Eggshell Lime For Soil Stabilization

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Abstract.
In the framework of a research project financed by Next Generation EU Programme with the Italian Ministry of University and Research, the proposed note explores the possibility of producing lime from eggshells for soil stabilization purposes. The calibration of the production procedure of eggshell lime by calcination is supported by the use of thermogravimetric analysis and X-Ray diffraction and verified by the fulfillment of International Standard requirements for lime in soil stabilization applications. Physico–chemical and mineralogical characterization of the produced lime is carried out and also a feasibility study of stabilization of a clayey soil with the produced eggshell lime is presented. Proctor compaction, initial consumption of lime test and permeability tests in flexible wall permeameters were carried out on untreated soil and on the same soil treated with 4% of eggshell lime. Obtained results are compared with those obtained for the same soil treated with 4% of commercial quicklime.

Keywords: eggshells, lime, soil stabilization.

1 Introduction

Nowadays, global societies share the target of implementing reuse practices and searching for sustainable technical solutions to reduce waste generation thus limiting landfilling and carbon emissions.

Among the contribution of environmental geotechnics to the purpose, the optimization of ground improvement techniques is surely included and soil stabilization is one of the most applied techniques.

Soil stabilization is a crucial process aimed at making problematic soils suitable for engineering applications. It involves treating soils that would otherwise be unusable, thus addressing environmental concerns associated with their disposal. In 1993, estimated losses attributed to expansive soil were approximately 0.15 billion USD in the UK, 1 billion USD in the USA, and over 4 million USD in South Africa [1]. Buhler et al. highlighted that considering inflation and population growth, the annual losses induced by expansive soil in the USA could surpass 15 billion USD [2].

Soil reuse carries significant environmental, energy, and economic implications. According to Blengini et al., substantial reductions in CO_2 emissions and non-renewable energy consumption can be achieved through soil reuse, amounting to up to 14 kg of CO_2 per ton and 250 MJ/ton, respectively [3].

To facilitate problematic soil reuse, meeting the requirements of geotechnical engineering designs, mechanical and hydraulic properties of the soil should be enhanced applying ground improvement techniques (e.g. compaction and addition of binders).

Lime and Portland cement have historically served as popular choices for stabilization due to their cost-effectiveness, ease of implementation, straightforward technology, and positive impacts on soil performance (e.g. [4],[5], [6], [7]). On the other hand, they are linked to significant greenhouse gas emissions and energy costs. Production of one ton of lime and cement is estimated to emit approximately 1.28 and 1 ton of CO_2, respectively [8],[9]. Moreover, their use has local environmental impacts, including mining activities, dust emissions, alterations to landscapes, changes in groundwater quality, noise pollution, and erosion [10].

The use of industrial residue for stabilization purposes is evolving due to increasing resource scarcity and rising landfill costs. Within this context, eggshells provide one of the viable options due to their abundance and availability. The global production of the eggs reached 87 million tons in 2022 [11] resulting in a total eggshell generation of 8.9 million tons[12].

Eggshell lime has been utilized instead of commercial lime in soil stabilization because calcium carbonate present in the eggshells showed almost similar characteristics to limestone used in the production of lime and cement. Related results indicated that traditional lime exhibits superior properties compared to eggshell lime [13],[14].

In another experimental investigation related to compressive strength and volumetric stability, eggshell lime has shown positive outcomes [15]. James et al. found that increasing the percentage of eggshell lime in soil led to enhanced strength and reduced plasticity and swelling [16]. Besides, the partial addition of eggshell lime with the natural lime followed similar results [17] and Surjandari et al observed a significant increase in compressive strength and young modulus of the stabilized soil [18].

The above discussion enlightens the potential of the eggshell in soil stabilization and the results are mostly encouraging. However, there are some discrepancies and contradictions in the findings therefore there is still the necessity of data and open discussion.

