



LIME TREATMENT OF SOILS FOR LIMITED-HEIGHT HYDRAULIC STRUCTURES STATE OF THE ART AND PRACTICE

INFORMATION GUIDE
FOR PROJECT OWNERS
FOR PROJECT MANAGERS
FOR ENGINEERING CONSULTANTS
FOR CONTRACTORS
AND QUALITY CONTROL OFFICES



Members of the DigueELITE Consortium



This guide is primarily intended for project owners, construction managers, engineering consultants, contractors, and quality control offices involved in the design, construction, quality control, and monitoring of levees, small dams, and hydraulic canals built with lime-treated soils no higher than approximately fifteen meters.

Cover photo: lime treatment of F1 soil with 2% lime on a dedicated platform, for construction of a protective outer layer on an existing structure – Vlassenbroek experimental site (B), October 2019 – Photo courtesy of Lhoist

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List of abbreviations

ADP	Aéroports de Paris
CBR	California Bearing Ratio
CBR_i	California Bearing Ratio after immersion
Cerema	Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning)
CFTR	Comité Français pour les Techniques Routières (French Committee for Road Engineering)
CIRIA	Construction Industry Research and Information Association
EDF	Électricité de France
EFA	Erosion Function Apparatus
EPTB Vidourle	Établissement Public Territorial de Bassin du Vidourle (Vidourle Public Basin Management Authority)
GTS	Setra/LCPC Technical Guide: Soil treatment with lime and/or hydraulic binders - Application to the construction of fills and capping layers
HET	Hole Erosion Test
HSL	High-Speed Line
ICOLD	International Commission on Large Dams
IDRRIM	Institut des Routes, des Rues et des Infrastructures pour la Mobilité (Institute of Roads, Streets, and Mobility Infrastructure)
INRAE	Institut National de la Recherche pour l'Agriculture, l'Alimentation et l'Environnement (French National Research Institute for Agriculture, Food, and Environment)
IPI	Immediate Bearing Index
JET	Jet Erosion Test
LCPC	Laboratoire Central des Ponts et Chaussées (Central Laboratory for Bridges and Roads)
LFP	Lime Fixation Point
MoJET	Mobile Jets Erosion Test
OMC	Optimum Moisture Content
PNEC	Predicted No-Effect Concentration
REACH	Registration, Evaluation, and Authorization of Chemicals
Sétra	Service d'études techniques des routes et autoroutes (Technical Department for Roads and Highways)
SOTREDI	SOil TREatment for Dikes (Lhoist internal research project)
SMDE	Erosion Measurement System (ARCOR Technologies)
SYMADREM	Syndicat Mixte Interrégional d'Aménagement des Dignes du Delta du Rhône et de la Mer (Interregional Association for the Development of Dikes on the Rhône River Delta and the Sea)
TerDOUEST	Sustainable Earthworks for Treated Soil Structures (ANR Research Project completed in 2012)

List of symbols

c'	(kPa)	Effective cohesion
C_c		Compressibility coefficient
C_s		Swelling coefficient
C_v	(m ² /s)	Coefficient of consolidation
CSLI	(inch)	Clopper Soil Loss Index
d	(%)	Lime dose by mass
E	(MPa)	Young's Modulus
E_c	(MPa)	Modulus of elasticity in compression
E_{it}	(MPa)	Diametral modulus of elasticity (Brazilian test / indirect tensile test)
G_{max}	(MPa)	Maximum shear modulus
CBR	(%)	California Bearing Ratio
CBR_i	(%)	California Bearing Ratio after immersion
$I_{e,HET}$		Fell Erosion Index (HET test)
IPI		Immediate Bearing Index
I_p	(%)	Plasticity index
k	(m/s)	Saturated permeability
$k_{d,HET} / k_{d,JET}$	(cm ³ /(N.s))	Hanson erosion coefficient (HET and JET tests)
R_c	(MPa)	Unconfined compressive strength
R_{it}	(MPa)	Diametral compressive strength (Indirect Tensile Strength)
s	(kPa)	Suction
S_r	(%)	Degree of saturation
V_{BS}	(g/100g)	Methylene blue value
w	(%)	Water content
w_L	(%)	Liquid limit
w_n	(%)	Natural soil water content
w_{OMC}	(%)	Optimum Moisture Content (Standard Proctor)
w_p	(%)	Plastic limit
w_s	(%)	Shrinkage limit
ν		Poisson's Ratio
ρ_{dm}	(Mg/m ³)	Average dry density
$\rho_{dmaxOMC}$	(Mg/m ³)	Maximum dry density at Optimum Moisture Content (Standard Proctor)
σ_c	(kPa)	Pseudo consolidation stress
$\tau_{c,HET}$	(Pa)	Critical hole erosion stress (HET test)
$\tau_{c,JET}$	(Pa)	Critical surface erosion stress (JET test)
ϕ'	(°)	Effective Internal Friction Angle

Foreword

Lime treatment is a proven technique that has been widely developed over the past sixty years. As a result, valuable know-how has been developed, particularly in France, benefiting infrastructure and development projects of all scales. However, there are few examples of applications in the field of hydraulic structures, and those that do exist remain relatively unknown. This is partly due to the caution of stakeholders in this field given the challenges they face, but also to a lack of awareness about the benefits and advancements of this technique.

Over the past fifteen years, extensive studies, investigations, and full-scale pilot projects have demonstrated the considerable benefits that lime treatment can offer for hydraulic structures. This scientific groundwork now makes it possible to expand the use of this technique within the relevant field.

In 2013, the DigueELITE research program, led by ISL Ingénierie and bringing together INRAE, EDF, Lhoist France, and Arcor Technologies, received support from the Joint Interministerial Fund (FUI) to carry out an ambitious research initiative focused on earthen hydraulic structures, especially flood protection dikes. The research was organized into four main Work Packages:

WP1: Material

WP2: Design and Dimensioning

WP3: Construction and Monitoring

WP4: Overflow testing

In 2015, these efforts culminated in the construction of a demonstrator along the Vidourle River in southern France, which was subjected to overflow testing in April 2016 and June 2017. Important insights were gained into the behavior of lime-treated soils and the design of resilient, long-lasting hydraulic structures.

In addition to this project, as part of the programme to secure the river dikes in the Rhône Delta, SYMADREM—the project owner for the strengthening of the Grand Rhône dikes at Salin de Giraud and Port Saint Louis—built some experimental test plots using lime-treated soils in 2017 to assess their resistance to surface erosion through similar overflow testing.

These two major projects complement the knowledge developed since 2005 by both public and private scientific institutions, thanks to academic and experimental research conducted on this subject. Numerous publications were authored as part of these studies, and a comprehensive bibliography is provided at the end of this document.

At the end of the DigueELITE program, the consortium decided to publish this comprehensive summary to provide the hydraulic structures community with key lessons learned from DigueELITE and the related research. The primary objective of this summary is to provide key insights to support studies, design, dimensioning, construction, and monitoring of hydraulic structures built with lime-treated soils. It enables readers to quickly become familiar with the key elements of lime treatment for hydraulic structures, including benefits, performance, and limitations. It provides a detailed overview of the key aspects of applying lime treatment and offers the entire relevant community - including project owners, project managers, design offices, contractors, and quality control offices - the technical and methodological elements required to incorporate lime-treated soils into the construction or repair of hydraulic structures not exceeding approximately fifteen meters in height.

This documents does not substitute established design and construction guidelines for hydraulic structures, as recommended by specialized institutions and documented in bulletins, handbooks, and standards. It offers complementary insights, presenting new technical and economic options, and refer to reliable documents when applicable. However, it is important to consider that this document is founded on French and European practices, regulations, and standards. Adapting it for use in another country requires careful modification to ensure compliance with local regulations and practices. Accordingly, this document may serve as a reference framework for developing versions tailored to the specific regulatory and practical context, in alignment with their respective guidelines and standards. Taking these elements into account will enable the construction of high-performance and long-lasting hydraulic structures.

The DigueELITE consortium thanks EPTB Vidourle and SYMADREM for enabling the dissemination of the knowledge gained through the construction of full-scale structures in 2015 on the Vidourle River and in 2017 at Salin de Giraud.

General introduction

French guidance and expertise on lime treatment for earthworks related to linear transport infrastructure and platforms are collected in the: *"Technical guide - Treatment of soils with lime and/or hydraulic binders - Application to the construction of fills and capping layers"* [1], published in January 2000 under the authority of the Laboratoire Central des Ponts et Chaussées (then Ifsttar, now Université Gustave Eiffel) and the Service d'Études Techniques des Routes et Autoroutes (now part of Cerema). The guide was developed through wide collaboration across the sector, including technical agencies, LCPC laboratories, project owners, project managers, contractors, equipment manufacturers, and binder suppliers. In December 2018, the European standard EN 16907-4 *"Earthworks – Part 4: Soil treatment with lime and/or hydraulic binders"* [2] was published. Rather than presenting a synthesis of European practices—which is difficult to achieve due to geological and climatic variability—it compiles the main practices in the form of a standard. Most of the French expertise is therefore presented, alongside practices of other countries, allowing the application of specifications best suited to the local context, such as those based on the GTS [1] in the French context.

The present document is a continuation of these existing technical references. Its scope includes the construction of hydraulic structures less than approximately fifteen meters in height, as well as the repair of such structures, using lime-treated soils (e.g. river dikes, small reservoirs, or flood control structures). Its role is to provide project owners, project managers, contractors, and quality control offices with justification for applying this technique, the advantages it offers, and the methodology to be followed.

Indeed, the performance achieved allows for considering lime treatment in broader contexts than merely reusing overly wet soils. The results in terms of mechanical strength and resistance to both internal and external erosion show that, when proper procedures are followed—including deposit characterization, lab testing, and field implementation—lime treatment offers technical, economic, and in some cases environmental advantages for hydraulic structures, excluding maritime structures which are still under investigation.

Furthermore, it has been demonstrated that the permeability of lime-treated soils is comparable to that of untreated soils when specific conditions of moisture content and compaction method are applied (water content on the wet side of OMC and compaction with a sheep's foot vibratory roller).

The document is organized into six sections, each one with a specific objective.

Section A

- Remind of the lime properties and its effects on soils.
- Identify potential applications of lime-treated soils in hydraulic structures based on their intended functions.

Section B

- Present the mechanical and hydraulic properties of lime-treated soils, especially the parameters used for the design:
 - laboratory and field test results,
 - quantification of internal and surface erosion resistance as measured in full-scale demonstrators.

Section C

- Describe the engineering and construction of a hydraulic structure using lime-treated soil:
 - sequence of studies,
 - deposit characterization and laboratory studies,
 - key design components.

Section D

- Present the applicable methodologies for constructing lime-treated soil structures:
 - o technical specifications, field test, and suitability field test,
 - o execution of the works.

Section E

- Identify key aspects of quality control in the construction of lime-treated soil structures.

Section F

- Describe the monitoring of hydraulic structures built with lime-treated soils.

Summary

Over more than fifteen years, numerous public and private laboratories and research institutions have confirmed and expanded the knowledge on lime treatment, enabling its practical application to hydraulic structures not exceeding fifteen meters in height. Intensive, multi-scale research has clearly demonstrated the benefits of lime treatment in terms of hydraulic performance, particularly regarding the resistance to internal and external erosion. It has been shown, both in laboratory and on full-scale structures, that the hydraulic conductivity of lime-treated soils can be comparable to that of untreated soils when applied correctly (wet-side moisture content and kneading compaction). Lime treatment significantly enhances the soil resistance to internal and external erosion. This has been repeatedly confirmed in laboratory tests across a wide range of soils using the Hole Erosion Test (HET). Similar results were found for the resistance to surface erosion, using various laboratory test devices (JET, MoJET, EFA). Notably, in many cases, the erosion resistance gained through lime treatment exceeded the measurement limits of current testing equipment.

Thanks to the involvement of EPTB Vidourle and SYMADREM, the construction of full-scale test plots (a demonstrator along the Vidourle River in the 2015 DigueELITE project and test plots at Salin de Giraud in 2017) played a key role in advancing knowledge and quantifying in-situ resistance of lime-treated soils to overflow-induced external erosion. Additional experimental structures—particularly the construction of a protective outer layer in lime-treated fine soil constructed by Lhoist in 2019 in Vlassenbroek, Belgium—have further enriched the existing knowledge. Because laboratory tests cannot faithfully simulate hydraulic loads caused by overflow, a dedicated apparatus was developed by INRAE and used for the first time in France during three testing campaigns on the aforementioned full-scale test plots. The device generates a real-size hydraulic load in a flow channel placed along the slope of the structure, with a water depth at the crest exceeding 0.30 m and a velocity at the bottom of the slope of approximately 5 m/s. The results showed that following the rapid erosion of the surface layer, lime-treated soils exhibited an overflow erosion resistance 3 to 10 times greater than that of the corresponding untreated soils. The results at the Salin de Giraud test plots were even more significant: no erosion occurred on the slopes treated with lime, while the untreated section experienced erosion depths of about 2 meters and a large erosion pit.

These significant research efforts—including laboratory testing, construction of full-scale experimental structures, development of innovative erosion resistance measurement tools, and in-situ performance assessments—enable the confident application of lime treatment in hydraulic structure construction. These studies provide quantitative evidence of the actual performance achieved on full-scale structures using conventional soil treatment and implementation methods.

