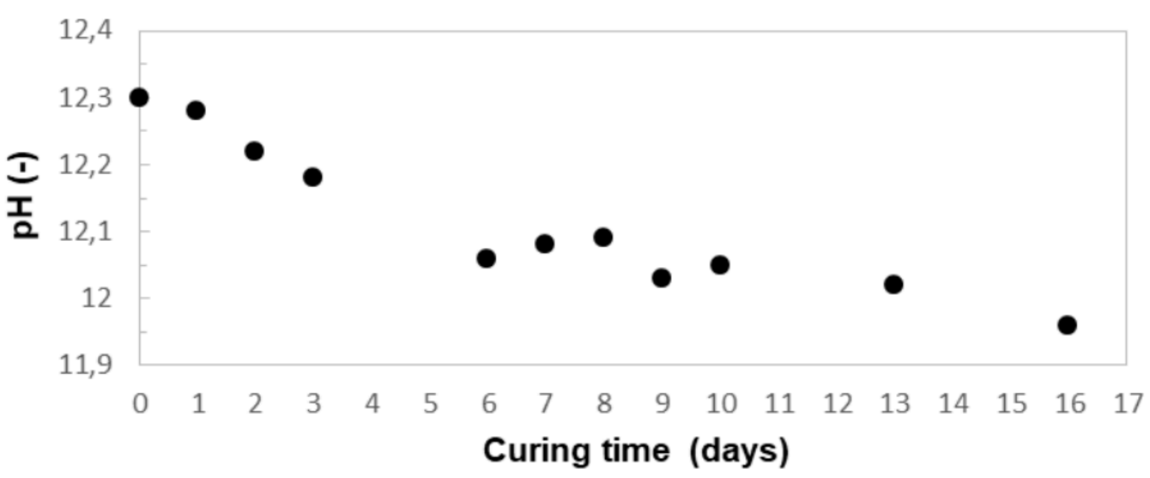

Figure 6. pH values - slurry of soil+2%FA+2%QL.

4 CONCLUSIONS

The combined use of fly ash and lime demonstrated to be a sustainable solution for the stabilization of the Finnish soil of concern. In particular, for the considered soil-fly ash-lime mixture, a general increase in hydraulic conductivity due to the addition of binders is observed. Permeability turns out to be very sensitive to a reduction in water content showing an increase of 2 orders of magnitude. Pozzolanic reaction development contributes to reduce the permeability in the long term (within 1 order of magnitude). Compressibility is significantly reduced 7 days after the treatment.

The soil treatment is generally economically convenient if compared to disposal in waste landfills, which would represent the only alternative for the soil type of concern. In addition, if a by-product such as fly-ash is able to act as effective binder in the mixture, this surely constitutes a promising perspective in terms of sustainability in the field of earthen structures.

The present work represent a preliminary feasibility study that should be completed with micro-structural investigation, strength tests and an in-situ test-pad.

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