In the framework of a research project financed by Next Generation EU Programme with the Italian Ministry of University and Research, the proposed note explores the possibility of producing lime from eggshells for soil stabilization purposes. Aims of the present study are (1) to contribute to finding a sustainable solution for the recycling of eggshell waste, (2) to study the physico-chemical and mineralogical characteristics of calcined eggshells for geotechnical application and (3) to present the preliminary results of a treatment of a clayey soil with the produced eggshell lime, comparing the results with those obtained with traditional quicklime.

2 Test methods

Eggshell waste was characterized by X-Ray diffraction (XRD) in order to identify the main chemical components after collecting, washing, drying and grinding phases (described in detail in section 3.1). XRD was performed by means of Philips diffractometer, PW1730 X-ray generator, PW 1050/70 goniometer and CuK radiation.

In addition, thermogravimetric analyses (TGA) was carried out on the eggshells in order to identify the best temperature for calcination process.

The produced eggshell lime (EL) was tested by XRD immediately after its production and after 30 days spent in sealed container. The produced EL was evaluated considering ASTM soil stabilization standard [19].

Wet slaking and calculation of residue was performed according to [20].

Samples were reconstituted by crumbling the air dried soil (to 2 mm in size), adding the amount of water necessary to reach the desired moisture content and then mixing the binder and the soil at the wet state (as usually done in the field) until a uniform distribution was achieved. The soil-lime mixtures were then compacted according to the Standard Proctor procedure [21] in one layer, obtaining samples of 101 mm in diameter and 40 mm in height.

The initial consumption of eggshell lime was determined (ICL) according to [19]; pH trend with time is monitored by daily measuring pH in the slurry of the mixture of concern (20g of dry soil+5%EL+100ml of distilled water).

Permeability tests were carried out in flexible walls permeameters at 35kPa of effective confining stress with tap water as permeant [22].

3 Experimental results

3.1 Characterization of the eggshell waste

The industrial chicken eggshell waste (shell plus membrane) used in this work was collected in a local biscuit factory. Shells were washed and then dried in the oven at 100°C for 24 h and then crushed, passed through a 1.0 mm sieve. After crushing, XRD and TGA were performed on the eggshells.

The XRD spectrum (Fig.1) highlights the only presence of calcite, $CaCO_3$.

TGA was performed applying a heating ramp of 10°/min until reaching a temperature of 1100°C, obtaining the results showed in Fig. 2.

The weight loss for eggshells can be divided in three steps: the first one between 507 and 698 °C can be attributed to the release of organic matter present in eggshell waste (membrane included) and corresponds to a weight loss of 0.4 mg (1.8%); the second step represents the main weight loss due to the thermal degradation of calcium carbonate to calcium oxide with the release of carbon dioxide:

$$CaCO_3 \rightarrow CO_2 + CaO$$

This process is named calcination and occurred from 698 and 792 °C; the corresponding weight loss is 5.3mg (23.7%). There is also a third, final step of weight loss for temperatures above 792°C that leads to a weight loss of 1mg (4.5%) when reaching 1100 °C.

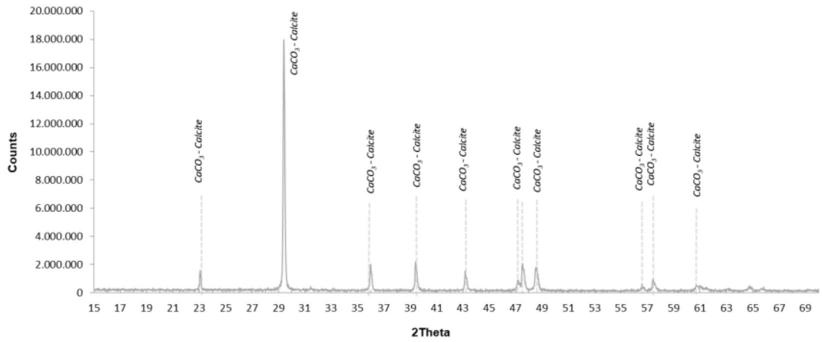

Fig. 1. XRD spectrum of the eggshell waste.