The approach adopted during the research work is based on a segmented method according to the functional requirements sought in the structures to be built or repaired: workability, stability, watertightness, resistance to internal and/or external erosion, and to overspill water. Accordingly, the scope of the laboratory studies to be conducted before the construction depends on the intended functional requirements. If certain site parameters remain unknown or uncertain, it is recommended—when economically justifiable—to establish an experimental jobsite during the study phase to evaluate the project feasibility and confirm the achievement of expected results.

Based on the current knowledge and the recent advancements, lime treatment can now be applied to hydraulic structures to meet the following functional requirements, defined in the ICOLD bulletin 195 [3] and referred to in § 2.2:

- workability (M)
- stability (S), subject to the justification of stability in accordance with professional practices
- watertightness (P), applicable to structures with non-permanent loads and/or with applied waterproofing, subject to appropriate measures for crack control and verification of internal erosion resistance
- resistance to internal erosion (EI), subject to laboratory verification
- resistance to surface erosion (ES) (overflow and runoff), if the materials are similar to those tested at the Vidourle demonstrator and the experimental plots at Salin de Giraud (F1 or F2 soils), or, for other materials, subject to laboratory testing or preferably in-situ testing on experimental plots to verify surface erosion resistance

Notes:

1. *This list highlights the specific parameters associated with each proposed function that must be evaluated to determine the suitability of the lime-treated soil for the intended function. Depending on its intended role, the lime-treated soil component may meet the requirements of a single function or a combination of functions. These parameters are in addition to those required to determine the composition of the lime-treated soil and characterize its general properties.*
2. *The overspill water function (EV) applies in cases where the component must resist high-velocity flows (e.g., in channels). This function has not been thoroughly investigated and requires further supporting documentation.*

Extreme conditions—such as highly compressible or heterogeneous foundations, or unusual load scenarios (e.g., seismic loads)—must be carefully assessed during the preliminary design phase of the project.

For standard construction projects, a set of actions should be implemented to ensure that both the design team and contractors possess—or can effectively acquire—the necessary knowledge and technical skills required for a successful execution (e.g., awareness programs, training, feedback from previous projects). The involvement of the project management team is also a key factor in the successful execution of such structures. On-site support and monitoring during construction are essential.

The successful construction of high-quality hydraulic structures in lime-treated soil depends largely on controlling the following phases:

- **design the structure considering the performance of the lime-treated soil:**
 - precisely determine the stresses the structure will be subjected to
 - identify the functions that the lime-treated soil component can fulfill
 - determine the measures to be implemented to justify the use of these functions
 - compare conventional technical solutions with the alternatives in lime-treated soil from a technical, economic, environmental, and execution time perspective, among others
- **conduct a site investigation to assess** soil type, moisture content, and available quantity
- **conduct a laboratory study on soil treatment conditions sufficiently early, ideally starting from the design phase**

- **prepare a clear and detailed specifications file that includes, in addition to standard practices and procedures for conventional earthworks for earthen dikes, also:**
 - extraction conditions and, where necessary, procedures for homogenization and temporary storage of material resources
 - the soil treatment methodology to be used
 - specifications on treatment and implementation equipment
 - the expected production output
 - practical procedures for execution
 - a description of the preliminary tests to be performed and the parameters to be monitored
 - the control operations to be conducted during the construction phase
- **require a detailed technical response** from bidding companies (proposed methods, prior experience, quality assurance plan) and verify their competence in soil treatment

As in the cases of the Vidourle and Salin de Giraud test sites, for structures primarily intended to resist internal or external erosion, the water content during the implementation and the lime dosage must be carefully controlled under site operational conditions. All operations—from the extraction of the natural soil, the potential temporary stockpiling, the treatment, to the final implementation—must be managed to consistently achieve and maintain this target. The grain size of the lime-treated soil should be as fine as possible, targeting a maximum particle size of approximately 0/30 mm. The lime dosage control and the quality assurance of the treatment operations—particularly for in-place or on a dedicated platform treatment—must be clearly specified and properly organized. To ensure the required quality, other key parameters include compliance with the specified requirements for the thickness of individual layers and the recommended compaction energy, along with the uniformity of its distribution.

The contractor must comply with the project manager's specifications and ensure that appropriate equipment and qualified personnel are provided. The project manager also plays a key role in monitoring and inspecting the execution of the works. The implementation of a control plan must enable the project manager to continuously monitor and assess performance, and, if needed, apply corrective actions or adjust construction procedures based on actual conditions and observed outcomes.

Ambitious designs, going beyond the scope of currently validated practices, would allow for an optimized use of the properties of lime-treated soil. For example, the authors suggest that the use of lime-treated soils could have beneficial impacts on the cost and design of overflow-resistant dikes, including the role of spillway and the overall structural safety.

A. GENERAL INFORMATION

1. Why treat soil with lime?

1.1 Experience on earthworks

Lime treatment of soils is an ancient technique used since ancient times, which has seen renewed interest since the 1960s with the launch of infrastructure modernization programs (motorways, high-speed rail, airports, etc.). Today, this technique is widely recognized as safe and cost-effective, and has become indispensable. By enabling the reuse of poor-quality soils, it helps preserve natural resources of high-grade materials, reduce landfill disposal and construction time, and achieve cost savings in earthworks.

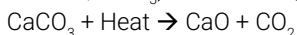
Despite the experience gained, the use of lime treatment in hydraulic structures remains limited. Examples in France include the Michelbach reservoir dam built in Alsace in the 1980s, small flood control dams in Normandy and the reservoir basins at the Paris Airports site (ADP, Roissy). Similar examples can also be found abroad. A list of hydraulic structures in France and abroad that used lime treatment with air lime (non-hydraulic calcic lime) is provided in Appendix 1.

This cautious development is due partly to the strict requirements regarding measures against water action, and partly to the reluctance among hydraulic structure designers toward soil treatment. Since retained water may flow within or on the surface of a hydraulic structure, it is essential to ensure that the components, design, and execution take into account the potential consequences of a failure, which could be catastrophic for the safety of the structure.

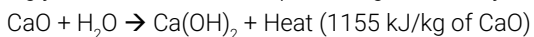
Today, the technological advances by equipment manufacturers, the expertise of designers and contractors, and the availability of guides and standards defining best practices and technical specifications have led to the development of high-performance equipment and execution methods capable of meeting the most demanding requirements, including those for hydraulic structures.

1.2 Lime

Lime is obtained by calcining limestone at around 900°C. When the limestone is primarily composed of calcium carbonate (CaCO_3), the resulting lime is referred to as calcic lime, consisting mainly of calcium oxide (CaO).



This lime is commonly known as quicklime because, when exposed to water, it hydrates very rapidly through a strongly exothermic reaction, producing calcium hydroxide (Ca(OH)_2), also known as hydrated lime or slaked lime.



In a humid atmosphere, hydrated lime reacts with atmospheric CO_2 to re-form calcium carbonate. This property is used in building mortars and plasters, where lime serves as a binder hardening upon contact with air. Hence the name "**calcium air lime**" for the lime derived from pure limestone. In the remainder of this document, the generic term "lime" will be used for simplicity.

Lime is manufactured at industrial sites and it has many different applications. In Europe, the lime used for soil treatment must comply with the specifications of the Standard EN 459-1 [4]. Since this standard covers a broad range of lime types and classes with distinct usage properties, it is essential to specify the desired type and class of lime when referencing this document. The mandatory CE marking certifies that the lime conforms to the European construction product regulations.

1.2.1 Effects of lime on silty clay soils

The most immediate and striking effect when treating soil with quicklime is the reduction in water content. This results from both the addition of dry matter and, more importantly, the highly exothermic hydration reaction. The heat released is nearly instantaneous and rapidly evaporates excess moisture, making quicklime ideal for treating wet soils—common across Europe.

In the case of dry soils, the use of hydrated lime—either in powder form or suspended in water (lime slurry or milk of lime)—is possible, but remains exceptional. For the same calcium content, transport and storage costs are lower for quicklime than for hydrated lime, whose bulk volume is roughly twice as high.

Regardless of the lime type used, its effects are classified as either short-term or medium- to long-term.

1.2.2 Short-term effects of lime on soils

Silty and clayey soils are water-sensitive: when excessively wet, they become plastic, sticky, and lose all bearing capacity. When such a soil is treated with quicklime, the immediate effect is a reduction in the water content.

Theoretically, 1% quicklime can reduce the soil water content by about 1%. In practice, the reduction can reach up to 5% under highly favorable conditions (e.g. hot, windy weather).

In parallel, lime alters the structure of clays in the soil by inducing their flocculation. This leads to a reduced plasticity and changes in particle size distribution after mixing (Figure 1).

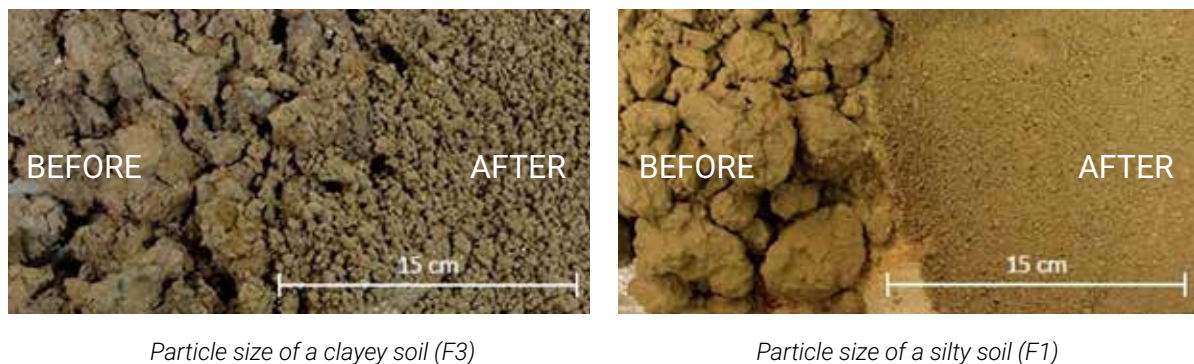


Figure 1: Examples of particle size distribution in wet clayey and silty soils before and after lime treatment (Photos: Lhoist)

As mentioned earlier, for dry soils, hydrated lime—either in powder form or as lime slurry—may be used, but its use remains rare in Europe. In such cases, the short-term effect primarily involves neutralizing clay activity, as outlined below.

Besides reducing the water content (in the case of quicklime), the short-term effects result from the cation exchange in aqueous conditions between Ca^{2+} ions from the lime and the cations in the clay minerals. These effects include:

- decrease in the plasticity index (I_p)
- increase in the shrinkage limit (w_s)
- reduction of the shrinkage-swelling behavior
- reduction in the maximum dry density at OMC ($\rho_{d_{\max\text{OMC}}}$)
- increase in optimum moisture content (w_{OMC})
- increase in the Immediate Bearing Index (IPI)

The lime dosage required for these short-term effects depends on clay type and soil moisture. It typically ranges from 1 to 3% of dry soil weight, but may be higher for highly clayey materials. Figure 2 illustrates the lime short-term effects on the clay soil properties (Atterberg limits, shrinkage limit). Figure 3 shows how lime treatment affects short-term workability and compaction behavior.

