Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1801

Compaction characteristics and hydraulic conductivity of a sandy silt treated with sustainable binders

Marta Di Sante
SIMAU Department, Università Politecnica delle Marche, Ancona, Italy, m.disante@univpm.it

Ivo Bellezza, Luca Calò, Evelina Fratalocchi, Marta Grazi, M. Khizar Khan, Francesco Mazzieri
SIMAU Department, Università Politecnica delle Marche, Ancona, Italy

ABSTRACT: In the framework of a research project financed by Next Generation EU Programme with the Italian Ministry of University and Research (currently ongoing at Università Politecnica delle Marche) related to the possibility of using sustainable binders in soil stabilization, the present note explores the possibility to treat a sandy soil with fly ash activated in an alkaline environment. With this approach two types of waste can be reused: the excavated soil, that otherwise should be disposed, and the by-product (fly ash) used as binder in the stabilization process. Physico–chemical and mineralogical characterization of the soil and the binder were carried out by X-Ray diffraction, SEM observations and Energy Dispersive X-Ray Spectroscopy. The soil was mixed with 2% fly ash activated with 2% calcium hydroxide from quicklime and the mixture was compacted at different moisture contents. Hydraulic conductivity tests were carried out on samples compacted dry and wet of optimum investigating also the long-term hydraulic behaviour. The experimental results are compared with those of the untreated soil compacted with the same energy, to evaluate the effect of the binder addition. Results show very small variation of the compaction characteristic and a reduction of the hydraulic conductivity of the soil-binder mixtures when compacted wet of optimum. Hydraulic conductivity values of the mixtures always reduces with curing time due to gel form pozzolanic products.

KEYWORDS: soil stabilization, fly ash, lime, hydraulic conductivity, compaction.

1 INTRODUCTION

According to the 2030 Agenda of the European Green Deal, global societies share the target of implementing reuse practices and search for sustainable technical solutions to reduce waste generation thus limiting waste landfilling and carbon emissions. The practice of reusing soil through chemical stabilization by binders (lime or cement, e.g. Beetham et al., 2014; Consoli et al., 2012) is nowadays well-known and diffusely applied. It offers environmental and economic advantages because there is no need of both soil disposal and extraction of suitable soil from quarries. The use of residues or by-products as stabilizers add sustainability to stabilization practice.

Soils treated with fly ash, ground granulated blast furnace slag, marble powder, mushroom waste, rice husk ash, or wet olive pomace are recent subject of environmental geotechnics. All these residues can enhance the mechanical properties of soils, although occasionally their benefits are undermined by adverse impacts (e.g., Devi et al., 2020).

"INSSPIRED SOULS" is a research project financed by Next Generation EU Programme with the Italian Ministry of University and Research that explores the possibility of using sustainable binders, such as fly ash, marble dust and eggshell lime, in soil stabilization. In this framework, the present contribution focuses on fly ash stabilization of a sandy soil using calcium oxide as activator.

1.1 *Fly ash in soil stabilization*

More than 350 Million tons/year of fly ash are worldwide yearly produced, with India, China and USA as major producers; the contribution of European countries is also significant, accounting for nearly 40 million tons/year. To date, only 50% of the worldwide produced fly ash is currently reused (Gollakota et al., 2019), while the remaining half is disposed, posing both environmental and sanitary issues. Exploring viable options to reuse fly ash can help solving these issues by assessing its stabilization capability (Noaman et al., 2022).

Fly ash can be used alone or in conjunction with other binders for soil stabilization, either as is or after activation. For example, Najafi et al. (2021) synthesized clay–fly ash geopolymer to improve the adsorption capacity of a clay, while Fujikawa et al. (2023) investigated the feasibility of recycling coal fly ash in mixed materials, looking into the durability and leaching properties of fly ash-cement-water mixtures.

