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Durability of hydraulic structures reinforced with lime: a French onsite experience

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ABSTRACT: Lime treatment of soil is a well-recognized, safe, and cost-effective method that enables the reuse of soils in the construction of transport infrastructures. This technique offers notable benefits, such as reducing landfill waste and shortening construction times. However, despite extensive experience, the application of lime treatment in hydraulic structures remains underdeveloped. Hydraulic structures have specific requirements beyond those of traditional embankments, including low permeability to prevent seepage, resistance to internal and external erosion, and the ability to withstand high water flows. The advantages of using lime treatment in the construction of hydraulic structures have been recognized through numerous studies, investigations, and full-scale projects conducted over the past fifteen years. Lime treatment allows for the use of locally available soils, simplifies the typical design cross-section, and enhances mechanical properties, erosion resistance, and overall cost efficiency, including reduced material transport. Nevertheless, concerns about durability still hinder the widespread adoption of lime treatment for hydraulic structures. As a relatively new technology for hydraulic structures design, there is limited documented evidence of its long-term performance and the consequences of prolonged exposure to weathering on the evolution of its specific functional requirements. It is therefore crucial to demonstrate that lime-treated hydraulic structures are not only efficient and sustainable but represent also viable long-term solutions. This paper presents the results of monitoring campaigns conducted on a lime-treated dike built in France in 2011. Initially, a brief description of the experimental dike, including construction details and procedures, are provided. Subsequently, the results from several monitoring campaigns over the years are presented and analyzed to gain a comprehensive understanding of the effects of exposure conditions on the lime-treated soil and the overall structure. The paper concludes with technical evidence gathered over the years and highlights areas that still require clarification.

KEYWORDS: lime treatment, soil improvement and stabilization, dikes and levees, durability, field monitoring.

1 INTRODUCTION

Lime treatment of soil is a well-established, safe, and cost-effective method that enables the reuse of substandard soils in the construction of transport infrastructure, such as roads, highways, railways, and airfield (Little, 1995). By minimizing landfill use and shortening construction timelines, this technique offers notable benefits. However, despite extensive experience with lime treatment in general earthworks, its application in hydraulic structures remains relatively underdeveloped.

Hydraulic structures demand not only the usual requirements of workability and stability seen in traditional embankments but also specific performance characteristics. These include watertightness (low permeability to prevent seepage), resistance to internal erosion (such as piping, contact erosion, suffusion, and regressive erosion), surface protection (resistance to external erosion), and the ability to withstand high water flows (Sharp et al., 2013).

Over the past 20 years, numerous studies, investigations, and full-scale projects have highlighted the advantages of using lime-treated soils in hydraulic construction (Bertola et al., 2025). This approach facilitates the use of locally available materials, simplifies typical design cross-sections, and enhances mechanical properties and erosion resistance, all while reducing costs and the need for material transport. Nevertheless, concerns about long-term durability continue to hinder the widespread adoption of lime treatment in hydraulic applications. As a relatively recent innovation in this context, there is limited documented evidence on its long-term performance, particularly regarding its resilience to weathering and its ability to meet the specific functional demands of hydraulic structures. Demonstrating that lime-treated hydraulic structures are not only effective and sustainable but also durable over time is crucial.

This paper compiles and shares insights gained from the construction and monitoring of a full-scale structure design to simulate a dike. It presents the case study of an embankment built in France using a lime-treated soil, detailing construction methods, properties measured shortly after completion, and findings from long-term monitoring campaigns. This experience offers valuable conclusions for future applications in the context of hydraulic and flood protection infrastructure.

2 EXPERIMENTAL EMBANKMENT

In September 2011, two experimental embankments were constructed at the Cerema Research and Experimental Center (CER) in Rouen as part of the DOFEAS project (Dikes and River Structures: Erosion, Scouring, Earthquakes). The embankments were built using a silty soil from Marche-Les-Dames, Belgium, a low plasticity fine soil classified as F1 according to EN 16907-2. One embankment was treated with 2.5% of quicklime (CL90Q according to EN 459-1), while the other served as reference and was built with the same untreated soil. Both structures were in dry conditions and were not subject to hydraulic stress.

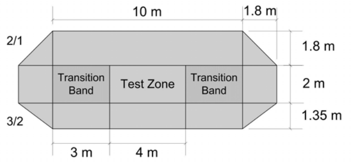
The lime-treated embankment featured an asymmetrical cross-section, with slopes of 3H/2V (facing southeast) and 2H/1V (facing northwest). It measured 21 m in length at the crest and 28.20 m at the base, with widths of 4 m and 10.30 m respectively, and a total height of 1.80 m (comprising six layers of 30 cm). The untreated embankment was smaller, measuring 10 m in length, 2 m in width, and 0.9 m in height (three layers), but shared the same asymmetrical geometry and the same slope coefficients. Figure 1 shows the geometry of the two embankments, while Figure 2 the global view after their construction.