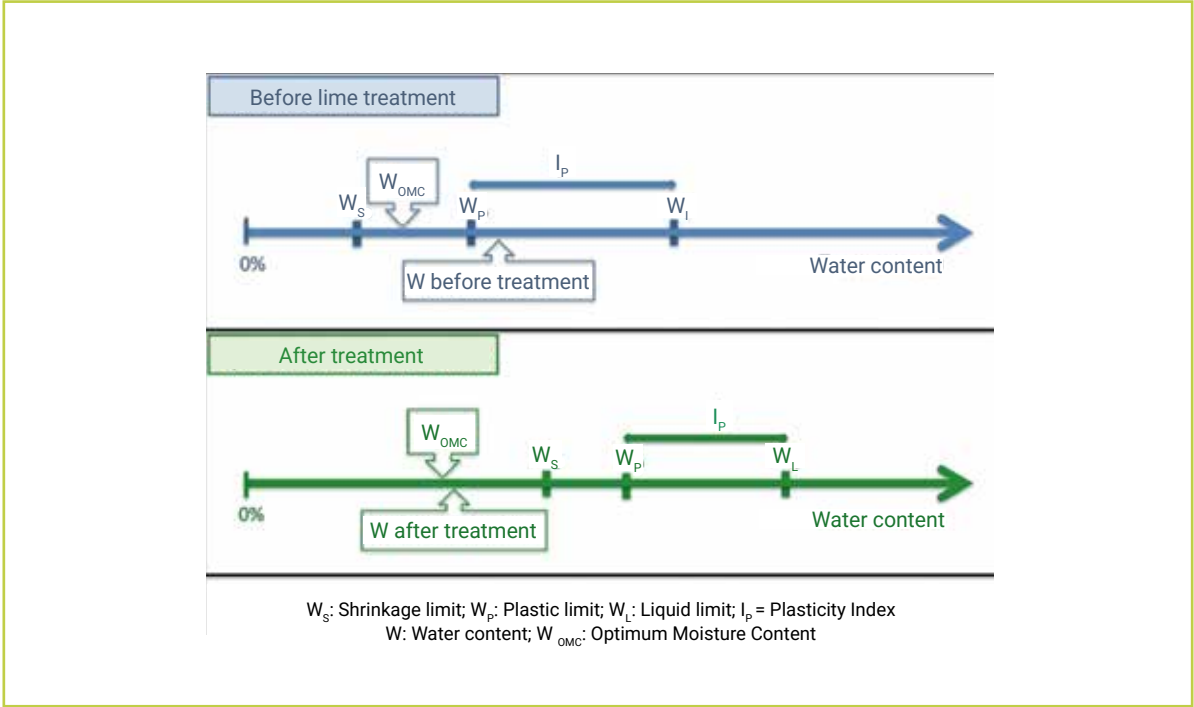


Figure 2: Effect of lime on Atterberg limits and shrinkage limit

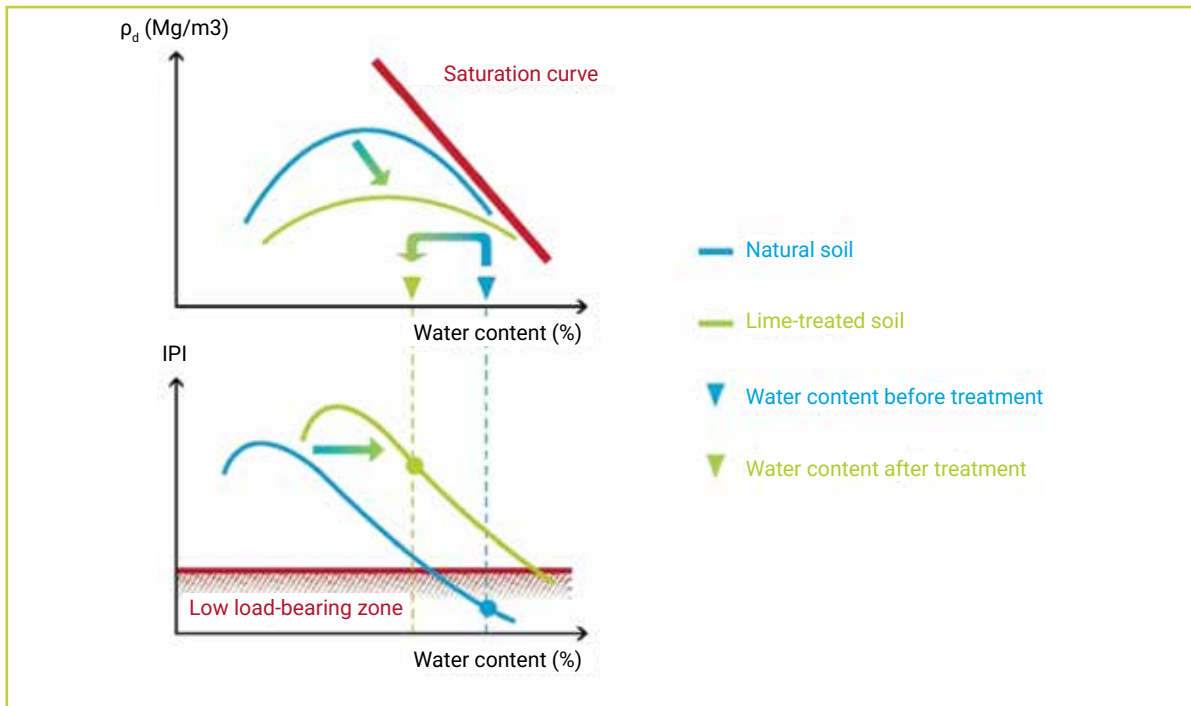


Figure 3: Typical Proctor and Immediate Bearing Index (IPI) curves of a silty-clay soil before and after lime treatment

Note: The Proctor curve of the lime-treated soil is flatter than that of the natural clayey soil. The incorporation of lime into natural soil favourably alters its sensitivity to water, as illustrated in Figure 4.



Figure 4: Behavior of specimens after 15 minutes of water soaking (untreated F1 soil on the left and specimen of the same soil treated with 2% lime on the right); specimens prepared 24 hours before soaking

1.2.3 Medium- and long-term effects of lime on soils

The medium- and long-term effects of lime on soils result from pozzolanic reactions, i.e. the combination of calcium provided by the lime with minerals in the soil (dissolved silica and alumina), forming a slow-setting cementitious compound. These reactions result in improved mechanical performance, increased resistance to static and dynamic loads, and enhanced durability against water and frost. The main effects are:

- increased resistance to immersion (measured using the CBR test after water immersion)
- gradual improvement in mechanical performance (strength, cohesion, modulus)
- increased resistance to erosion (internal and surface)

As an example, Figure 5 illustrates the increase in unconfined compressive strength of lime-treated soils as a function of time and lime dosage.

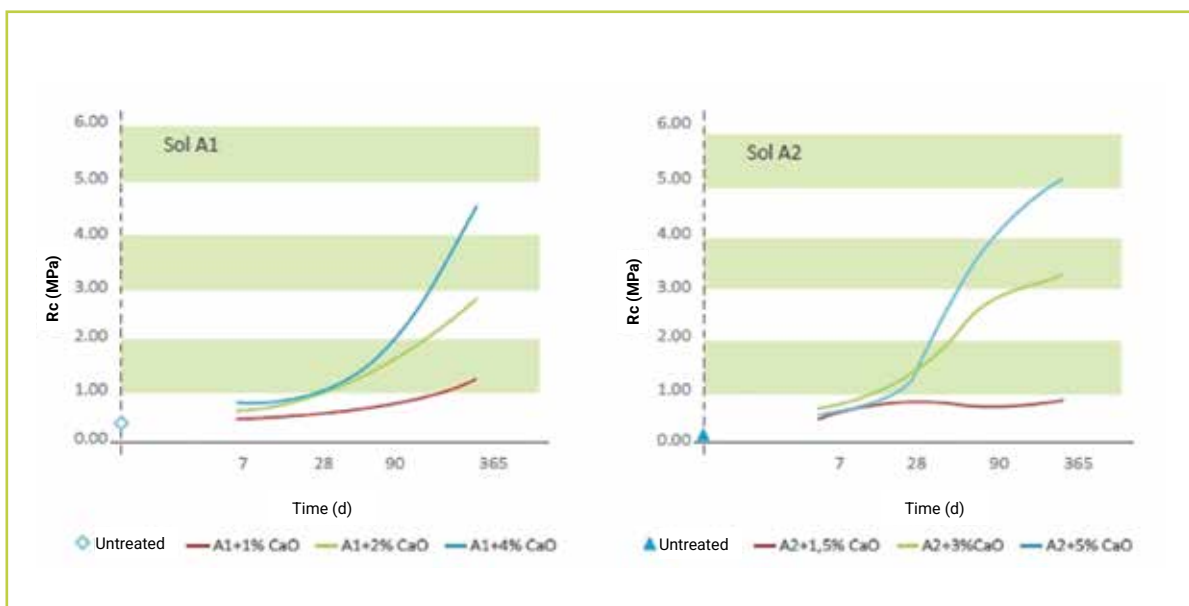


Figure 5: Examples of changes in unconfined compressive strength over time and lime dosage for F1 and F2 soils; the natural soil is shown at 0 days of curing

The kinetics of the soil-lime reactions depend on the type of clays present in the soil and the temperature at the time of the work. However, unlike hydraulic binders which only allow handling (or application) times of between one and a few hours, lime allows for much longer handling times, which are broadly compatible with the constraints of execution and the proper conduct of the works. When recycling fine soils, it is common practice to treat the soil with lime, store it, and reuse it several weeks later for construction.

To benefit from the medium- and long-term effects of lime, the soil must contain a sufficiently abundant and active clay fraction (particles passing through 2 μm). As a guideline, the plasticity index (I_p) of the soil should be equal to or greater than 5 ($I_p \geq 5$). For highly clayey soils, the decision depends on construction site constraints, such as equipment efficiency and execution methods.

In any case, laboratory testing is essential to determine the appropriate lime dosage based on the required performance. This dosage can range from 2 to 4% for silty soils with low clay content, and exceed 4%, even up to 6%, for highly clayey soils.

Quantitative data comparing the mechanical and hydraulic properties of various lime-treated soils with those of untreated counterparts are provided in Part B of the document. These data are drawn from bibliographic sources and from laboratory and in-situ measurements conducted during experimental construction projects.

1.3 Benefits of lime treatment for soils

The most widely recognized benefit of lime treatment is the reuse of wet or low-quality soils—typically silty-clayey soils, but also certain shales, marls, and chalks—by imparting new engineering properties through various processes:

- easier and more flexible extraction and implementation (workability)
- reduced sensitivity to water during rainfall or submersion
- dimensional stability of the clay fraction during drying and wetting cycles
- improved mechanical properties (bearing capacity, cohesion, strength, etc.)

At the project scale, this translates into:

- optimized use of on-site materials
- reduced need for external borrow materials and temporary storage
- less heavy vehicle traffic (site → storage or borrow areas)
- fewer work stoppages due to bad weather
- shorter construction schedules
- lower earthworks costs

Numerous studies have shown that when poor-quality soils are present on a road or rail project site, lime treatment can reduce earthwork costs by 20 to 40% compared to replacing them with imported borrow material.

For river dikes, initial estimates show cost savings of up to 35–40% compared to traditional construction methods. Part of the cost savings result from eliminating certain components such as filters, riprap protection, and anti-burrowing systems.

1.4 The scope of lime treatment for soils

As with any construction technique, the applicability of lime treatment is defined by certain limits that must be clearly understood to ensure a proper execution. These limits depend primarily on the geotechnical properties, the chemical and mineralogical composition of the natural soils.

1.4.1 Deleterious substances

The presence of certain compounds in the soil can reduce the effectiveness of lime treatment or adversely affect the behavior of treated soils over time. These include:

- sulfates (e.g. gypsum, plaster) and sulfides (e.g. pyrite), which can lead to delayed swelling due to the formation of ettringite—a swelling reaction product formed by the recombination of calcium with aluminates and sulfates in the presence of water. This may result in excessive swelling that could compromise the integrity of the structure after construction. If sulfate presence is suspected, an accelerated swelling test should be performed in accordance with EN 13286-49 [5] to evaluate the risk of ettringite swelling
- organic matter, which may consume lime to correct soil acidity and reduce the treatment effectiveness. If the organic content exceeds 3%, specific testing is required to assess its impact on treated soil performance
- phosphates and nitrates, often found in agricultural or industrial soils, which may act as retarders or inhibitors of lime-induced hardening
- chlorides, which in small quantities may accelerate curing and shorten the workability time. They are not considered deleterious as such, but their effects are uncertain when present in significant proportions
- mica-type minerals, whose flaky morphology weakens cement bonds and reduces the lime treatment effectiveness

In general, the impact of deleterious substances is assessed via water immersion testing. If test results are unsatisfactory (e.g. unacceptable swelling or loss of strength vs. non-immersed specimens), possible solutions include increasing lime dosage, adjusting application methods, using an alternative soil, or abandoning the lime treatment option. Such decisions must be based on well-documented laboratory studies and a full understanding of the influencing factors.

1.4.2 Highly plastic cohesive clays

Recent laboratory research and experimental test sections have demonstrated that lime treatment of very clayey soils (F3/F4 classifications) can be used to build structures of limited height. These advances make it possible to consider the reuse of such soil classes for the construction of hydraulic structures or parts of them, provided that the performance complies with the required functions.

The use of highly plastic soils requires particular care during both design and construction execution phases. In particular, due to their high cohesion, it can be difficult to mix the natural soil, lime, and any added water uniformly. This may require a two-stage treatment process, potentially with an intermediate curing period to allow flocculation and achieve a suitable texture. In such cases, the treatment methodology should be defined in the preparatory phase and validated through testing plots at the beginning of the works. For these soil types and based on the current best practice, the use of horizontal-shaft mixers is recommended.

1.4.3 Blocks

The quantity and size of blocks in the soil must be compatible with the capacity of the mixing equipment. Equipment like horizontal shaft mixers and centralized treatment units can currently handle particles up to 100 to 150 mm, depending on the petrographic nature of the rock fragments.

If the presence of large elements poses a risk of damaging the mixer tools, the coarse fraction should be removed using various techniques (in-situ disaggregation or scarification to bring the clusters to the surface, in-situ crushing, windrowing, screening, etc.).

In treatment plants, just like blocks, clods can hinder the operation of the equipment. These materials must be removed or reduced using various devices that are generally integrated into the plant (tilting scalping grid, clod breaker, screen, etc.). A soil preparation prior to being fed into the treatment plant is also possible—and often necessary—for moderately to highly clayey soils. This may include shoveling, pre-mixing, or the use of specific agricultural equipment such as harrows or rotary tillers to break up clods.

2. Using lime-treated soils for hydraulic structures

2.1 Historical references

The use of fine soils treated with lime in hydraulic structures is not a recent development. Several publications report the use—in France in particular, during the second half of the 19th century—of clayey soil aggregates treated with lime to reduce the water content of soils, to prevent clay shrinkage, and thereby to create dam or canal seals that were described at the time as "tough and flexible." The practice became less common during the first half of the 20th century.