As widely known, fly ash has pozzolanic properties that needs to be activated in an alkaline environment in order to enhance its stabilization capability. Activators are usually strong bases, as hydroxides (Huang et al., 2021; Khatka, et al., 2018; Costa et al., 2023). When using class F fly ash (which is very rich in silicon and aluminum) an activator rich in calcium, such as lime, is one of the best options for the system efficiency (Kampala & Horpibulsuk, 2013; Palomo et al., 2014). The aim of the present note is to contribute to the findings about the use of fly ash in soil stabilization. Results obtained on soil-fly ash-lime mixtures are specifically shown, with an emphasis on compaction characteristics and long-term hydraulic conductivity, highlighting the effects of binder addition.

2 MATERIALS AND METHODS

2.1 *Materials*

The soil used in the present study is a silty sand (MS according to USCS), suitable for traditional lime treatment (grain size distribution and plasticity index as per UNI EN 14227-11; Italian Standard CNR, 1972). Table 1 summarizes the soil characteristics.

The lime is a fine calcic quicklime (QL) classified as CL80-Q dp (UNI EN 459-1), completely passing through the ASTM 200 sieve (75 μm sieve opening).

Table 1. Characteristics of the tested soil

Characteristic	Value	Unit
Sand	63	%
Fine	37	%
Clay (<2µm)	8	%
Liquid Limit	18	%
Plastic Limit	-	%

The Fly Ash (FA), supplied by General Admixtures S.p.A, is a class F, high pozzolanic fly ash, consisting of 45% Silicon, 23% Aluminum, 10% Iron, 10% Calcium, 4% Potassium and 7% other components (% by weight, excluding Oxygen); its specific gravity is 2.20. The chemical composition was determined by Energy Dispersive X-Ray Spectroscopy, EDS (FESEMSUPRA40–ZEISS), after air dewatering of samples and their gilding (by an Emitech K550 sputter coater). Microstructure was observed by Scanning Electron Microscope (SEM) as displayed in Figure 1. The fly ash of concern is composed by spherical particles of diameters within the interval 0.35-61 µm (data retrieved by analyzing several SEM measurements). The main mineralogical components were identified through X-Ray diffraction (Philips diffractometer, PW1730 X-ray generator, PW 1050/70 goniometer and CuK radiation): they are quartz (SiO_2), calcium oxide (CaO) and mullite ($Al_{4.56}Si_{1.44}O_{9.72}$).

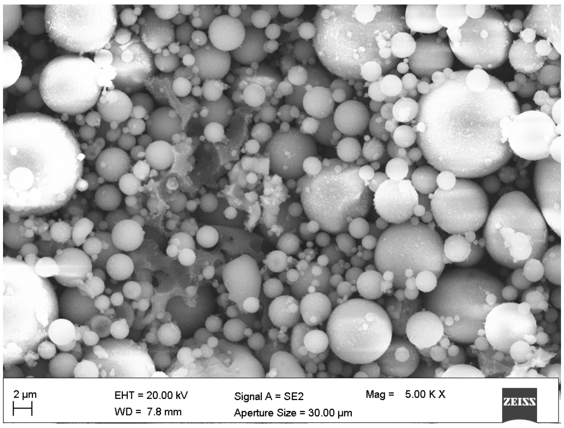

Figure 1. SEM image of fly ash.

2.2 *Methods*

To prepare each sample, the air-dried soil was crumbled to a size of 2 mm, water was then added to provide the required moisture content. Finally fly ash and lime, previously mixed together at the dry state, were thoroughly mixed with the wet soil until a uniform distribution was achieved. Mixtures were prepared adding 2% FA and 2% QL by dry weight of soil, for a total binder amount equal to 4%.

The Standard Proctor method (ASTM D698-12) was used to compact the soil-binder mixture. The samples (diameter = 10 cm and height = 11.65 cm) were cured in airtight plastic containers at a controlled temperature until testing.

Falling-head hydraulic conductivity tests (ASTM D5084-10) were carried out on samples after 1 day since compaction in flexible walls permeameters at 35 kPa of effective confining stress with tap water as the permeant. Saturation was done in steps (few hours in all, at 5 kPa of effective stress) before 24 hours consolidation at 30 kPa of effective confining pressure (back pressure=290kPa). Therefore, samples permeation started at the second day of curing; continuous permeation was imposed until, at least, 28 days of curing.