The objective of the project was to evaluate the use of lime-treatment of fine soil in the construction of hydraulic structures (e.g., dikes, channels) and to validate laboratory findings at full scale. Key focus areas included the homogeneity of the lime-treatment and the permeability of the treated, compacted material. For these latter reasons, specific implementation conditions were adopted:

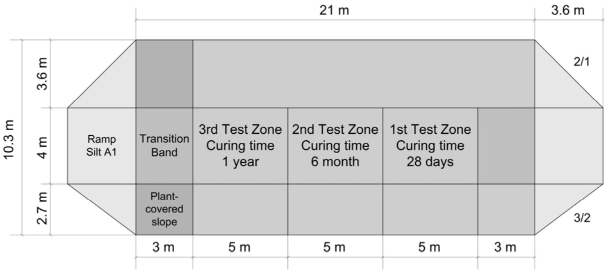
- Lime treatment was performed using a mobile mixing plant, selected for its precise control of lime and water dosing.
- Compaction was carried out on the wet side of the optimum moisture content (OMC) using a sheep foot roller (kneading compaction).

The untreated embankment was compacted under the same conditions.

Construction quality was monitored through systematic checks of parameters such as water content, density, and layer thickness. Post-compaction average water contents were 19.4% for the treated embankment and 17% for the untreated one. Further construction details can be found in Makki-Szymkiewicz et al. (2015).



Untreated silty soil dike



Lime-treated silty soil dike

Figure 1. Geometry of the two embankments.

Figure 2. Global view of the two embankments soon after their construction (lime-treated on the left and untreated on the right).

3 RESULTS OF PREVIOUS MONITORING CAMPAIGN

Following the construction of the embankments, extensive experimental campaigns were conducted over several years to evaluate the mechanical and hydraulic performance of the structures and their evolution under oceanic environmental exposure.

Initial investigations carried out at one month, six months, and one year after the construction (Charles et al., 2012; Charles et al., 2015; Makki-Szymkiewicz et al., 2015) revealed the following:

- The permeability of the lime-treated soil was found to be comparable to that of the untreated soil (approximately 10^{-9} m/s) and remained stable over time. This result is attributed to the specific construction practices, notably kneading compaction on the wet side of the OMC.
- Lime traitement significantly enhanced soil cohesion and overall stability, as confirmed by mechanical property measurements.
- Tests conducted just after 28 days from the construction, using Hole Erosion Test (HET) and Mobile Jets Erosion Test (MoJET), demonstrated a marked increase in both internal and surface erosion resistance due to lime treatment.
- After one year, the presence of topsoil layer was shown to effectively protect the lime-treated soil from environment degradation, with erosion levels significantly reduced compared to those observed at 28 days.

In October 2018, after 7 years of exposure to natural conditions, a comprehensive monitoring campaign was launched to assess the long-term properties and homogeneity of the treated soil. Loose samples were collected from the slopes to analyze the physico-chemical characteristics and microstructure, while blocks were extracted and reshaped in the laboratory to determine mechanical and hydraulic properties. Due to the high mechanical strength and brittle nature of the treated soil, as well as the presence of flint inadvertently introduced during construction, intact core sampling was not feasible.

Prior to the sampling, the embankment was stripped of topsoil and vegetation, and 60 cm-wide trenches were excavated without disturbing the core of the dike. Soil samples were collected within two hours of trench opening and stored in hermetically sealed bags until measured.

Key findings from this campaign (Saussaye et al., 2020; Das et al., 2021) include:

- pH values above 11 were recorded at the core of the lime-treated embankment, confirming the persistence of lime effect. A pH reduction to values between 8 and 9 was observed in the first 12 cm due to atmospheric exposure and vegetation growth
- Water content variations were within 2% of the value measured during the construction, indicating long-term water retention capacity of the lime-treated soil.
- An average Unconfined Compressive Strength of 3.29 MPa was measured on samples extracted at depths of 0.30 and 0.75 m perpendicular to the surface.

During the campaign in 2018, the untreated embankment was dismantled, and no further data were collected from it.

One year after the trench excavation, additional samples were taken to evaluate the extent of carbonation. The carbonation depth was measured at 4.2 cm from the surface, suggesting a deceleration in the carbonation front over time. Microstructural changes were also observed (Das et al., 2022; Saussaye et al., 2024).