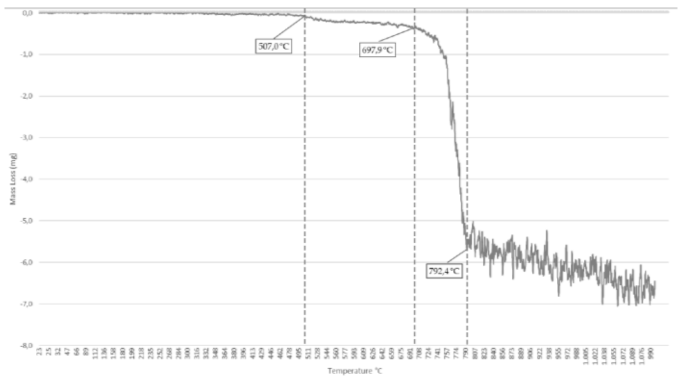

Fig. 2. Thermogravimetric plot for the eggshell waste.

Based on TGA results, eggshells must then be calcined in a furnace at a temperature above 800°C, therefore 900°C was selected as the temperature of calcination.

Immediately after the calcination and the cooling phase of a small amount of egg-shells, XRD was performed obtaining the spectrum showed in Fig. 3.

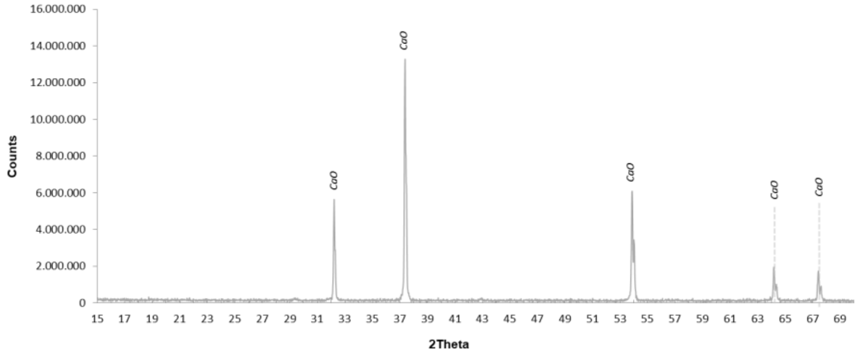

Fig. 3. XRD spectrum of the calcined eggshell – diffraction immediately after calcination.

The calcium oxide is the only component, chemically classifying the produced EL as quicklime (i.e. calcium oxide higher than 90% [19]).

3.2 Eggshell lime production and characterization

The dried, grinded shells were placed in several ceramic pots (225 g each) and fired in the furnace at T = 900°C for 3 hours after applying a heating ramp of 10°/min to reach the reference temperature. The material is cooled to the ambient temperature, gradually, remaining in the turned off furnace.

During the calcination process the loss of mass was approximately 30%.

Chemical composition. It is important to underline that, when firing a greater amount of eggshells and after storing the produced binder in sealed container for 30 days, the XRD spectrum (Fig. 4) highlighted also the presence of Portlandite $Ca(OH)_2$ and a small amount of Calcite ($CaCO_3$), probably due to hydration due to air moisture and to carbonation reaction with CO_2 from air, respectively.

Free moisture resulted in less than 0.1% complying with the maximum free moisture value admitted by the ASTM standard (2%) [19].

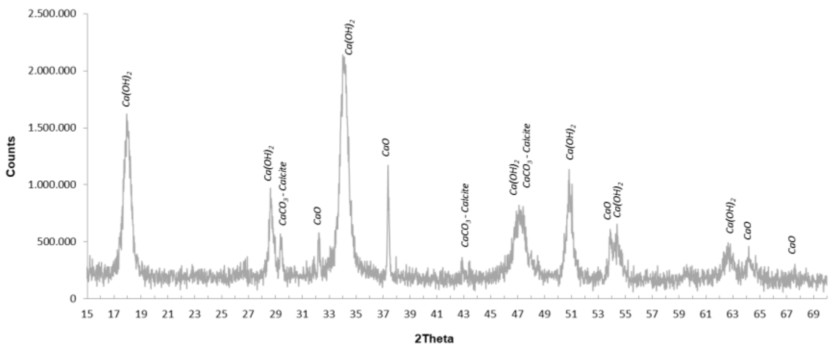

Fig. 4. XRD spectrum of the calcined eggshell – diffraction after 30 days since calcination.