3 EXPERIMENTAL RESULTS

3.1 *Compaction characteristics*

Compaction curves are shown in Figure 2. An increase from 14 to 15% in the optimum water content, w_{opt}, for the mixtures soil+2%FA+2%QL is observed if compared with the untreated soil. With reference to the maximum dry unit weight, a slight increase can be noticed after binders addition (Table 2). No flattening of the Proctor curve, typical of traditional lime treatment, can be observed after FA and QL addition.

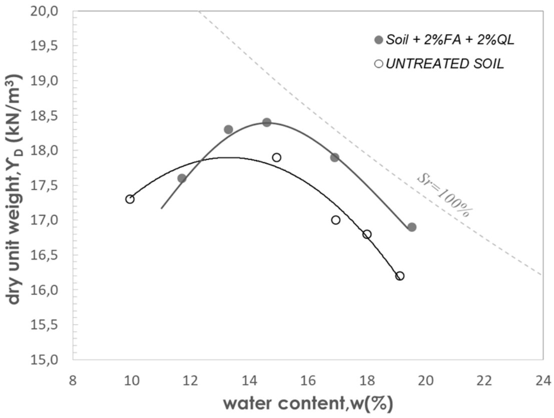

Figure 2. Proctor compaction curves of treated and untreated soil

Table 2. Compaction characteristics of treated and untreated soil

	Optimum w (%)	Maximum dry unit weight (kN/m^3)
Soil + 2%FA + 2%QL	15	18.4
Untreated soil	14	17.9

After mixing with binders there is a systematic reduction of the water content (Figure 3), equal to 1.2 % on average. This reduction is related to the presence of the quicklime that both undergoes exothermic hydration and hydrates.

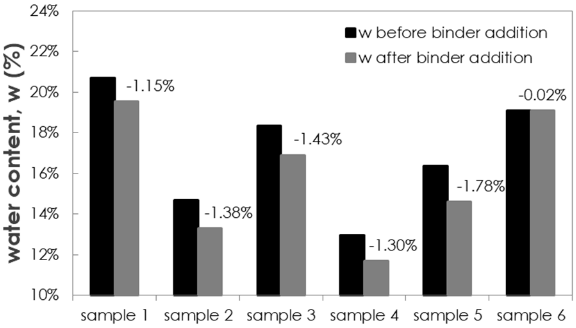

Figure 3. Reduction of moisture water content after binder addition

3.2 *Hydraulic conductivity*

Given that the compaction water content, w, is one of the main factors affecting the hydraulic conductivity, k, of compacted soil and soil-mixtures (e.g. Daniel & Benson, 1991; Di Sante et al., 2016), k tests were carried out on samples prepared at different water contents, in the range from 11% to 20% (dry and wet of optimum).

Figure 4 shows the hydraulic conductivity values measured from 2 to 80 days of curing on the treated sample compacted at w = 13.3% (dry of optimum). It is worth noticing that most of measurements were repeated almost daily. A progressive decrease in the hydraulic conductivity occurs with curing time; in particular, 3 reduction phases can be identified:

- a first phase, within the first 2 weeks of curing, in which a significant reduction of k occurs, halving the initial k value from about $4\cdot10^{-7}$ to $2\cdot10^{-7}$ m/s;
- a second phase that lasts until about 45-50 days of curing in which the k reduction continues but at a slower rate, approaching k value of $6\cdot10^{-8}$ m/s
- a third phase with no significant reduction.

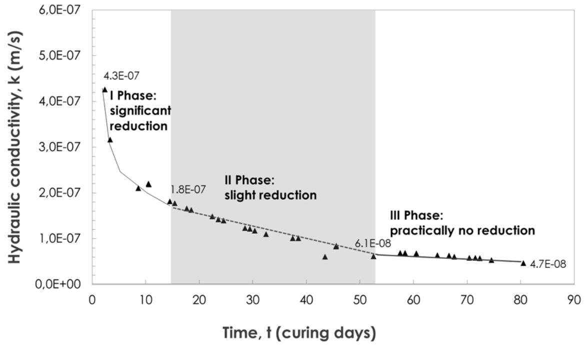

Figure 4. Permeability trend with curing time, w=13.3%.