Starting in the mid-20th century, lime treatment re-emerged as a technique to improve the behavior of poor soils, particularly swelling or dispersive soils. Several examples can be found of lime-treated soils used as protection layers or shells, including on dams of significant height, in the USA, South Africa, Swaziland, Australia, and Thailand.

One of the most well-documented examples is the early-1970s restoration of a section of the Friant-Kern irrigation canal in California, using in-situ treatment of swelling clays with quicklime (Figures 6 and 7). The site materials—highly plastic (I_p of 35 to 45)—were reused despite their high moisture content. They were treated with 4% quicklime and used to line the banks and the bottom of the canal, protecting the underlying native soil, stabilizing the slopes, and ensuring watertightness. Since then, lime-treated soil dikes have been regularly constructed in the United States, including along the Mississippi River.

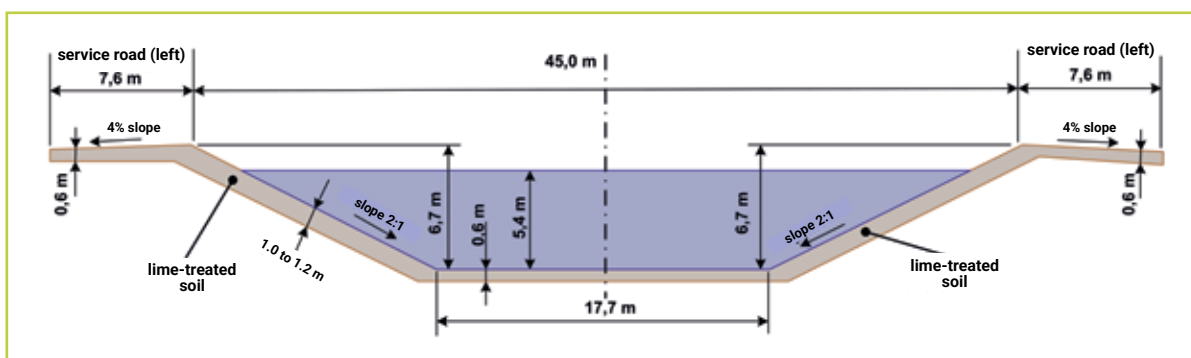


Figure 6: Cross-section of the Friant-Kern canal after the restoration using lime-treated soil



Lime-treated soil banks (Lhoist photo);



Surface cleaning after canal drainage (Lhoist photo)

Figure 7: View of the Friant-Kern canal banks (USA) made with lime-treated soil

Another significant example is the 40-meter-high and 1,500-meter-long dam constructed in the early 1980s at Mnjoli in Swaziland. Dispersive soils (average $I_p = 25$) were used for the core, which was protected against internal erosion on the downstream face by a layer of the same dispersive soil treated with 2% hydrated lime.

From the 1980s onward, the hydraulic structure sector benefited from the growing use of lime treatment in road and rail projects, along with associated technological progress and results. Beyond the simple improvement of poor soil behavior, lime treatment has increasingly become recognized as a way to impart beneficial properties that can be taken into account during the design of hydraulic structures. Thus, temporary cofferdams, small dams, and dikes have been built—particularly in Europe—by leveraging the mechanical and hydraulic properties of lime-treated soils.

In the past 20 years, small flood control dams have also been built in Normandy and the Czech Republic, using wet silty-clayey soils treated with lime to facilitate their implementation and improve the stability of the structures.

A more comprehensive list of identified reference structures is provided in Appendix 1. The performance of these structures, which remain in service today, is considered excellent.

Given the good results obtained, research initiatives have been launched by both private and public investors to better characterize the properties of lime-treated soils and to leverage their performance. Examples include the French research program DigueELITE and the construction of experimental test plots initiated by SYMADREM.

Following the emergence of this practice, the International Commission on Large Dams (ICOLD) tasked its Technical Committee P, “Cemented Material Dams” with drafting a bulletin titled “Cemented Soil Dams” on the subject [3]. “Cemented” refers to bonding via a cementation reaction—in this case, the combination of clay and lime—and “soil” refers to fine natural soil with a significant clay fraction, as opposed to natural or processed sands and gravels of varying cleanliness. This bulletin was approved by ICOLD at the Marseille Congress in June 2022 and is available on the ICOLD website.

2.2 Classification of the functions of the soil-lime component

Depending on its intended role within the hydraulic structure, the soil–lime component can fulfill different functions. The following six functions are proposed.

Workability (M): this function corresponds to the simplest case—ensuring ease of placement when working with wet silty–clayey soils.

Stability (S): this function applies when the mechanical stability of the structure—under its own weight and potentially under external loads (e.g., seismic loads)—is ensured by lime treatment.

Watertightness (P): this function is applicable when the soil–lime component must enable the structure to temporarily store or retain water.

Resistance to internal erosion (EI): this function is critical when resistance to internal seepage is a key performance criterion.

Resistance to surface erosion (ES): this function applies when the structure must retain or resist water inflow or overtopping—such as in a flood retention dam, protection levee, or overflow-resistant embankment.

Overspill water (EV): this function applies when the structure incorporates discharge facilities specific to hydraulic works.

For functions M and S, conventional in-situ lime treatment methods are generally adequate. However, for the other functions, producing and implementing the soil–lime component requires more stringent construction techniques. In particular, ensuring homogeneity of the compacted material is essential, regardless of the project scale or the nature of site-specific uncertainties. Indeed, maintaining the homogeneity is critical to minimize the risk of localized seepage—whether within the material (which may trigger internal erosion) or along the surface (which may cause surface erosion).

Table 1 summarizes the key characteristics of each proposed function. These parameters are required to assess whether the lime-treated soil can meet the functional objective in question. Depending on its role, the soil–lime component may be tailored to fulfill a single functions or a combination of several ones. These parameters are in addition to those required to determine the soil–lime mixture composition and to characterize its overall properties.

Table 1: The various functionalities proposed for the soil–lime component and their specific characteristics

Target functionality	Workability (M)	Stability (S)	Watertightness (P)	Resistance to internal erosion ⁽¹⁾ (EI)	Resistance to surface erosion ⁽²⁾ (ES)	Overspill water ⁽³⁾ (EV)
Properties of the soil–lime component	Ease of application (wet and/or clayey soils)	Stability under self-weight and potentially under seismic loading	Watertightness	Resistance to internal erosion	Resistance to external erosion	Resistance to high-velocity flow (channel, etc.)
Recommended treatment method ⁽⁴⁾	In situ or In plant	In situ or In plant	In situ with homogenization ⁽⁵⁾ or in plant	In situ with homogenization ⁽⁵⁾ or in plant	In situ with homogenization ⁽⁵⁾ or in plant	Using a mixing plant
Parameters studied	<ul style="list-style-type: none"> • Load-bearing capacity • Density of compacted material 	<ul style="list-style-type: none"> • Shear strength (cohesion) • Tensile and/or compressive strength 	<ul style="list-style-type: none"> • Homogeneity • Permeability 	<ul style="list-style-type: none"> • Homogeneity • Resistance to internal (hole) erosion 	<ul style="list-style-type: none"> • Homogeneity • Resistance to surface erosion under overflow conditions 	<ul style="list-style-type: none"> • Homogeneity • Resistance to surface erosion in discharge structures
Properties verified for the soil–lime component	<ul style="list-style-type: none"> • Common practice • Standardized ([1], [2]) 	<ul style="list-style-type: none"> • Common practice • Standardized ([1], [2], [6]) 	<ul style="list-style-type: none"> • Controlled if application guidelines are followed • Verified on the Rouen dike 	<ul style="list-style-type: none"> • Controlled if application guidelines are followed • Verified by HET testing and on the Rouen dike 	<ul style="list-style-type: none"> • Controlled if application guidelines are followed • Verified through Jet and MoJET tests, as well as at the Vidourle demonstration project and the Salin de Giraud test plot 	<ul style="list-style-type: none"> • To be documented

- (1) Hole erosion is the final stage of internal erosion mechanisms and is studied in laboratory using the Hole Erosion Test (HET). The HET critical shear stress is currently the most practical parameter for quantifying a material's resistance to internal erosion.
- (2) According to current knowledge, performance and specifications for the resistance to surface erosion (ES) are established either by analogy with a tested material or through an experimental jobsite incorporated into the study phase.
- (3) The overspill water (EV), which differs from the resistance to surface erosion (ES) due to the intensity of resistance to hydraulic loads—especially velocity and flow—is currently under study.
- (4) The recommended treatment process refers to the available technology at the time of writing. As technology evolves, these recommendations may be revised. The goal is to achieve mixing quality (particle size, homogeneity) compatible with the desired performance. For example, a 0/20 mm particle size was achieved with soil ($I_p = 7$) treated in plant, while 0/31.5 mm was achieved with soil ($I_p = 40$) treated in situ.
- (5) When necessary, particularly with heterogeneous deposits, the homogenization process involves extracting the material, storing it in horizontal layers, then retrieving it vertically (using a loader or excavator) prior to use. For highly clayey and/or wet soils, a preliminary lime treatment may be performed during homogenization. This pre-treatment must be followed by final lime treatment to achieve the dosage required for the target performance.

2.3 Soils usable after lime treatment

Current knowledge and insights from laboratory and full-scale studies provide a basis for identifying soil types usable in hydraulic structures after lime treatment, depending on the intended role and function of the soil–lime component within the structure. The soil classes correspond to those defined in the Standard EN 16907-2 [7].

For the workability (M) function, ease of placement is required. This concerns standard embankment fill. Any soil that can be treated with lime is potentially usable. Lime treatment is carried out to achieve an IPI ≥ 8 , depending on the clay content, allowing for proper workability in terms of trafficability and compaction. During the construction, the lime content may be adjusted based on moisture conditions to meet the required performance levels. If the moisture conditions are favorable (soil condition close to OMC), lime treatment is unnecessary.

For the stability (S) function, mechanical characteristics such as cohesion and internal friction angle must ensure long-term structural stability, as defined by the stability study. In this case, a uniform lime treatment across the entire structure is necessary. As a first approach, the following soil classes may be used after lime treatment:

- F1, F2, I1, I2
- Fine soils containing coarse elements can be also considered

Provided that effective construction methods are used and the mechanical properties achieved meet the expected performance (stability), the list may be extended to the following soils:

- F3
- Fine soils containing coarse elements can be also considered

In some cases, it may be advisable to carry out experimental projects to confirm actual performance and define conditions for the use of such soils.

For the watertightness (P) and resistance to surface erosion (ES) functions, the current usage is limited to fine soils of types F1 and F2, supported by recent case studies including results from the DigueELITE program. Findings from the *TerDOUEST* research program: "*Enseignements de TerDOUEST - Propositions de compléments au Guide Traitement des Sols*" (Lessons from TerDOUEST - Proposals for additions to the Soil Treatment Guide) [8] also suggests the potential extension to F3 soils; however, this would require additional steps (tests conducted as part of laboratory studies followed by experimental test sections). For these functions, the moisture content of the lime-treated soil at the time of compaction must be approximately $1.10 \times w_{OMC}$ while ensuring an IPI ≥ 8 to maintain adequate trafficability for equipment and a minimum bearing capacity.

For the resistance to internal erosion (EI) function, laboratory studies carried out as part of the Héricourt (TerDOUEST) embankment and the Vidourle and Salin de Giraud dikes suggest that fine soils F1, F2, F3, and certain F4 soils can be lime-treated to enhance internal erosion resistance. Nevertheless, for highly plastic F3 and F4 soils, it is important to note that the mixing and placement methodology must be validated through full-scale testing prior to any use onsite. Special care must be taken to achieve a sufficient particle refinement, meet the prescribed moisture content, and satisfy the required compaction targets.

For the overspill water (EV) function— resistance to surface erosion under high-velocity flow—proposals are still premature. Additional studies are necessary. However, it is reasonable to assume that fine F1 and F2 soils, which respond well to lime treatment with strict homogeneity and performance requirements, are likely to have an advantage over other soil types.

B. PROPERTIES OF LIME-TREATED SOILS

In addition to reducing the water content and thereby improving the workability, the addition of lime initiates a series of physicochemical reactions within the material. These reactions lead to the formation of cementitious compounds that act as binders between soil particles. As a result of these reactions, the mechanical properties of the material are often significantly improved. These changes result in increased mechanical strength, improved resistance to water and frost, and in a substantial enhancement of the resistance to both internal and surface erosion for the soil–lime component.

Moreover, provided that certain conditions regarding moisture content and compaction method are met, the addition of lime does not increase the permeability of the soil. Such application conditions promote the formation of dense cementitious phases at the microstructural level of the treated soil and alter its porosity by significantly reducing the number of macropores that govern its permeability.

3. Mechanical and hydraulic properties of fine lime-treated soils

The following tables (Table 2 through Table 8) list indicative values for various mechanical and hydraulic properties cited in the literature and compare them with values measured during the construction and monitoring of several well-documented experimental works: the Rouen and Vidourle (DigueELITE) structures, the test plots at Salin de Giraud, and the Vlassenbroek experimental site. Values are provided for both untreated soil and the same soil treated with lime at various curing times. The bibliographic data come from references [9] to [19] listed at the end of the document. For further details on the test conditions (moisture content, dry density, etc.), refer to these publications. The behaviour of these structures was monitored over time, leading to communications presented during specific events such as the “Digue 2024” workshops organized by INRAE, JNGG meetings, and through publications by ICOLD, CFBR, and specialized journals. These publications should be consulted to complement the results provided in this document.