Physical properties. The produced EL shows no material retained on a 75 μm (No. 200 sieve), fully satisfying the grain size requirements of [19] for both quicklime and hydrated lime.

In order to assess reactivity of quicklime in water, temperature rise was verified hydrating the material in the ratio 1:4 (solid/liquid) [20]. The wet slaking curve for the first 25 minutes is displayed in Fig. 5 where the temperature increase is plotted as a function of time.

Temperature increased to 28.7°C in 20 min, therefore, in this case, standard requirements were not met (30°C of rise in the first 20 minutes) and the hydration process is very slow if compared with that of quicklime from limestone; Ferraz et al. attributed this slower reactivity pattern to the larger particle size of eggshell lime if compared to those of quicklime from limestone [23]. Also the composition of the EL probably contributed to the slow temperature rise, because it is not pure CaO.

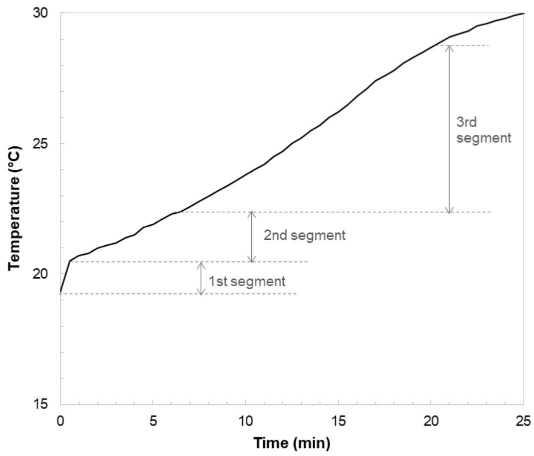

Fig. 5. Wet slaking curve of the calcined eggshell (EL).

For the EL of concern, three different hydration rates can be identified (Fig. 5): the first rate is 2.5°C/min, the second one equal to 0.3°C/min and the third, 0.5°C/min, until 20 minutes of contact with water. Anyway, no lump formed during the slaking process.

After the wet slaking test also the residue of quicklime was determined [20] resulting equal to 0,84%, significantly lower than the maximum value admitted for soil stabilization applications (10% - [19]).

3.3 Preliminary results of soil treatment application

4% of the produced EL was added to a clayey soil of low plasticity (CL according to USCS) whose characteristics are summarized in Table 1. The initial consumption of commercial quicklime, ICL, reported in Table 1, was determined according to [19].

In a previous research study the soil was treated with 4% of commercial fine calcic quicklime, QL, classified as CL80-Q (UNI EN 459-1:2010). Data retrieved for the soil treated with commercial quicklime were used as a comparison to assess the performance of the soil treatment by EL.

Table 1. Characteristics of the soil of concern

characteristic	SGT soil
sand (%)	3
fine (%)	97
clay (<2μm,%)	39
Liquid limit (%)	40
Plasticity index (%)	20
ICL – % commercial CaO	2

Initial consumption of eggshell lime. In Fig.6a the pH values are displayed as a function of the EL amount. The initial consumption of eggshell lime value for the soil of concern is defined as the lowest percentage that gives a pH of 12.40 and represents the lime amount needed to run out the cation exchange (i.e. short term) reactions.

For the soil and the EL of concern the ICL value was equal to 3% (Fig.6a).

In monitoring the pH values of the slurry of the mixture of the soil+4%EL (Fig.6b) constant pH values were observed for the first 2 days (prevailing of cation exchange reaction), then a decreasing trend started to develop. In pozzolanic reactions, each calcium ion reacting with SiO_2 links 2 hydroxyl ions, causing the decrease in pH.