The trend of the k values for the samples compacted at different moisture contents, w, is displayed in Figure 5 focusing on the first 50 days of curing (k values are displayed in log scale for a comprehensive visualization). It is evident that there is a progressive decrease in hydraulic conductivity with curing time, regardless of the compaction water content. Also for the water content wet of optimum, a major decrease occurs within the first 2 weeks of curing (the same as in Figure 4) and, after that period of time, k values continued to decrease at a lower rate. For this reason, the long-term hydraulic conductivity k_{LT}, was calculated as the mean value considering the k measurements taken after 15 days of curing.

For all the tested mixtures the reduction is within one order of magnitude, with the exception of the mixture compacted slightly wet of optimum (w = 16.9%), for which the decrease is higher (from $1\cdot10^{-8}$ to $8\cdot10^{-10}$ m/s). This decrease in the long term is linked to the formation of amorphous pozzolanic products that fill the soil pores (e.g. Beetham et al., 2014; Wild, 1987); pozzolanic products arose from the reaction between calcium from lime and the silica and alumina coming mainly from the FA and also from the clay fraction of soil.

As observed for a clayey soils treated with the same combination of binders (Di Sante et al., 2025), in the majority of cases the reduction trend is well fitted (R^2 =0.92-0.99, Figure 5) by the power law:

$$k = A \cdot k_2 \frac{1}{\sqrt{t/t_{REF}}} \tag{1}$$

where t is the time variable in days, t_{ref} is the reference time of 1 day, k_2 is the value of k measured at 2 days of curing and A is a numeric coefficient that depend on the compaction moisture content, w. In particular, A = 2.5 at w_{opt} and A =1.5 in dry and wet of optimum conditions.

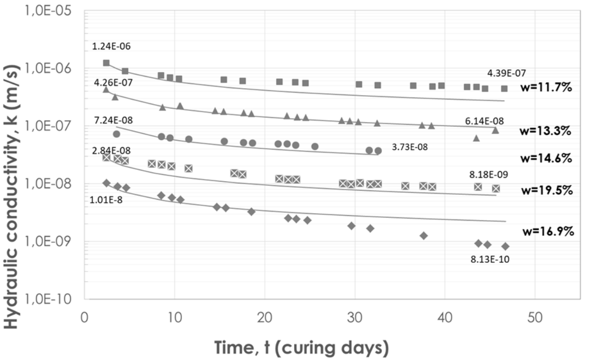

Figure 5. Hydraulic conductivity values with curing time, for different compaction moisture contents, w.

By observing the variation of the long term hydraulic conductivity coefficient, k_{LT}, of the soil+2%FA+2%QL with compaction moisture content (Figure 6), it is possible to state that the higher the compaction moisture content, the lower the k value in the long term; in particular, k progressively reduces from $5\cdot10^{-7}$ m/s to the value of $2\cdot10^{-9}$ m/s, in slightly wet of optimum conditions.

The sample compacted at the highest water content (w=19.5%, wet of optimum) showed a k coefficient higher than one order of magnitude if compared to that of the sample compacted in slightly wet conditions (16.9%). As observable from Figure 5, this difference is not very marked at two days of curing but the hydraulic conductivity of the sample compacted at w=16.9% is more affected by curing time, reducing to a greater extent than that of the other samples and not reaching a constant k value until 50 days. This suggests that, probably, in this sample, the pozzolanic products developed to a bigger extent and for a longer time. Further data at longer curing times and microstructure analysis are needed to investigate this occurrence.

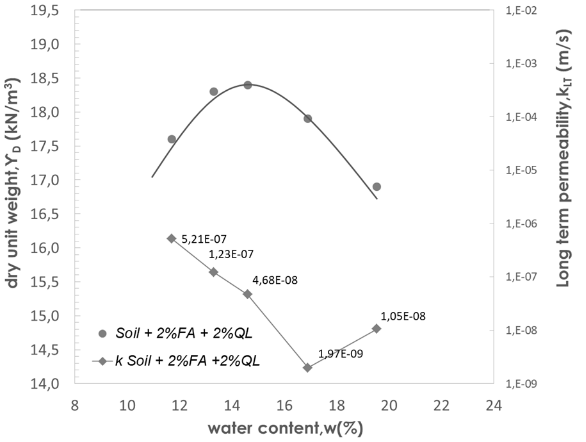

Figure 6. Long term permeability values as a function of the compaction condition in term of water content.