Later in this document, Section 4 provides graphical illustrations of the short-term hydraulic properties of fine lime-treated soils, corresponding to Tables 6 through 8. Section 5 outlines key findings from the Vidourle and Salin de Giraud experimental sites concerning the surface erosion resistance of fine lime-treated soils under overflow conditions. Finally, Section 6 provides additional insights into specific properties of lime-treated soils.

Table 2. Mechanical properties of fine lime-treated soils (Table 1/4)

MECHANICAL PROPERTIES (1/4)								
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times			
					Natural soil	Lime-treated soil (age)		
Maximum shear modulus G_{max}	Laboratory testing	Vibration method	Bibliographic data	F1 soil treated with 2% CaO	0.2 GPa	0.8 GPa (7 days)	1.3 GPa (28 days)	2.8 GPa (90 days)
					-	0.6 GPa (7 days)	1.4 GPa (28 days)	2.4 GPa (90 days)
				F2 soil treated with 2.5% CaO	-	0.8 GPa (15–30 days)	1.0 GPa (30 days)	3.0 to 5.0 GPa (180 days)
					0.1 GPa	0.5 GPa (7 days)	2.2 GPa (365 days)	
Young's modulus E	Laboratory tests under small strain (measured using strain gauges bonded to specimens)	Secant modulus under 150 kPa confining pressure, unsaturated tests	Rouen Dike	F1 soil treated with 2% CaO	-	1.2 to 1.4 GPa (365 days)		
					-	50 MPa (30 days)	110 MPa (365 days)	
	Triaxial CD and CU laboratory tests under large strain	Secant modulus under 100 kPa confining pressure (saturated CD test)		F2 soil treated with 2.5% CaO	3 to 5 MPa	30 to 50 MPa (60 days)	stable value for longer curing times	
					1.6 MPa	37.8 MPa (28 days)	52.7 MPa (180 days)	81.6 MPa (380 days)
	Pressuremeter tests EN ISO 22476-4 [20]	Ménard pressuremeter		4 cycles with deviator: 0.25 MPa – 1.00 MPa – 1.25 MPa – 1.25 MPa average over three channels	-	cycle 1: 560 MPa – cycle 2: 480 MPa cycle 3: 420 MPa – cycle 4: 400 MPa (365 days)		

Table 3: Mechanical properties of fine lime-treated soils (Table 2/4)

MECHANICAL PROPERTIES (2/4)						
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times	
					Natural soil	Lime-treated soil (age)
Poisson's ratio ν	Laboratory testing		Rouen Dike	F2 soil treated with 2.5% CaO	≈0.15 value increasing with strain up to 0.60 for 0.3% strain	-
				Vidourle Dike	0.29 to 0.36 (Grindosonic method)	-
				Salin de Giraud Dike	0.19	0.14 (7 days) 0.15 (28 days) 0.18 (90 days)
Compressibility coefficient C_c	Oedometer tests		Bibliographic data	F4 soil treated with 5% CaO	0.20 to 0.30	0.14 to 0.45
				F4 soil treated with 3% CaO	0.26	0.25 (7 days) 0.23 (28 days)
				F2 soil treated with 2.5% CaO	0.16	0.08 (75 days) constant value for longer curing times
				F1 soil treated with 2% CaO	0.042	0.053 (7 days) 0.029 (28 days)
Swelling coefficient S	Oedometer tests		Bibliographic data	F1 soil treated with 2% CaO	0.05 to 0.06	0.01 (3 days)
				Rouen Dike	-	0.007 (75 days) 0.007 (210 days)
				Vidourle Dike	0.003	0.002 (7 days) 0.001 (28 days)
Pre-consolidation stress σ_c	Oedometer tests		Bibliographic data	F4 soil treated with 5% CaO	32 - 100 kPa	490 - 660 kPa (3 days)
				Vidourle Dike	109 kPa	565 kPa (7 days) 503 kPa (30 days)

Table 4: Mechanical properties of fine soils treated with lime (Table 3/4)

MECHANICAL PROPERTIES (3/4)							
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times		
					Natural soil	Lime-treated soil (age)	
Effective angle of internal friction ϕ'	Triaxial laboratory tests	CU conditions – peak values	Bibliographic data	F2 soil treated with 3% CaO	37°	35° (30 days) 38° (730 days)	
				F2 soil treated with 2.5% CaO	-	37° (45 days) 39° (405 days)	
	Triaxial laboratory tests	CU conditions – peak values	Vidourle Dike	F1 soil treated with 2% CaO	33°	46° (7 days) 42° (30 days)	
				F1 soil treated with 2% CaO	36°	39° (390 days)	
	Effective cohesion c'	Triaxial laboratory tests	CU conditions	Bibliographic data	F2 soil treated with 3% CaO	5 kPa	40 kPa (180 days) 80 kPa (195 days) 140 kPa (730 days)
					F1 and F2 soils	-	20 - 50 kPa (14 days) 40 - 100 kPa (90 days) 100 - 200 kPa (365 days)
Triaxial laboratory tests		CU conditions	Rouen Dike	F2 soil treated with 2.5% CaO	20 kPa	60 kPa (30 days) 300 kPa (225 days) 550 kPa (450 days)	
				F2 soil treated with 2.5% CaO	-	71 kPa (45 days) 90 kPa (210 days) 110 kPa (405 days)	
Triaxial laboratory tests	CD conditions peak values	Rouen Dike	F1 soil treated with 2% CaO	11 kPa	28 kPa (7 days) 40 kPa (30 days)		
			F2 soil treated with 2.5% CaO	20 kPa	75 kPa (75 days) 110 kPa (390 days)		

Table 5: Mechanical properties of fine lime-treated soils (Table 4/4)

MECHANICAL PROPERTIES (4/4)											
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times						
					Natural soil	Lime-treated soil (age)					
Unconfined compressive strength R_c	Laboratory testing	EN 13286-41 [22]	Rouen Dike	F2 soil treated with 2.5% CaO	0.35 MPa	0.67 MPa (7 days)	0.84 MPa (30 days)	1.61 MPa (180 days)	2.64 MPa (365 days)		
					0.21 MPa	0.32 MPa (7 days)	0.39 MPa (28 days)	0.53 MPa (90 days)	0.73 MPa (180 days)	1.20 MPa (365 days)	
			Salin de Giraud Dike	F1 soil treated with 2% CaO	0.17 MPa	0.23 MPa (7 days)	0.28 MPa (28 days)		0.42 MPa (90 days)		
					-	0.40 MPa (7 days)	0.60 MPa (28 days)	1.10 MPa (90 days)	1.10 MPa (180 days)	2.05 MPa (365 days)	
			Vlassenbroek dike	F1 soil treated with 2% CaO	0.018 MPa	0.048 MPa (7 days)	0.070 MPa (30 days)	0.110 MPa (180 days)	0.272 MPa (365 days)		
					-	0.027 MPa (7 days)	0.054 MPa (90 days)	0.063 MPa (180 days)	0.150 MPa (365 days)		
			Rouen Dike	F2 soil treated with 2.5% CaO	Splitting tensile strength test EN 13286-42 [23] EN 13286-43 [24]	0.018 MPa	0.020 MPa (7 days)	0.030 MPa (28 days)	0.041 MPa (90 days)		
						-	-	-	-	-	-
			Vidourle Dike	F1 soil treated with 2% CaO	Splitting tensile strength test EN 13286-42 [23] EN 13286-43 [24]	0.018 MPa	0.027 MPa (7 days)	0.054 MPa (90 days)	0.063 MPa (180 days)	0.150 MPa (365 days)	
						-	-	-	-	-	-
Salin de Giraud Dike	F1 soil treated with 2% CaO	Splitting tensile strength test EN 13286-42 [23] EN 13286-43 [24]	0.018 MPa	0.020 MPa (7 days)	0.030 MPa (28 days)	0.041 MPa (90 days)					
			-	-	-	-	-	-			

Table 6: Hydraulic properties of fine lime-treated soils (Table 1/3)

HYDRAULIC PROPERTIES (1/3)								
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times			
					Natural soil	Lime-treated soil (age)		
Saturated permeability k	Triaxial laboratory tests	CD conditions	Bibliographic data	F1 soil treated with 2% CaO	8×10^{-11} m/s	20×10^{-11} m/s (28 days)	9 to 30×10^{-11} m/s (180 days)	
				F1 soil treated with 4% CaO	8×10^{-11} m/s	40 to 70×10^{-11} m/s (180 days)		
				F2 soil treated with 3% CaO	4×10^{-11} m/s	5 to 10×10^{-11} m/s (28 days)	20×10^{-11} m/s (180 days)	
				F2 soil treated with 5% CaO	4×10^{-11} m/s	400×10^{-11} m/s (180 days)		
				F3 soil treated with 4% CaO	4×10^{-11} m/s	5 to 10×10^{-11} m/s (28 days)	20×10^{-11} m/s (180 days)	
				F2 soil treated with 2.5% CaO	1.1×10^{-9} m/s	2.8×10^{-9} m/s (28 days)	1.0×10^{-9} m/s (180 days)	1.0×10^{-9} m/s (380 days)
	In-situ testing	Double-packer permeability test in a screened borehole	Rouen Dike	Vidourle Dike	6.8×10^{-9} m/s	2.2×10^{-8} m/s (28 days) dynamic compaction	1.2×10^{-9} m/s (28 days) kneading compaction	
				Vidourle Dike		1.0×10^{-8} m/s (28 days) dynamic compaction	2.5×10^{-9} m/s (28 days) kneading compaction	
				Rouen Dike	1.5×10^{-9} m/s	7.7×10^{-10} m/s (28 days)	4.5×10^{-9} m/s (180 days)	8.5×10^{-9} m/s (380 days)

Table 7: Hydraulic properties of fine lime-treated soils (Table 2/3)

HYDRAULIC PROPERTIES (2/3)							
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times		
					Natural soil	Lime-treated soil (age)	
Critical hole erosion stress $\tau_{c,HET}$	Laboratory testing Hole Erosion Test (HET)	XP P94-065 [25]	Rouen Dike	F2 soil treated with 2.5% CaO	179 Pa	critical erosion stress > test limit (28 days and 180 days)	
					95 Pa	2030 Pa (2 days)	critical stress for erosion > test limit (28 days)
					35 Pa and 139 Pa	179 Pa (7 days)	833 Pa (90 days)
					154 Pa	634 Pa (8 days)	1080 Pa (28 days)
Fell's erosion index $I_{e,HET}$	Laboratory testing Hole Erosion Test (HET)	XP P94-065 [25]	Rouen Dike	F2 soil treated with 2.5% CaO	4.02	Not calculated for lime-treated soil after 28 days critical stress > test limit	
					3.45	3.24 (2 days)	Not measured for lime-treated soil after 28 days critical stress > test limit 3.27 (28 days + 32 days of immersion)
					4.17 and 3.90	4.25 (7 days)	6.09 (90 days)
					3.56	5.15 (8 days)	4.88 (28 days)

Characterization of resistance to internal erosion

Table 8: Hydraulic properties of fine lime-treated soils (Table 3/3)

HYDRAULIC PROPERTIES (2/3)									
Parameter studied	Test method	Comments	Jobsite case	Soil and treatment	Results obtained on natural soil and lime-treated soil at various curing times				
					Natural soil	Lime-treated soil (age)			
Critical surface erosion stress $\tau_{c,JET}$	JET tests ASTM D 5852	Laboratory JET tests	Rouen Dike	F2 soil treated with 2.5% CaO		Critical stress > test limit (28 days)			
		In-situ JET tests	Vidourle Dike	F1 soil treated with 2% CaO	5.9 Pa to 17.1 Pa (based on the critical stress applied at the beginning of the test)	Critical stress > test limit			
		Laboratory JET tests	Salin de Giraud Dike	F1 soil treated with 2% CaO	0 Pa	135 Pa (7 days)	600 Pa (90 days)		
		In-situ JET tests	Vlassenbroek dike	F1 soil treated with 2% CaO		165 Pa to 225 Pa (330 days)			
Hanson erosion coefficient $k_{d,JET}$	JET tests ASTM D 5852	Laboratory tests	Rouen Dike	F2 soil treated with 2.5% CaO		Not calculated for the lime-treated soil as critical stress > test limit			
		In-situ testing	Vidourle Dike	F1 soil treated with 2% CaO	17 to 45 cm ³ /N.s	Not calculated for the lime-treated soil as critical stress > test limit			
		Laboratory test	Salin de Giraud Dike	F1 soil treated with 2% CaO	1 cm ³ /N.s	Not calculated for the lime-treated soil as critical stress > test limit			
		In-situ testing	Vlassenbroek dike	F1 soil treated with 2% CaO		0.3 to 3.3 cm ³ /Ns (330 days)			

Characterization of resistance to external erosion

4. Additional notes on selected hydraulic properties

In the context of hydraulic structures, this section presents key factors used to characterize the behavior of fine soils treated with lime in presence of water. These results are based on laboratory tests carried out as part of academic research and experimental construction projects.