4 MONITORING CAMPAIGN 2025

At the beginning of 2025, an additional monitoring campaign was conducted to continue gathering information on the evolution of the performance of the lime-treated embankment under study, which had been exposed to environmental conditions for approximately 14 years (Figure 3).

This paper presents a first analysis of loose samples, focusing on moisture content, pH, and carbonation degree in function of exposure and depth.

Samples were extracted on both slopes of the dike, from 6 different locations, always within a trench opened between 2018 and 2020 (Figure 4). For each location, several sampling points were chosen, with depth reaching 35 cm in the direction perpendicular to the trench wall (Figure 5). The moisture content of every collected sample was determined by drying part of it at 105°C for 24h. After drying, the samples were used to determine their carbonation via thermogravimetric analysis (TGA), performed using a NAVAS Instrument TGA-2000 operated at 5°C/min from room temperature to 950°C. The loss of CO_2, i.e. the mass loss occurring between 600 and 950°C, was fully associated with that of $CaCO_3$, either present in the untreated soil ($CO_2(untr)$) or due to the carbonation of the quicklime used for the treatment ($CO_2(tr)$). The degree of carbonation was calculated according to the following equation:

$$\mathit{Carbonation\ degree}\ (\%) = \frac{(CO_2(tr) - CO_2(untr)) \cdot 1.27}{CaO_{tot}} \cdot 100$$

The pH was determined in undried samples with a dry soil to water ratio of 4, analogously to what it is used to determine the lime fixation point of the soil (ASTM D6276-19).

Figure 3. View of the treated embankment in lime-treated soil after 14 years from its construction.

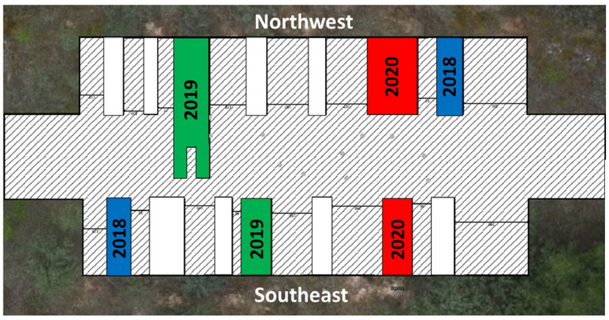


Figure 4. Scheme of the sampling. The colors assigned to the different trenches are used in subsequent figures to identify samples according to their origin in the structure.

Figure 5. Example of the sampling of loose material.

4.1 *Results*

Figure 6 shows a wide distribution of moisture content in the superficial layer of the dike, ranging from 17% to 32% in the very external layer (i.e. first few cm), regardless the date of trench opening (and the soil-atmosphere exposure of 5 to 7 years). As the sampling depth increases the moisture content becomes less variable and stabilizes around 15-17% once below 10 cm, compared to 12 cm in 7 years (Das et al., 2021). A similar trend is observed in Figure 7, which displays the soil pH as function of depth. In the first 5 cm, the pH ranges between 8.5 and 11 while it quickly stabilizes around 11.5 at greater depths.

A pH of 10 is typically indicated as the threshold between systems where there is still enough CaO available for further pozzolanic reactions, and systems where the potential for further reactions is exhausted because of leaching, carbonation or the occurrence of pozzolanic reactions themselves (Little, 1995). Figure 7 thus suggests that little to no degradation via carbonation and/or leaching occurred below 10 cm from the surface. Following the previous assumption, no further pozzolanic reactions are expected in the first 10 cm of soil while they are on-going at greater depths.

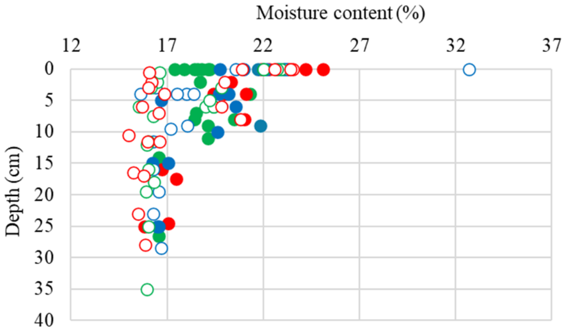


Figure 6. Evolution of the moisture content with the sampling depth. The colors of the scatterers refer to those of the trenches in Figure 4. Open circles correspond to samples taken from the northwest slope, while full ones to those taken from the southeast slope.