Comparing the long term permeability coefficient, k_{LT}, of the soil+2%FA+2%QL mixtures with those measured for the untreated samples, compacted at two different moisture contents (Figure 7), it is possible to state that the addition of the binders reduced the hydraulic conductivity in wet of optimum compaction conditions (by nearly one order of magnitude), while the presence of the binders seemed to have no significant effect on the hydraulic conductivity values when approaching w_{opt}.

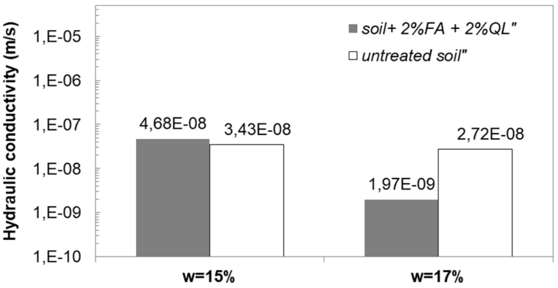

Figure 7. Comparison of long-term hydraulic conductivity of treated and untreated samples, w being equal.

The outcome is completely different if compared with the hydraulic behaviour of a clayey soil (CF=39%) treated with the same binders amount (details in Di Sante et al., 2025): in that case, the binders addition cause an increase in the hydraulic conductivity value and not a reduction as in in the present case. This different behavior can be explained by the cation exchange reaction between calcium ions from lime and ions on the clay fraction that give rise to a flocculated, open structure; the CF of the sandy soil of concern (CF=8%) is lower than that of the clayey one (CF=39%) therefore the previous cited reaction took place at a greater extent in the clayey soil while they are nearly absent in the present case.

4 CONCLUSIONS

The present paper investigated the use of fly ash as binder for the stabilization of a sandy silt once activated with calcium hydroxide coming from quicklime (soil + 2% fly ash + 2% quicklime). The experimental results obtained for the studied mixtures allow to draw the following conclusions.

- The binders addition systematically reduced the value of compaction water content (1.2% on average).
- The optimum water content rose by 1% due to the presence of fly ash and lime while there was a slight increase in the maximum unit weight due to the presence of binders.
- The hydraulic conductivity of the soil-binder mixtures reduced with time due to the formation of gel form pozzolanic products. The major contribution to reduction is within the first 15 days of curing.
- Switching from dry to slightly wet condition the hydraulic conductivity values of the mixture reduced of more than one order of magnitude.
- At optimum conditions no variation in the hydraulic conductivity was observed while in slightly wet conditions the binders addition caused a reduction of one order of magnitude.

By substituting fly ash, a by-product, for half of the binder amount, the current study contributes to the search for sustainable soil stabilization options. Activating the pozzolanic precursor with quicklime enhances the stabilizing effect because, in contrast to other hydroxides, lime can not only create the necessary alkaline environment to maximize the stabilization capability of fly ash but also participates in the advantageous cementation reactions.

Further investigations on compressibility and shear resistance are needed to evaluate the stabilization capability of the combination of fly ash and lime on the soil of concern.

5 ACKNOWLEDGEMENTS

The authors thank the Italian Ministry of University and Research and the European Union – NextGenerationEU for the funding of the research project and Dr. Eng. M. Del Cane for his valuable cooperation in the experimental laboratory activities.

Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component C2 Investment 1.1 - Call for tender No. 104 of Feb 2nd, 2022 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU.
Award Number: Project code: 2022EFFE52, Concession Decree No. 961 of Jun 30th 2023 adopted by the Italian Ministry of University and Research, CUP: I53D23001710006, Project title: INnovative and Sustainable Stabilization Processes Involving REcycleD SOils and Used materiaLS – INSSPIRED SOULS.

