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/ICSMGE2026-1226

Carbonation process of lime treated soil: from field observations to laboratory studies

Federica Bertola, Marcello Mutti, Jorrit Gillijns
Lhoist Research and Development, Belgium, federica.bertola@lhoist.com

Giacomo Russo, Enza Vitale
Department of Earth Science, Environment and Resources, University of Napoli Federico II, Italy

ABSTRACT: Carbonation of lime-treated soils is a crucial process that involves the capture of atmospheric CO_2 by the lime used to enhance soil properties in transport infrastructure construction. Among the other reactions intervening, carbonation naturally occurs both during the construction process and throughout the lifetime of the structures. This paper investigates the effects of carbonation on lime-treated soils through a comprehensive approach, encompassing laboratory experiments and field observations. Field studies were performed on lime-treated embankments and dikes built in various locations in Europe. These structures were monitored over several years to assess the impact of environmental-driven carbonation on their performance. Results indicate that carbonation occurs early after the construction in the shallow layers of lime-treated embankment. Laboratory tests were conducted on lime treated silt soil exposed to different conditions, including accelerated carbonation, to evaluate the ongoing of carbonation of lime during the construction process and its effect on treated soil performance. Results show that carbonation is highly influenced by exposure conditions, particularly by CO_2 availability in the environment. Overall, this study underscores the need for continued investigation into the carbonation of lime-treated soils, integrating laboratory data with field performance. Understanding the carbonation process is crucial for optimizing lime treatment applications and ensuring the long-term stability of lime treated structures. Carbonation of lime-treated soils not only supports carbon capture and reduces the carbon footprint, but also contributes to the sustainability and resilience of construction projects.

KEYWORDS: lime treatment, carbonation, field monitoring, laboratory testing.

1 INTRODUCTION

The use of lime to treat clayey soils, which are not suitable for earthwork in their natural state, is a widely diffused improvement technique which allows to minimize construction costs and preserve natural resources (Little, 1996; Boardman et al., 2001; Al-Mukhtar et al.,2014). Lime is produced though the calcination process i.e., the thermal decomposition of limestone (mainly calcium carbonate, $CaCO_3$) into quicklime (CaO) and carbon dioxide (CO_2). However, lime production is an energy-intensive process and is estimated to account for around 1% of the global anthropogenic CO_2 emissions (Campo et al., 2021). Some of the CO_2 released during calcination can be reabsorbed by lime trough the carbonation process, which allows for the permanent storage of CO_2 in a stable form, as lime reacts with atmospheric carbon dioxide to reform $CaCO_3$.

In geotechnical applications, the addition of lime to clayey soils significantly alters their physical and mechanical properties as result of the chemical reactions which take place after the treatment (Tremblay et al. 2001; Rao and Shivananda 2005; Vitale et al., 2020). In the short-term, the exchange of surface cation with calcium ions promotes flocculation of clay particles, leading to changes in plasticity, workability, and particle size distribution of treated soil. Furthermore, the high alkaline environment induced by lime enables the dissolution of siliceous and aluminous compounds from clay mineral lattice. This process favors the time-dependent pozzolanic reactions, resulting in the formation of cementitious secondary phases which enhance the mechanical performance of lime treated mixtures.

During the construction stage and after, the available lime added to the soil can react with atmospheric CO_2 to form calcium carbonates (lime carbonation). During the service life of lime treated earthworks, also the carbonation of the cementing compounds resulting from pozzolanic reactions can take place, weakening the overall mechanical performance (Vitale et al., 2021), and then affecting the durability of the improvement technique.