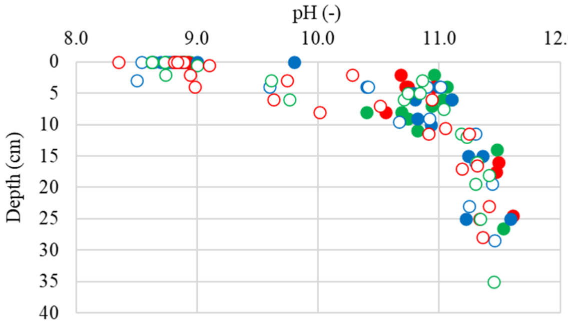


Figure 7. Evolution of the pH with the sampling depth.

Soil treated with lime is known to develop a certain resistance to water, a resistance that can diminish over time due to the carbonation process. The relationship between water susceptibility and the persistence of lime treatment is illustrated in Figure 8, which juxtaposes moisture content and pH measurements along with their fitted curves. The latter clearly indicates that these two parameters evolve similarly with depth. It should be noted that the greater variability observed in both moisture and pH in the most superficial samples is significantly influenced by the decision to present the data as a function of the average depth and that not all samples were taken at comparable ones. For example, the sample with 33% moisture was the only one obtained by scraping just the surface of the trench, whereas all other samples encompass depths of 4 to 10 cm.

Lastly, the carbonation degree of CaO, with the assumption that none is lost due to leaching, is shown in Figure 9. Whereas up to 60% of the added lime appears to be carbonated in the superficial layer, this proportion rapidly decreases to below 20% at depth greater than 10 cm. Although these results are consistent with the pH measurements shown in Figure 7, the carbonation of lime observed in deeper layer cannot be associated univocally with that occurring after compaction of the soil. In fact, it is not possible to experimentally distinguish between carbonation that occurred during the construction of the embankment, i.e. mixing of lime and soil and mellowing period, and carbonation that occurred at later stages (Kleib at al., 2024) if the first was not measured at the time of compaction. Moreover, the determination of carbonates via TGA does not allow to determine whether the uncarbonated part of the lime is still available for pozzolanic reaction, and in which quantity.

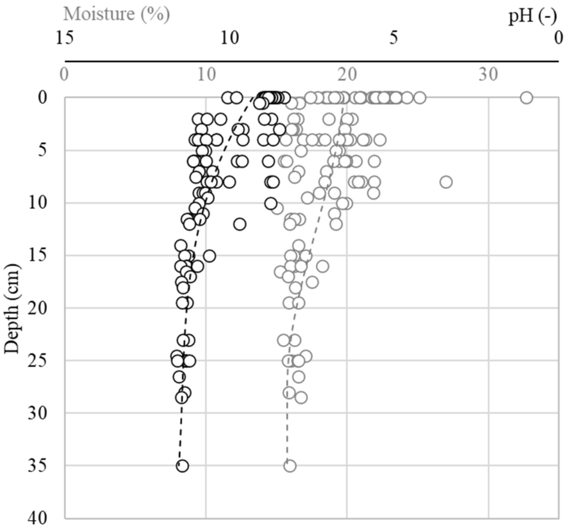


Figure 8. Comparison between the evolution of the moisture content (in grey) and the pH (in black) in function of the sampling depth.

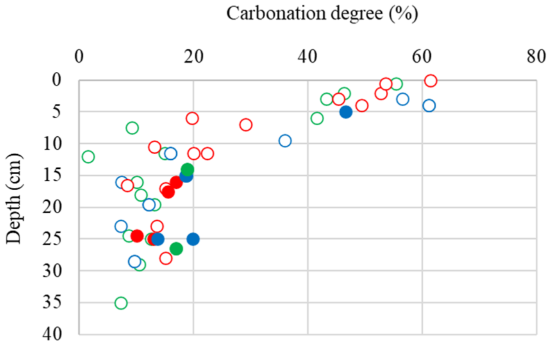


Figure 9. Carbonation degree as a function of the sampling depth.

5 CONCLUSIONS

The following conclusions can be drawn based on the multiple monitoring campaigns.

- Carbonation proceeds relatively quickly on scrapped surfaces, but the advancement of the carbonation front diminishes rapidly with depth.
- Moisture contents inside the embankment decrease at a very reduced rate (-2% and -3% after 7 and 14 years respectively).
- 14 years after construction, the pH level inside the structure is still sufficiently high to enable pozzolanic reactions.
- It is impossible to distinguish between carbonation occurred during the construction and that which took place during years of exposure, if the former was not initially assessed.
- No significant difference was observed between samples collected from the different slopes. The different orientation of the two slopes probably does not substantially affect the environmental conditions to which the material is exposed.

These initial observations will be complemented with results coming from additional analysis, such as microstructural analysis, investigation of the natural vegetation grown, onsite measurements of the surface erosion through MoJET and JET, dilatometer tests, and assessment of geo-mechanical properties.

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