4.1 Water retention

Water retention curves for untreated and lime-treated fine soils of classes F1, F2, and F3—at various lime contents and curing times—are presented in Figure 8 [9]. Suction values are determined either by the filter paper method (PF) or by the potentiometer method (WP4) through relative humidity measurement.

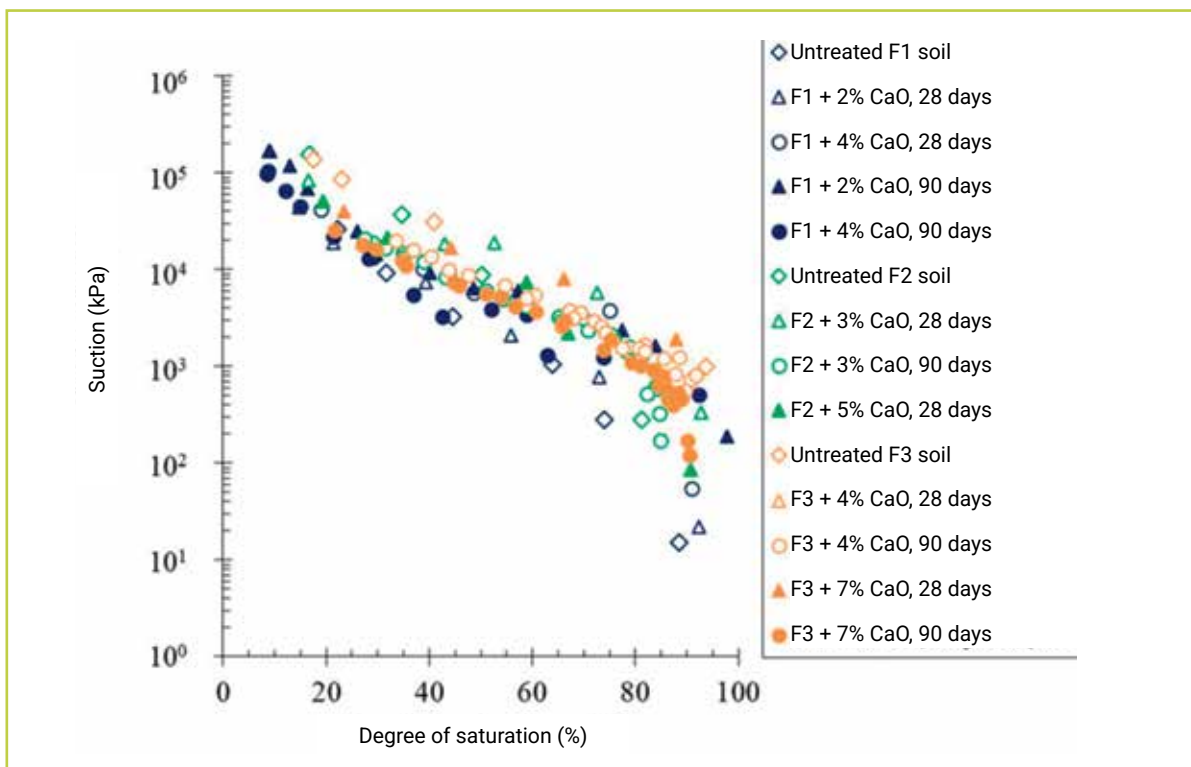


Figure 8: Suction curves [9]

According to the author, this comprehensive representation of the various cases of untreated and lime-treated fine soils shows that:

- the water retention curves for untreated and lime-treated F2 and F3 soils largely coincide
- the water retention curves for untreated and lime-treated F1 soil lie slightly below those for F2 and F3 soils, likely due to the lower clay content of F1
- lime treatment has minimal impact on the water retention behavior of F2 and F3 soils, regardless of lime content or curing time
- for the least clayey soil (F1), no difference is observed between treated and untreated soils at high suction levels ($S_r < 40\%$)
- at lower suction values ($S_r > 40\%$), lime-treated F1 soil shows slightly higher water retention than the untreated sample—likely indicating a more granular structure induced by lime treatment

4.2 Permeability

Prior to recent studies, the understanding of the permeability of lime-treated soils was limited and poorly documented. Often, the conclusions from one study to another were contradictory, or even controversial. In particular, it was commonly assumed, a priori, that lime treatment increased the soil permeability due to a reduction in the dry density compared to that of the same untreated soil under constant compaction energy. Therefore, it became necessary to conduct new studies to improve the understanding of the permeability of lime-treated soils, a parameter that must be properly controlled in the construction of hydraulic structures.

Laboratory tests conducted as part of the SOTREDI (SOil TREatment for Dikes) project, led by Lhoist between 2005 and 2011, showed that the permeability of a lime-treated F2 soil ($I_p = 12.7$ and $V_{BS} = 3.1$ g/100g) was equivalent to that of the same untreated soil, provided it was compacted in wet state and using kneading compaction. The study compared laboratory permeability measured using a constant-head permeameter with:

- two compaction methods: dynamic compaction with a Standard Proctor hammer, and a modified version of the Standard Proctor hammer simulating the kneading compaction mode, typical of a sheepsfoot roller,
- two moisture contents: w_{OMC} and $w_h (\approx 1.2 w_{OMC})$.

Tests were performed on the natural soil and on the soil treated with 2% and 3% CaO after 28 days of curing at 20°C. For the soil treated with 2% CaO, additional measurements were taken after 28 days + 2 months of water immersion and 28 days + 5 months of water immersion at 20°C. Results are shown in Table 9 and Figure 9.

Table 9: Permeability of untreated F2 silt and silt treated with 2% CaO, measured at w_{OMC} and w_h , in function of the compaction method

Compaction method	Soil	Curing time	Permeability obtained at w_{OMC} (m/s)	Permeability obtained at $w_h (\approx 1.2 \times w_{OMC})$ (m/s)
Dynamic compaction	Untreated		12×10^{-9}	$< 0.1 \times 10^{-9}$
	Treated with 2% CaO	28 days	33×10^{-9}	4.9×10^{-9}
		28 days + 2 months of water immersion	33×10^{-9}	4.8×10^{-9}
		28 days + 5 months of water immersion	16×10^{-9}	4.9×10^{-9}
	Treated with 3% CaO	28 days	42×10^{-9}	5.2×10^{-9}
Kneading compaction	Untreated			$< 0.1 \times 10^{-9}$
	Treated with 2% CaO	28 days	5.7×10^{-9}	0.1×10^{-9}
		28 days + 2 months of water immersion	7.8×10^{-9}	0.11×10^{-9}
		28 days + 5 months of water immersion	6.3×10^{-9}	$< 0.1 \times 10^{-9}$
	Treated with 3% CaO	28 days	47×10^{-9}	3.5×10^{-9}

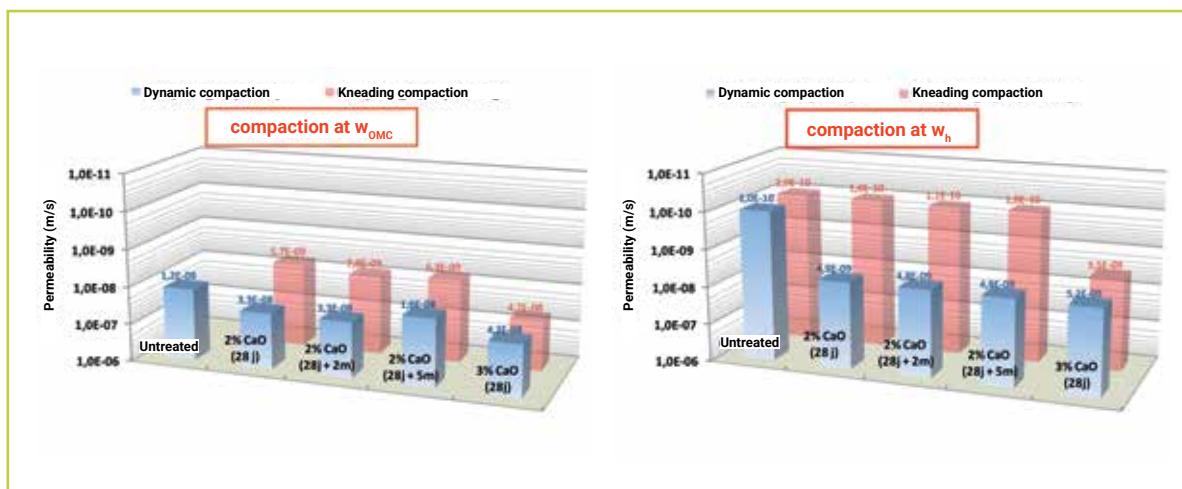


Figure 9: Evolution of the permeability of untreated and 2% CaO-treated F2 silt in function of the curing time and the compaction method

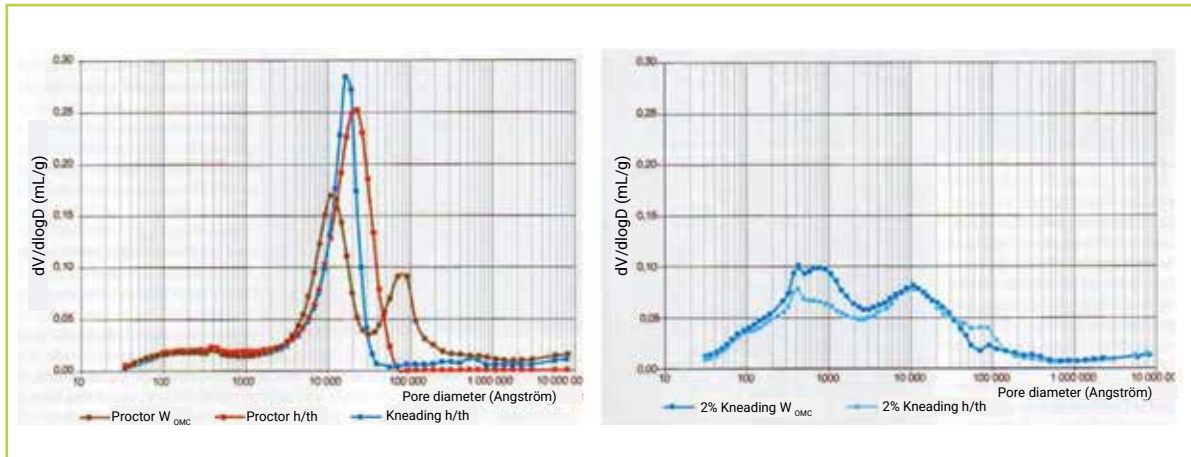
Results confirmed that, for the natural soil, a compaction at higher moisture content reduces the permeability compared to a compaction at w_{OMC} (from $k = 12 \times 10^{-9}$ m/s at w_{OMC} to $k < 0.1 \times 10^{-9}$ m/s at w_h). For the lime-treated soil compacted at w_{OMC} , the permeability values—whether compacted dynamically or by kneading—are of the same order of magnitude as those for the natural soil compacted dynamically at the same moisture content. If compacted on the wet side, regardless of compaction method, lime treatment, and curing conditions, the permeability measured at w_h is consistently lower than that measured at w_{OMC} .

Therefore, it can be concluded that a fine F2 soil treated with lime exhibits similar permeability behavior to that of the same untreated soil.

The critical factor in achieving a low permeability is the compaction method. Kneading compaction systematically leads to lower permeabilities thanks to more efficient compaction and the reinforcement of the soil due to shear compared with a vibrating single drum roller. At high water content, the permeability of a lime-treated soil (ranging from 3×10^{-9} m/s to 1×10^{-10} m/s) is comparable to that of the same untreated soil at the same moisture content.

In this study, permeability measurements were supplemented by microstructural investigations of the soil–lime mixture using mercury intrusion porosimetry (Figure 10), which demonstrated that:

- for untreated F2 soil, the pore size distribution varies significantly depending on the water content at compaction; under dynamic compaction, compaction at w_{OMC} produces a bimodal pore distribution (two pore classes, from 0.1 to 3 μ m and from 3 μ m to 0.1 mm). Using the same compaction method but with a higher water content ($w_h \approx 1.2 \times w_{OMC}$) eliminates macropores, resulting in a lower permeability. At these higher water contents, kneading compaction reduces micropore diameter, which further decreases permeability.
- Treating the same soil with 2% lime causes the formation of a new class of pores (very small nanopores ranging from 0.003 μ m to 0.3 μ m). For lime-treated soil compacted by kneading at w_{OMC} or w_h , a trimodal pore distribution is observed, with a substantial decrease in macropores that govern permeability.



Pore size distribution of untreated F2 silt as a function of water content and compaction method

Pore size distribution of F2 silt treated with 2% CaO as a function of water content and compaction method

Figure 10: Pore size distribution of untreated F2 silt and silt treated with 2% CaO

It can therefore be concluded that the permeability of lime-treated fine soils follows similar principles to that of untreated fine soils, namely that the most favorable conditions for achieving low permeability are:

- the materials should be conditioned on the wet side of w_{OMC} , between 1.05 and $1.15 \times w_{OMC}$,
- compaction according to a kneading process, for example using a vibrating padfoot roller.