Several laboratory (Paige-Green et al., 1990; Deneele et al., 2021; Kleib et al., 2024) and field studies (Hass and Ritter 2018; Das et al. 2022; Chabrat et al., 2024; Bertola et al. 2024) have investigated the impact of carbonation on the durability of lime treated soils. Vitale et al. (2021) performed a comprehensive multiscale laboratory investigation highlighting the influence of both lime carbonation and carbonation of cementing compounds through microstructural analyses and mechanical testing. Padmaraj et al. (2024) investigated the influence of clay mineralogy on the nature and effects of carbonation on different time scale, highlighting that carbonate cementation, decalcification of calcium silicate hydrates (C-S-H), and precipitation-induced microcracking are strongly dependent on the availability of unreacted lime and the microstructural characteristics of the treated soils. Studies conducted on samples retrieved from lime-treated embankments exposed to environmental-driven processes (i.e., wetting and drying, leaching) over extended periods have provided valuable insights into the long-term effects of carbonation on earth structures constructed using conventional construction procedures.

In the current context, earthworks for large-scale civil engineering projects represent a significant contributor to the overall carbon footprint of construction. Recognizing this, Part 1 of the European Standard on Earthworks (EN 16907:2018) has already underscored the necessity of integrating sustainable development principles and environmental considerations into both the design and execution of earthworks. To align with these objectives, the use of low-quality or marginal soils treated with lime for the construction of earth structures must evolve towards more sustainable practices.

In this context of sustainability, lime-treated embankments are increasingly being reconsidered as passive reservoirs of atmospheric CO_2, capable of absorbing carbon dioxide over the decades following construction, and thereby reducing the overall (life-cycle) carbon footprint of large infrastructure projects. This carbon capture strategy requires a thorough understanding of the carbonation processes affecting lime-treated soils at various stages—both lime carbonation and the carbonation of cementitious compounds. The goal is to adapt current construction practices by introducing processing phases that promote the controlled development of carbonation, while ensuring compatibility with the expected mechanical performance of the treated soil.

This paper presents the preliminary results of an experimental study aimed at enhancing the carbon sink potential of lime-treated embankments. The core concept involves introducing a dedicated mellowing phase during embankment construction—prior to soil compaction—during which the precipitation of calcium carbonate is promoted through the capture of atmospheric CO_2 by a part of the available lime. A critical requirement in the design of this phase is to preserve the functional performance of the treated soil, which is intrinsically linked to the advancement of pozzolanic reactions supported by the remaining lime in the system.

In this paper, a section dedicated to case studies highlights the effects of carbonation observed in situ in lime-treated soils that form part of existing, operational infrastructures. Long-term field monitoring of lime-stabilized embankments and dikes is discussed to illustrate the occurrence and influence of carbonation processes on their mechanical behavior. The subsequent section, devoted to the experimental program, focuses on quantitatively assessing calcium carbonate formation during the mellowing phase under varying exposure conditions, as well as evaluating the impact of this precipitation on the overall mechanical performance of the treated soil. Preliminary findings from the ongoing laboratory investigation are also presented and discussed.

2 CASE STUDIES

Only a limited number of real structures have been analyzed to determine the extent of carbonation under actual exposure conditions.

One of the earliest studies in this area is described by Haas and Ritter (2018), which focused on assessing the degree of carbonation in a real motorway embankment constructed with lime-treated soil. Samples were extracted from the embankment built in 1979 and analyzed after 34 years of environmental exposure. The results indicated that, relative to the initial lime content, approximately 47% had reacted with the soil to form pozzolanic products, 37% had undergone carbonation, and 16% remained unreacted and available for further reactions.

Further insights were provided by Das et al. (2021; 2022), who investigated an experimental embankment in Rouen, France, after seven and eight years of natural exposure. This embankment was specifically designed to simulate the construction of a hydraulic structure using lime-treated soil, with implementation conditions tailored to limit the hydraulic conductivity of the material. In 2018, a superficial reduction in pH was observed, while the core of the dike maintained a pH around 11. The carbonation front had progressed to a depth of 12 cm after 7 years. A follow-up investigation one year later focused on areas previously exposed during the 2018 campaign. The study revealed a reduction of the pH of the treated soil and an increase in soil macroporosity due to carbonation up to a depth of about 4.2 cm perpendicularly to the surface. These findings suggest that the carbonation rate decreases over time.