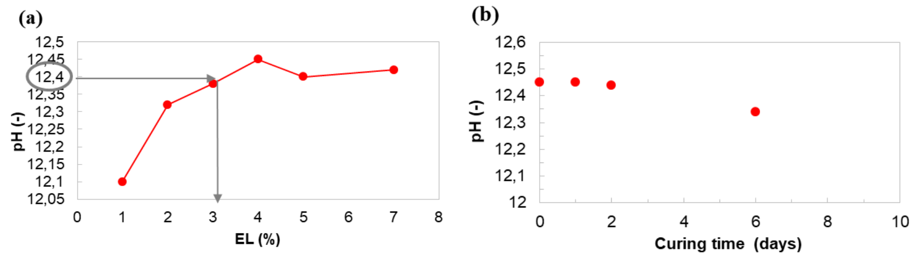

Fig. 6. Slurry of soil+4%QL and of soil+4%EL: (a) ICL plot (b) pH values with time

Compaction characteristics. Compaction curves of the untreated soil and of soil treated with binders are shown in Fig. 7. Binders addition increases the optimum water content from 17% to 18% while slightly reducing the maximum dry unit weight, γ_{dmax}. In Fig. 7 it is possible to identify the range of water contents able to guarantee a dry unit weight higher than 90% of the γ_{dmax}, (as most of technical specifications for construction works). It is worth noticing that binder addition systematically reduces the water content (0.8-4% points) mainly due to CaO hydration process.

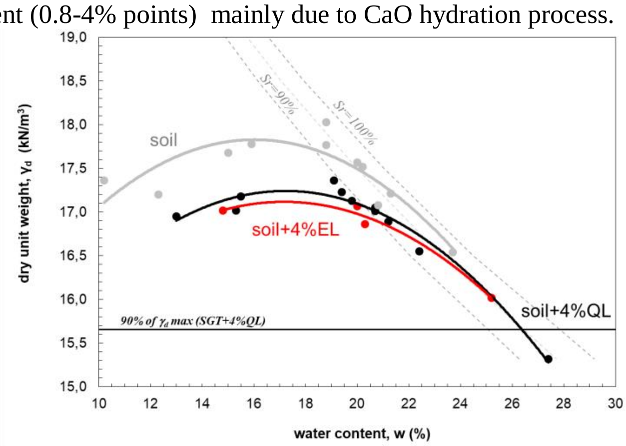

Fig. 7. Proctor compaction curves of untreated soil and soil treated with 4% QL and 4%EL

Hydraulic conductivity. Hydraulic conductivity values, k, are shown in Fig.8 for the untreated soil and for the soil treated with the two types of lime (EL and QL), water content being equal. An increase in k values due to binders addition is evident when comparing data for treated and untreated soil. This increase is probably due to the aggregation of clay particles after cation exchange reaction. k values are more than 2 order of magnitude higher than those of the untreated compacted sample.

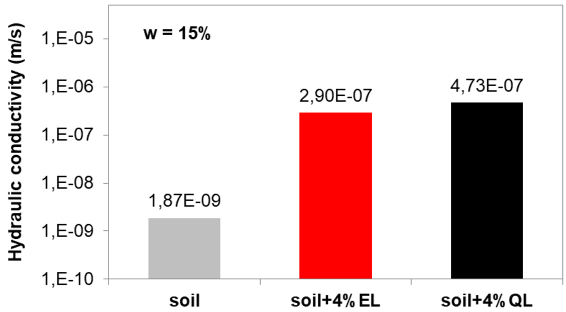

Fig. 8. Hydraulic conductivity of treated and untreated compacted samples

4 Final Remarks

The present work evaluated the potential of eggshells to produce lime for soil stabilization purposes. With reference to free moisture, grain size and residue requirements, the obtained eggshell is suitable for soil treatment. When firing a big quantity of eggshells and after storage, both calcium oxide and Portlandite were found as main chemical components and the obtained lime is not as reactive as commercial quicklime from limestone. Nevertheless, when treating a clayey soil with the produced lime, alkaline effect, compaction characteristics and hydraulic conductivity of the mixture were very similar to those obtained with commercial quicklime treatment.

Acknowledgements

Funder: 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

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