4.3 Resistance to internal erosion

The resistance of a soil to internal erosion is assessed using the Hole Erosion Test (HET) conducted in the laboratory. This test is defined in the French pre-standard NF XP P94-065 [25]. The test is described in the document "L'essai d'érosion de conduit (HET Hole Erosion Test)" [26] and used by several laboratories in France (Figure 11). The test can be performed on intact soil samples obtained through coring operations or on laboratory-reconstituted specimens. The device allows the determination of the critical shear stress for internal erosion, which marks the erosion initiation threshold, as well as the erosion coefficient characterizing the erosion rate; the soil can then be qualitatively classified by erosion rate using the Fell classification system.



Figure 11: Device for measuring the resistance to internal erosion (HET test) (photo: INRAE)

Figure 12 presents the results obtained on a F1 soil untreated and treated with 2% lime after curing times ranging from 3 to 240 days.

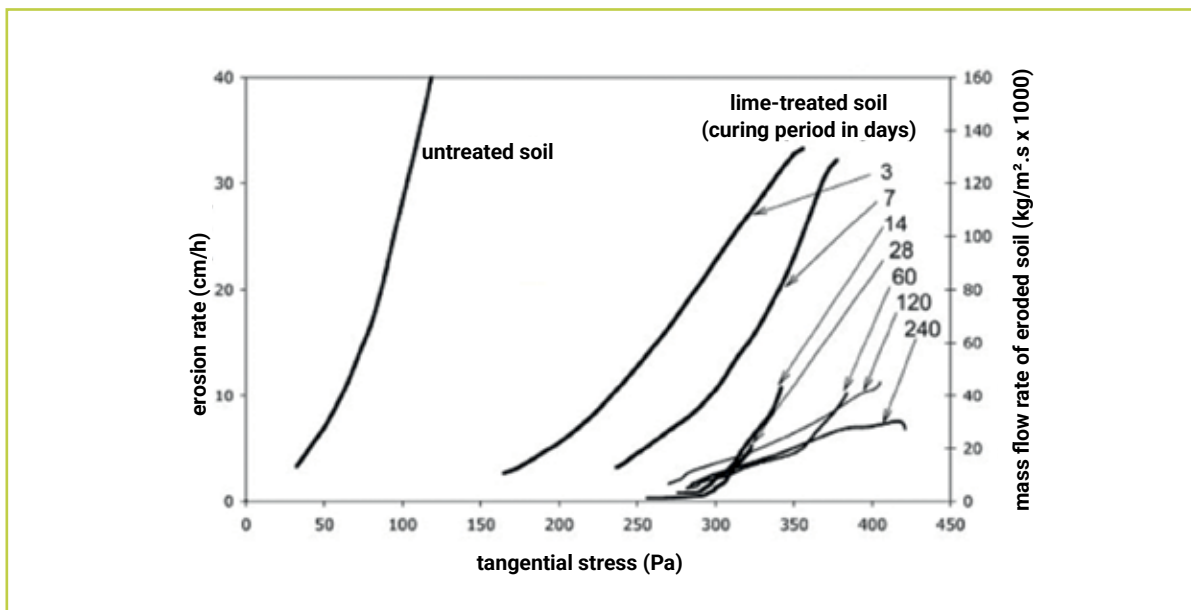


Figure 12: Hole erosion curves (HET test) for the untreated Rhône clayey silt (F1 soil) and the same soil treated with 2% lime after various curing times [45]

The erosion curves clearly distinguish the behavior of lime-treated soil from that of untreated soil under internal flow conditions. The critical stress, at which erosion starts, increases from 53 Pa for the untreated soil to 190 Pa for the lime-treated soil after only 3 days of curing. The critical stress further increases for the lime-treated soil, mainly for curing times between 3 and 14 days, reaching approximately 300 Pa. The critical stress remains stable and high with longer curing times; however, the erosion rate decreases significantly. In the presence of water, the resistance of lime-treated soils to internal erosion decreases slightly, but remains at a very high level and significantly higher than the resistance of untreated soils.

Figure 13 shows the results obtained on the soil used for the construction of the Vidourle dike. The critical hole erosion stress increases from 95 Pa for the untreated soil to 2030 Pa for the lime-treated soil after a short curing period of 2 days. After 28 days of curing followed by 32 days of water immersion of the sample, the critical stress remains at a high level of 1815 Pa.

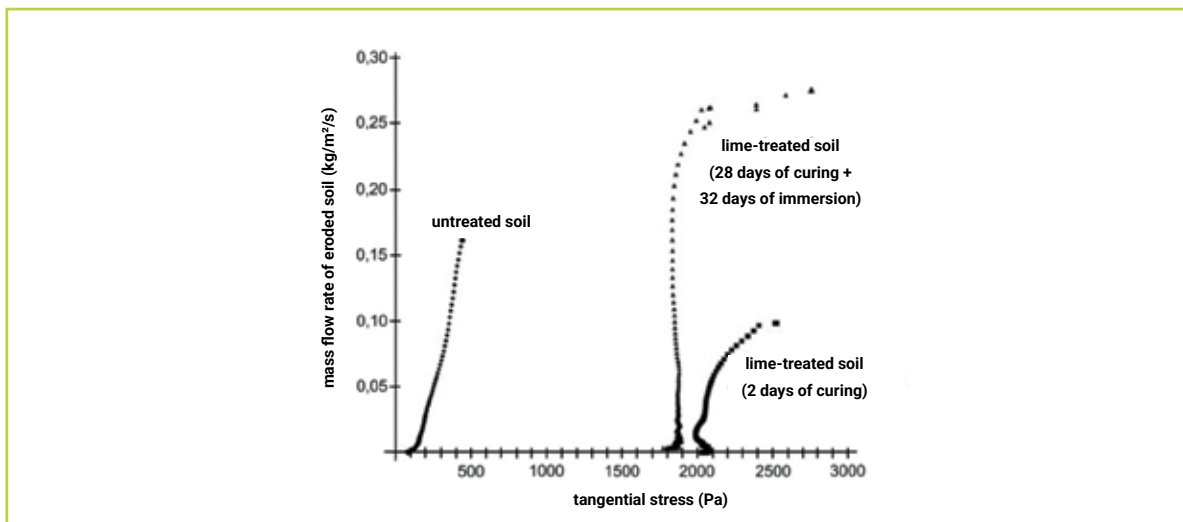
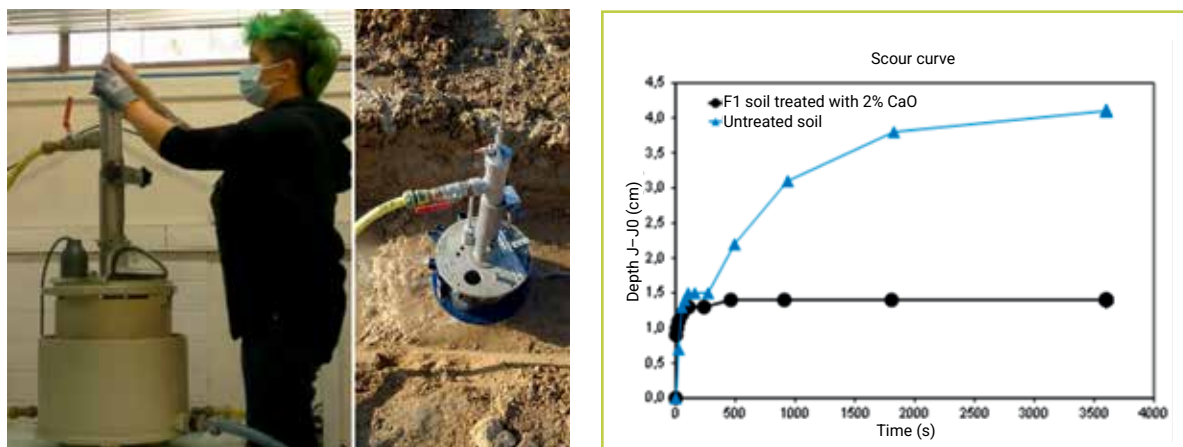


Figure 13: Hole erosion curves (HET test) on the F1 soil used for the Vidourle Dike, untreated and treated with 2% lime after a curing in immersion conditions

4.4 Resistance to surface erosion

The JET (Jet Erosion Test) device, derived from ASTM 5852 [27], is used to characterize the resistance to surface erosion, either in the laboratory or in situ being easily transportable. By measuring the depth of scour caused by a perpendicular water jet impacting the soil surface, both the critical surface erosion stress and the Hanson’s erosion coefficient can be determined.

Figure 14 shows the JET apparatus (left) and an in-situ scour depth measurement from the Vlassenbroek experimental site built with a F1 silt treated with 2% lime (right).



Device for measuring the surface erosion resistance, usable in both laboratory and field (photo: INRAE)

Scour curves obtained for a F1 soil treated with 2% lime after 7 months and 2 years of curing, and for the same untreated soil (Vlassenbroek experimental site – INRAE measurements, June 2022)

Figure 14: Characterisation of the surface erosion resistance (JET test)

5. Resistance of lime-treated soils to surface erosion caused by overflow

5.1 Test method for determining overflow-induced surface erosion resistance

The existing tests used to quantify the soil resistance to surface erosion are not well suited for assessing the overflow erosion. Because no established correlation exists between internal and surface erosion resistance, the Hole Erosion Test [28] is inconclusive for this application. The in-situ JET test is useful because it reflects what occurs at the toe of a levee and provides quantitative results [29]. However, it is not currently used for design purposes since it does not adequately represent the water action on the slopes during overflow events. As such, current testing methods are inadequate for qualifying the overflow erosion resistance of soils used in levee construction.

For this reason, the INRAE center in Aix-en-Provence developed a field overflow simulator as part of the DigueELITE project. This device generates free-surface flow on a steep slope within a channel defined by two lateral walls placed or embedded along the crest, the downstream slope, and the toe of the levee (Figure 15). A measuring device quantifies the surface erosion observed between the two lateral walls. This simulator was used on the Vidourle demonstrator in 2016 and 2017, and in 2018 on the experimental plots at Salin de Giraud.

A series of flow sequences, each lasting 30 to 60 minutes, is conducted by gradually increasing the flow rate at each stage. The erosion resulting from each flow sequence is measured. ASTM Standard D6460-7 [30], which simulates overflow in the laboratory, was used to design the overflow simulator and the associated experimental protocol.



General view of an overflow test (Salin de Giraud, May 2018) (Lhoist photo)



View of the 420 l/s/m flow on the lime-treated soil (Salin de Giraud, May 2018) (INRAE photo)

Figure 15: Overflow tests using the INRAE experimental device

During the overflow tests conducted in Salin de Giraud in 2018, the initial phase was conducted with a nominal flow rate of 95 l/s/m and the final phase with a flow rate of 570 l/s/m. For the maximum flow rate, the water depth at the crest was approximately 0.30 m and the velocity at the toe of the slope was around 6 m/s. At each flow rate stage, the hydraulic load was determined by measuring the inflow rate, flow velocity, and water depth (Figure 16).

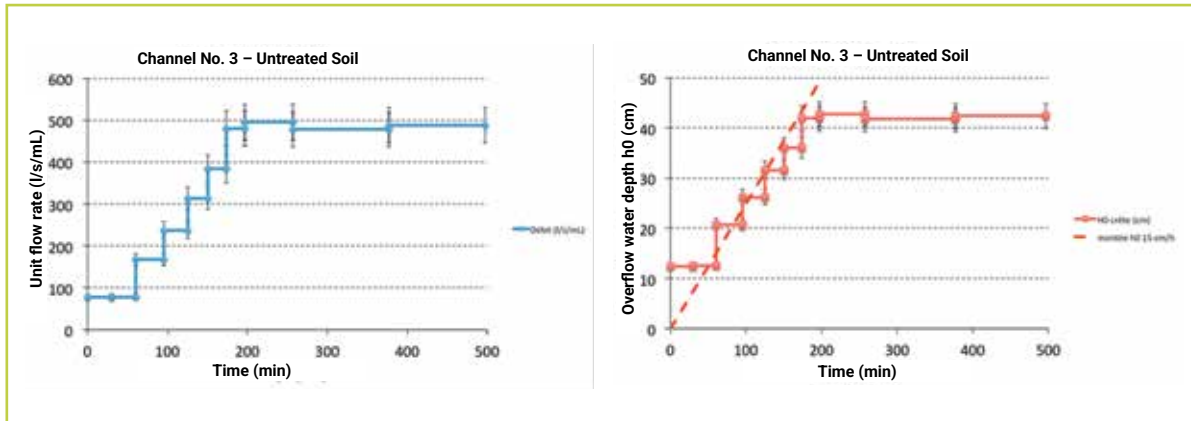


Figure 16: Hydraulic stresses obtained using the INRAE device on the experimental plots at Salin de Giraud (May 2018); flow rate steps on the left, water depth and overflow rise velocity on the right

After each sequence, corresponding to a specific flow rate, the quantity of eroded soil is measured using different techniques; the most accurate uses a terrestrial LIDAR-type 3D scanner, which operates by measuring distances at very high resolution via light wave reflection off an object. Based on this principle, the SMDE (Erosion Measurement and Detection System) was developed by ARCOR Technologies and used as part of the DigueELITE project (Figure 17). With its post-processing software, the system calculates the coordinates of scanned points in an absolute coordinate system with sub-millimetric resolution, surveys the internal surface of the channels between each flow stage (Figure 17), and quantifies erosion.