As part of the rehabilitation works of the dike network along the Vidourle river, a dike section (Bertola et al., 2024; Nicaise et al., 2024) was built in July 2015 in the South of France in lime treated soil (Figure1).

The soil used was a silty one characterized by a clay content of 23% and a plasticity index of 5, and it was treated with 2% quicklime. As reference, a section was built with the same soil but without any treatment. No topsoil was applied on the slope of the dike to mitigate the exposure to the environment. Details of the construction can be found in Nerincx et al. (2016; 2018).

Figure 1. View of the dike built along the Vidourle river.

After the construction, many campaigns were organized during the years to monitor the evolution of the performance. In 2021 and 2024, respectively 6 and 9 years from the construction of the dike, samples were extracted along the horizontal direction (starting from the surface of the embankment) to investigate the effect of the environmental exposure and assess the mechanical and hydraulic properties of lime treated soils.

Figure 2 shows the evolution of the pH with the depth; the reduction of pH towards the shallow part of the embankment highlights the effect of carbonation of the lime treated soil. Between 20 ÷ 30 cm from the surface, the pH is still high (around 11), showing that the available lime is still present in the system to maintain the high alkaline environment.

Satisfactory results were found in terms of hydro-mechanical performances (high strength, low permeability, high erosion resistance).

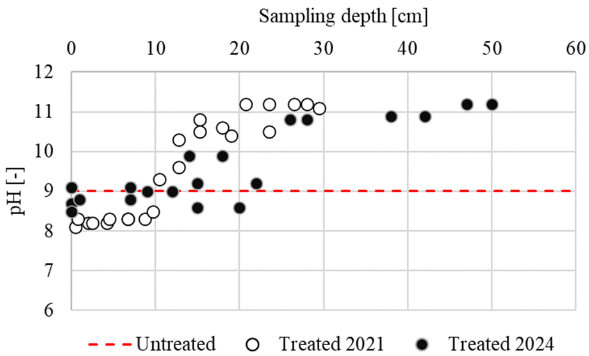

Figure 2. pH in function of the sampling depth.

When monitoring existing structures, detailed information about the materials used and the construction methods is often lacking. Furthermore, accurately assessing the real exposure conditions over time presents a significant challenge. Carbonation in such structures results from a combination of factors: the initial carbonation that occurs during construction (shaped by the implementation conditions), and the progressive carbonation due to long-term environmental exposure. These two contributions are difficult to distinguish from one another. The experimental study is therefore aimed at quantitatively assessing the formation of calcium carbonate during the mellowing phase under different exposure conditions of the treated samples, and at evaluating the effect of such carbonate precipitation on the mechanical performance of the treated soil.

3 LABORATORY INVESTIGATION

3.1 *Materials and Methods*

A F1 silty soil, according to EN 16907-2, and a CL90Q R5 P3 (CaO available = 91%), according to EN 459-1: 2015, were used in this study. The characterization of the soil is reported in Table 1.

Table 1. Properties of the soil used in this study.

Parameter	Symbol	Value	Unit	Method
Methylene blue value	*VBS*	2.5	g/100 g	PrEN 17542-3
Liquid limit	*LL*	29	%	EN ISO 17892-12
Plastic limit	*PL*	22	%	
Plasticity index	*PI*	7	%	
Fines	/	97	%	EN 933-1
Lime Fixation Point	*LFP*	1	%	ASTM D6276

The quantity of lime used for the treatment, i.e. 2%, has been chosen as Lime Fixation Point (LFP) +1% to ensure the occurrence of pozzolanic reactions into the system. The LFP method (ASTM D6276) is, in fact, used to determine the percentage of lime that results in a soil-lime pH of approximately 12.4. An initial mass moisture content of 20% was chosen to achieve the Optimum Moisture Content (OMC) after treatment. An OMC of 18% was determined in previous, unpublished, studies.

The mixing was performed using a Cutter Villa C15 to replicate as close as possible the action of a Pulvimixer on site. After 3 minutes of mixing the treated soil was transferred into three different plastic containers, except for what has been used to assess the time zero (t_0). Each, open, container was then exposed to a different environment for 24 hours. The whole procedure has been repeated twice.