6 REFERENCES

Beetham, P.; Dijkstra, T.; Dixon, N.; Fleming, P.; Hutchinson, R.; Bateman, J. 2014. Lime stabilisation for earthworks: a UK perspective. Proc. Ins. Civ. Eng. – Ground Impr. 168(GI2), 81-95.

Consoli, NC; Fonseca, AVD; Silva, SR; Cruz, RC; Fonini, A. 2012. Parameters controlling stiffness and strength of artificially cemented soils. Geotechnique 62(2), 177–83. https://doi.org/10.1680/geot.8.P.084.

Costa, L.T.; Vitale, E.; Cappelletti, P.; Graziano S.F.; Rispoli, C. and Russo, G. 2023. Alkaline activation of volcanic ash as binder for soil improvement. Proc. of the 8th Italian Conf. of Res. in Geotech. Eng. Springer, 792-799.

Daniel, D.E.; Benson, C.H. 1991. Water content – density criteria for compacted soil liners, J. Geotech. Eng. 116, 1811-1831

Devi, K.; Chhachhia, A.; Kumar, A. 2020. Soil Improvement using waste materials: a review. J. Build. Mat.Sci. 2,11-17.

Di Sante, M.; Fratalocchi, E.; Mazzieri, F. 2016. Effects of Variation in Compaction Water Content on Geotechnical Properties of Lime-treated Clayey Soil. Procedia Eng. 158, 63-68.

Di Sante, M.; Khan, M.K., Calò, L., Fratalocchi, E.; Mazzieri, F. (2025) The combined use of fly ash and lime to stabilize a clayey soil: a sustainable and promising approach. *Geosciences* 15, 346. https://doi.org/10.3390/geosciences15090346

Fujikawa, T; Sato, K.; Koga, C. 2023. Long-term durability and environmental safety of slurry type of coal ash mixed material. Environmental Geotechnics 10(2), 102-111 https://doi.org/10.1680/jenge.20.00002

Gollakota, A.R.K.; Volli, V.; Shu, C.M. 2019. Progressive utilisation prospects of coal fly ash: A review. Sci of the Total env. 672,951-989. https://doi.org/10.1016/j.scitotenv. 03337

Huang, J.; Kogbara, R.B.; Hariharan, N.; Masad, E.A.; Little, D.N. 2021. A state-of-the-art review of polymers used in soil stabilization. Constr. And Building Mat. 305 124685 https://doi.org/10.1016/j.conbuildmat.2021.124685

Kampala, A.; Horpibulsuk, S. 2013. Engineering properties of silty clay stabilized with calcium carbide residue J. Mater. Civ. Eng. 25 (5) 632–644 https://doi. org/10.1061/(asce)mt.1943-5533.0000618

Khadka, S.D.; Jayawickrama, P.W.; Senadheera S. 2018. Strength and shrink/swell behavior of highly plastic clay treated with geopolymer Transp. Res. Rec. 2672 (52) 174-184 https://doi.org/10.1177/0361198118797214

Najafi, E.K.; Arabani, M.; Jamshidi Chenari, R. 2021. Clay–fly ash geopolymer characterisation and application for the removal of lead and zinc. Environmental Geotechnics 10(1), 32–43. https://doi.org/10.1680/jenge.20.00065

Noaman, M.F.; Khan, M.A.; Ali, K.; Hassan, A. 2022. A review on the effect of fly ash on the geotechnical properties and stability of soil. Cleaner Materials 6, 100151. https://doi.org/10.1016/j.clema.2022.100151

Palomo, A.; Krivenko, P., Garcia-Lodeiro, I., Kavalerova, E. Maltseva, O., Fernandez-Jimenez A.. 2014. A review on alkaline activation: new analytical perspectives, Materiales de Construccion 64 (315) https://doi.org/ 10.3989/mc.2014.00314

Wild, S.; Arabi, M.; Rowlands, G.O. 1987. Relation between pore size distribution, permeability and cementitious gel formation in cured clay-lime systems, Mat. Sci.Techn. 3, 1005-1011.