- Outdoor. The container was placed in an outdoor but sheltered area, thus protected from sun and rain. During the exposure of the sample the temperature ranged from 24 to 5°C, while the Relative Humidity (RH) ranged from 54 to 97%.
- Indoor. The container was placed inside a laboratory with uncontrolled temperature and humidity. Over the course of the experiment the former was around 23°C and the latter around 50%.
- Carbonation chamber. The container was placed inside a carbonation chamber operated at 20°C, 70% RH, and 2% CO_2.

At predetermined times, representative samples were taken from every container and analyzed to monitor the carbonation process. A reduced sampling time was used to follow the process in the carbonation chamber due to instrumental limitation.

After collection, the specimens were oven-dried at 105°C for at least 24 hours before being analyzed. Carbonates were determined *via* thermogravimetric analyses (TGA) performed using a TGA-2000 from Navas Instrument (RT to 950°C, 5°C/min, N_2 50ml/min). The untreated soil was also measured to determine its initial CO_2 content, enabling to assess the quantity of CO_2 reacted with the lime. All the CO_2 not present in the soil before treatment was considered to be of the latter kind.

3.2 *Results*

The evolution of the soil humidity over time is reported in Figure 3, as an indicator of the evaporation rate accommodated by treated soil as function of the exposure conditions. A decrease of approximately 3% was observed as result of the lime treatment. Among the samples, those kept in the carbonation chamber exhibited the lowest reduction in humidity, reaching 12.9% after 24 hours. In contrast, the treated soils exposed to uncontrolled environmental conditions showed remarkably higher drying with humidity levels dropping to 7.8% (Indoor) and 4.8% (Outdoor).

Figure 4 displays the formation of $CaCO_3$ over time, corrected for the quantity of CO_2 initially present in the soil. The carbon uptake of the Indoor and Outdoor samples followed a similar trend, although the latter ultimately sequestered significantly more CO_2. In contrast, the samples placed into the carbonation chamber exhibited a rapid formation of $CaCO_3$ during the first few hours, followed by a plateau where little to no further carbonation occurred.

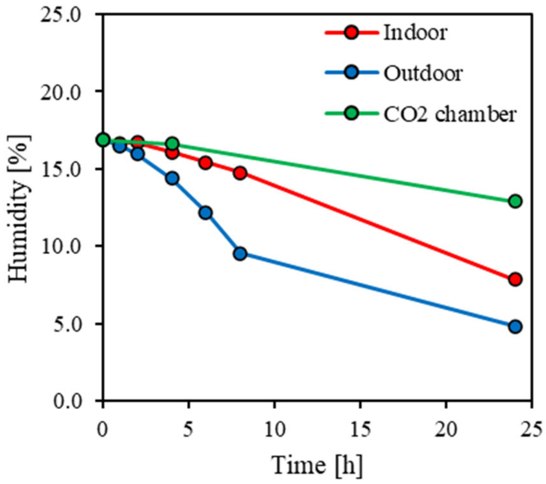

Figure 3. Evolution of the soil humidity over time

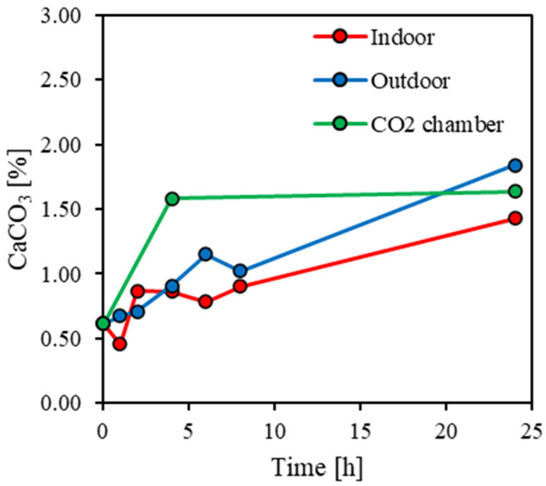

Figure 4. Calcium carbonate formed over time

The CO_2 content estimated by TGA was then used to evaluate the carbonation rate of the lime, as shown in Figure 5. This figure reports the proportion of carbonated available lime as function of time. These preliminary results indicate that in realistic environmental conditions, as for the Outdoor samples, a substantial amount of the lime used for the treatment is already carbonated after 1 day. However, a significant quantity of carbonates was also detected in the samples analyzed immediately after mixing. These carbonates were not present in the untreated soil and must therefore be due to lime carbonation. As shown in Figure 5, the carbonates present at t_0 account for

20% of the available lime introduced into the system. It is plausible that a large share of these carbonates is formed during the sample handling, especially during the drying step. Furthermore, the results suggest that the carbonation process of lime in soil treatment should be further investigated under accelerated conditions, given the specific trend observed for the carbonation degree.

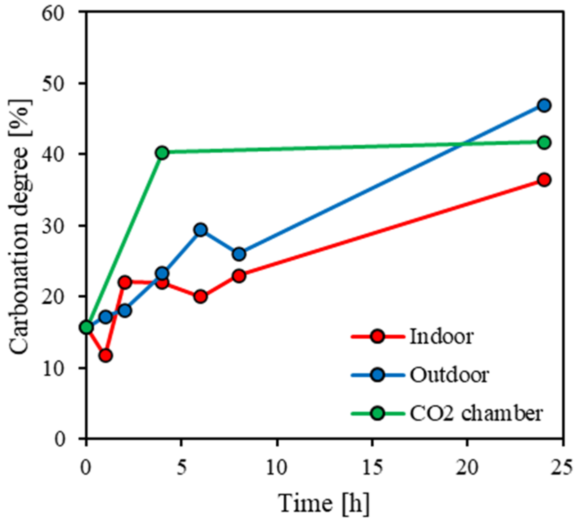

Figure 5. Carbonation degree of the lime over time

4 CONCLUSIONS

In the broader context of using lime-treated embankments as reservoirs for atmospheric CO_2 capture, the laboratory study focused on investigating lime carbonation, which represents the short-term phase within the overall carbonation process affecting treated soils. To this end, thermogravimetric analyses were carried out on samples treated with varying lime contents and subsequently subjected to different mellowing conditions (indoor, outdoor, and accelerated carbonation).

Experimental results revealed that carbonates are already formed in the system immediately after the soil-lime mixing phase (about 0.6%), and that outdoor mellowing conditions are the most favorable for carbonate precipitation due to the higher CO_2 availability. The carbonation trend observed under accelerated conditions in the climatic chamber suggests the need of deeper experimental investigations of the phenomenon to determine its representativity.

The ongoing experimental campaign aims to assess the impact of carbonation during the mellowing phase on the mechanical performance of lime-treated soils. This part of the study will enable short-term carbonation to be properly calibrated so as not to compromise the long-term performance expected from lime stabilization.

In perspective the mellowing phase could be integrated as an additional operational step within the construction practice of lime-treated embankments, with the objective of optimizing atmospheric CO_2 capture and contributing to the environmental sustainability of the geotechnical infrastructure.

5 REFERENCES

Al-Mukhtar M., Lasledj A., Alcover J.F., 2014. Lime consumption of different clayey soils. Appl. Clay Sci. 95, 133-145.

Bertola F., Klotz F., Gerard P. François B., 2024. Evaluation of the geomechanical properties of lime-treated silt samples extracted from an experimental levee 6 years after the construction. In: Proceedings of the *XVIII ECSMGE 2024*, Lisbon (P), 26-30 Aug. 2024.

Boardman D.I., Glendinning S., Rogers C.D., 2001. Development of stabilization and solidification in lime-clay mixes. Géotechnique 50, 533–543.

Campo F.P., Tua C., Biganzoli L., Pantini S., Grosso M., 2021. Natural and enhanced carbonation of lime in its different applications: a review. Environmental Technology Reviews, vol. 10, issue 1, pp. 224–37. https://doi.org/10.1080/21622515.2021.1982023.

Chabrat N., Russo G., Vitale E., Masrouri F., Cuisinier O., 2024. Long-term characteristics of a stabilized expansive clay exposed to environmental-driven processes, Transportation Geotechnics, 46, 101257, ISSN 2214-3912, https://doi.org/10.1016/j.trgeo.2024.101257.

Das G., Razakamanantsoa A., Saussaye L., Losma F., Deneele D., 2022. Carbonation investigation on atmospherically exposed lime-treated silty soil. Case Studies in Construction Materials 17.

Das G., Razakamanantsoa A., Herrier G., Saussaye L., Lesueur D. Deneele D., 2021. Evaluation of the long-term effect of lime treatment on a silty seven years of atmospheric exposure: Mechanical, physicochemical, and microstructural studies. Engineering Geology 281(6).

Deneele D., Dony A., Colin J., Herrier G., Lesueur D., 2021. The carbonation of a lime-treated soil: experimental approach. Materials and Structures, 54, pp. 1–12. https://doi.org/10.1617/s11527-021-01617-w.

Haas S., Ritter H.-J., 2018. Soil improvement with quicklime – long-term behaviour and carbonation. Road Materials and Pavement Design, DOI:10.1080/14680629.2018.1474793.

Kleib J., Lesueur D. Maherzi W., Benzerzour M., 2024. Carbonation of lime treated soil subjected to different curing conditions. Transport Geotechnics 44(2024) 101174.

Little D.N., 1996. Fundamentals of the stabilization of soil with lime: National Lime Association. Bulletin vol. 332. Arlington, USA, pp. 1–20.

Nerincx N., Bonelli S., Nicaise S., Herrier G., Lesueurs D., Tachker P., Puiatti D., Cornacchioli F., 2018. The DigueELITE project: lessons learned and impact on the design of levees with lime treated soils. *Hydropower and Dams*, vol. 25, issue 6.

Nerincx N., Bonelli S., Puiatti D., Herrier G., Fry J.-J., Tourment R., Nicaise S., 2016. Impact of lime treated soils performance on design of earthfill dikes. In: Proceedings of *FLOOD risk 2016 - 3rd European Conference on Flood Risk Management*, E3S Web of Conferences 7, 14004.

Nicaise S., Klotz F., Bertola F., Byron F., Chaouch N., Grémeaux Y., Aubriet J., Ozturk T., Doghmane A., Bonelli S., 2024. Evolution des performances de digues traitées à la chaux en climat méditerranéen. In: Proceeding of *Digue 2024,* Aix-en-Provence (F), Mar. 2024.

Padmaraj D., Cherian C., Arnepalli D.N., 2024. Multiscale analysis of carbon mineralization in lime-treated soils considering soil mineralogy, J. Rock. Mech. Geotech. Eng. 16 (6) 1–14, https://doi.org/10.1016/j.jrmge.2024.03.013.

Paige-Green P., Netterberg F., Sampson L.R., 1990. The carbonation of chemically stabilized road construction materials: guide to its iden tification and treatment. Project Report No DPVT-123, CSIR-ISBN 0-7988-4961-4, Division of Roads and Transport Technology, Pretoria.

Rao S.M., Shivananda P. (2005) Role of curing temperature in progress of lime-soil reactions. Geotech Geol Eng 23(1):79–85.

Tremblay H., Leroueil S., Locat J., 2001 Mechanical improvement and vertical yield stress prediction of clayey soils from eastern Canada treated with lime or cement. Can Geotech J 38:567–579.

Vitale E., Deneele D., Russo G., 2020. Microstructural investigations on plasticity of lime-treated soils. Minerals, 10(5), 386; https://doi.org/10.3390/min10050386.

Vitale E., Deneele D., Russo G., 2021. Effects of carbonation on chemo-mechanical behaviour of lime-treated soils. Bulletin of Engineering Geology and the Environment, vol. 80, pp. 2687-2700.