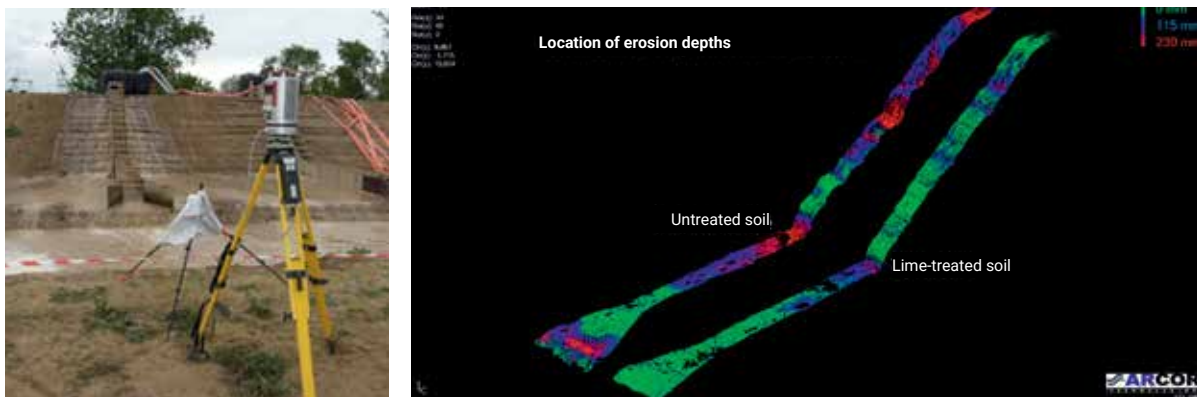


Figure 17: In-situ SMDE device (DigueELITE photo) Assessment of the overflow erosion in the two test channels on the Vidourle demonstrator using the SMDE system (May 2017)

Figure 17: In-situ SMDE device

After each flow sequence, the following indicators are calculated:

- **eroded volume (m³):** quantity of material eroded over a given surface
- **unit erosion (m³/m²):** quantity of material eroded per unit area [*]
- **erosion depth (m), either spot, average, or maximum:** thickness of the eroded layer measured at a specific point, average value, or maximum value over a given surface

[*]: this indicator corresponds to the CSLI (Copper Soil Loss Index from ASTM Standard D6460 [27]); it is equivalent to

the average erosion or the average eroded layer thickness.

5.2 Summary of the overflow test results on the Vidourle demonstrator and the experimental plots at Salin de Giraud

At both sites where the device was used, leaching of the superficial layer of the structure was observed during the first low-flow sequence. At the Vidourle demonstrator, the top layer of the embankment—uncovered by topsoil and weathered during a 10-month curing period—was eroded during the initial flow. Similarly, at the Salin de Giraud experimental plots, the unvegetated topsoil layer was eroded during the first flow sequence. After the initial leaching of the slope surface, the behavior of the untreated and lime-treated soils diverged significantly under the successive flow sequences at increasing discharge rates. The results obtained at the Vidourle demonstrator, shown in Figure 18, illustrate these observations.

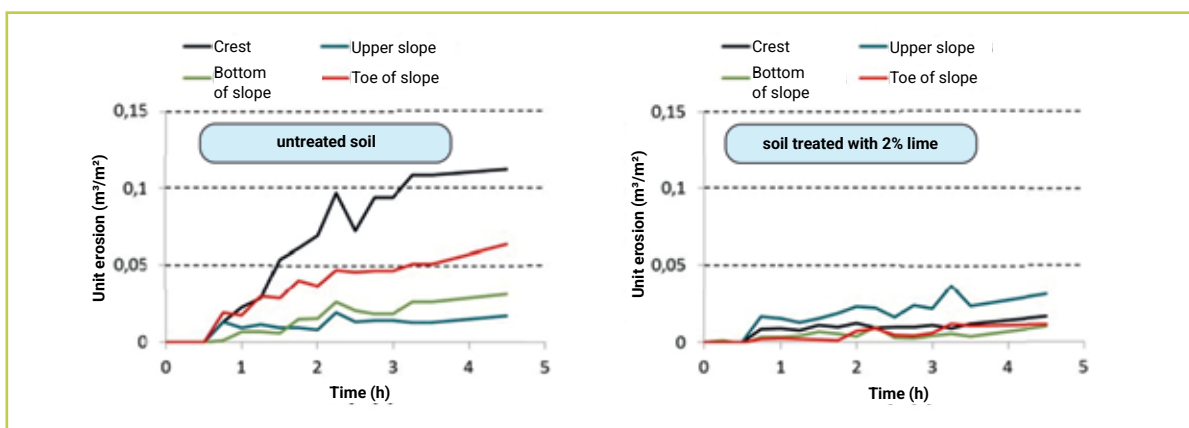


Figure 18: Unit erosion over time at increasing flow rates for untreated and 2% lime-treated soils (Vidourle demonstrator, April 2016)

In the case of the lime-treated soil, the unit erosion remained low across all zones (dike crest, upper and lower downstream slope, and dike toe). By comparison, the untreated soil showed substantial erosion, particularly at the dike crest and toe of the slope. In these two areas, the erosion of the untreated soil was 5 to 10 times greater than that of the treated soil.

Figure 19 shows the mean and maximum erosion depths measured at the Salin de Giraud plots for different flow sequences. The topsoil thickness, ranging from 0.30 to 0.40 m, is also shown. For both soil types, the topsoil eroded rapidly at the minimum flow rate, at a velocity of approximately 60 cm/h.

For the untreated soil, after the topsoil was washed away, the erosion has begun at a water depth of around 0.40 m, continued steadily, and then accelerated after 3 hours of flow, reaching an erosion rate of 12 cm/h.

For the lime-treated soil, only the topsoil layer was subject to erosion. The lime treated soil underwent no significant erosion, regardless of the flow rate or duration, which lasted approximately 8 hours 30, including 5 hours 30 at a unit flow rate of around 370 l/s/m and an overflow water depth of about 0.35 m.

The picture in Figure 20 shows the condition of the flow channels at the end of testing.

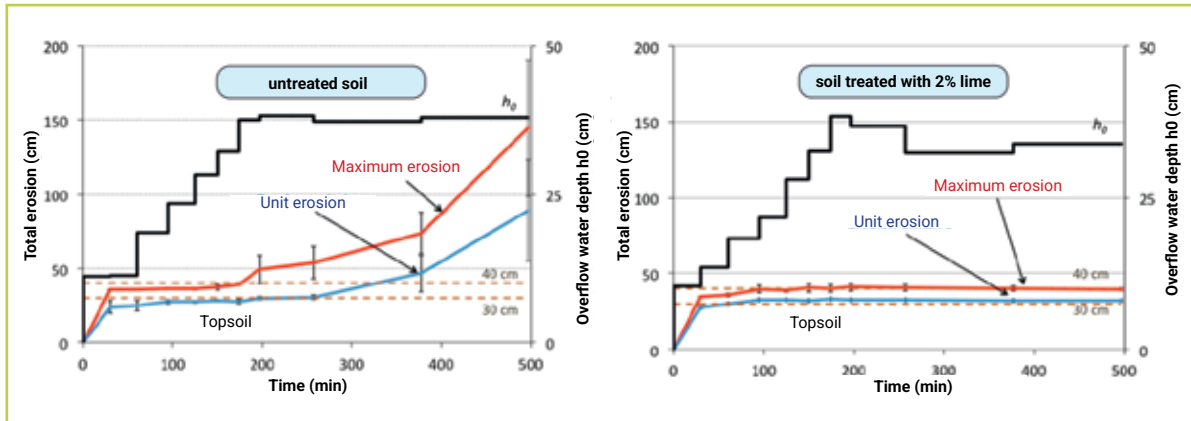


Figure 19: Unit and maximum erosion over time at increasing flow rates for the untreated and the 2% lime-treated soils (experimental plots at Salin de Giraud, May 2018)

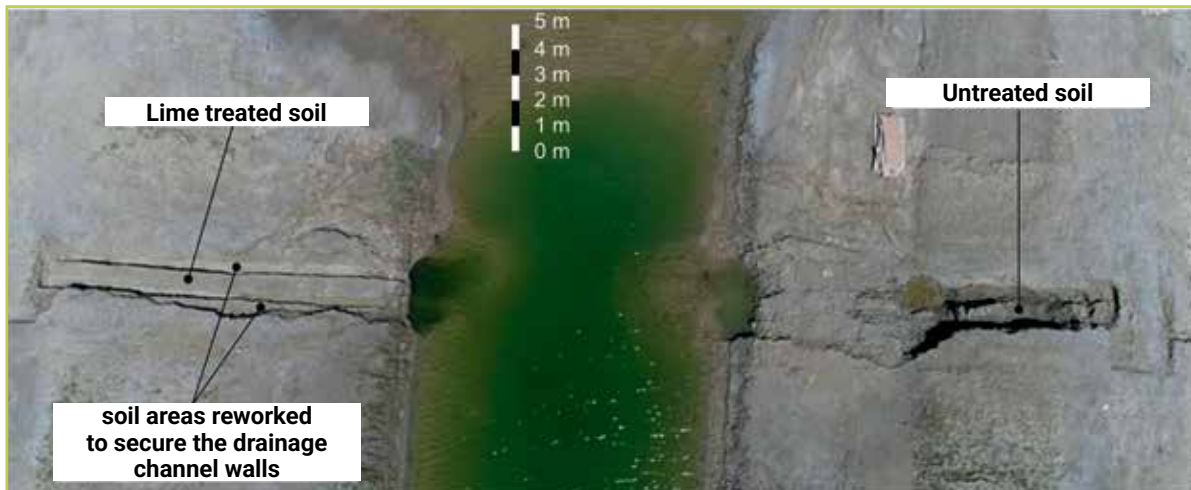


Figure 20: Experimental plots at Salin de Giraud; aerial view after overflow tests and dismantling of the discharge channels (scale for reference only)

5.3 Conclusions on the assessment of the resistance of lime-treated soils to overflow-induced surface erosion

The results obtained from the tests on the Vidourle demonstrator and the Salin de Giraud experimental plots enabled the comparison of the surface erosion resistance of lime-treated soils with that of the same soils in their natural state.

Under the following test conditions:

- for the Vidourle demonstrator:
 - maximum water flow rate: 570 l/s/m
 - maximum velocity: 6 m/s
 - peak water depth at the crest: 47 cm
 - cumulative volume of water discharged per plot: ~ 6,000 m³ (April 2016)

- for the experimental plots at Salin de Giraud:
 - maximum water flow rate: 447 l/s/m
 - maximum velocity: 5 m/s (treated soil) and 4 m/s (untreated soil)
 - peak water depth at the crest: 40 cm
 - cumulative volume of water discharged per plot: ~ 10,000 m³

The following behavioral differences were observed:

- for the Vidourle demonstrator:
 - at the crest of the structure, the erosion of the untreated soil was 6 to 7 times greater than that of the same lime-treated soil
 - on the upper part of the slope, both soils eroded similarly
 - on the lower part of the slope, the erosion of the untreated soil was 3 times greater than that of the treated soil
 - at the toe of the slope, the erosion pit in the untreated soil was 5 to 10 times deeper than in the treated soil
- for the experimental plots at Salin de Giraud:
 - after a rapid erosion of the topsoil layer covering the slope, the erosion of the lime-treated soil was almost negligible
 - after 3 hours of flow and the erosion of the topsoil, the untreated soil underwent rapid and severe erosion (erosion rate exceeding 20 cm/h), with observed erosion depths reaching nearly 2 m

The results from these innovative full-scale testing campaigns made it possible to evaluate the resistance of lime-treated soils to overflow erosion and quantify it in comparison with conventional protection methods.

The data acquired using the SMDE make it possible to calculate the Clopper Soil Loss Index (CSLI), as defined in ASTM D6460 [30]. According to this standard, the acceptable erosion threshold corresponds to CSLI < 0.5 inch (1.27 cm). Based on the channel tests, surface protections such as geosynthetics and rock mattresses were classified in a chart proposed by CIRIA [31], shown in Figure 21. The chart indicates, for each protection type, the flow velocity threshold as a function of flow duration where CSLI > 1.27 cm. As an example, the overflow tests on the Vidourle demonstrator made it possible to classify the soils used in the experimental embankments on the chart. The limiting flow velocity corresponds to a maximum erosion depth of 1.27 cm (see procedures in [31], page 813). It is 3 m/s for the untreated soil, installed using a procedure designed to achieve optimal resistance. Applying the erosion process to the demonstrator at the maximum flow velocity (5 m/s) for 4.5 hours did not cause erosion greater than 1.27 cm. On the chart, this implies that the erosion threshold velocity of the treated soil is at least 5 m/s for 4.5 hours. This means that a flow velocity below 5 m/s (as in most embankments), sustained for 4.5 hours, will not cause more than 1.27 cm of erosion. For longer durations, an overflow test matching the intended time period should be carried out.

The results shown in Figure 21 highlight the substantial increase in surface erosion resistance of a lime-treated soil compared with the same untreated soil, and its performance compared to that of conventional protection methods.

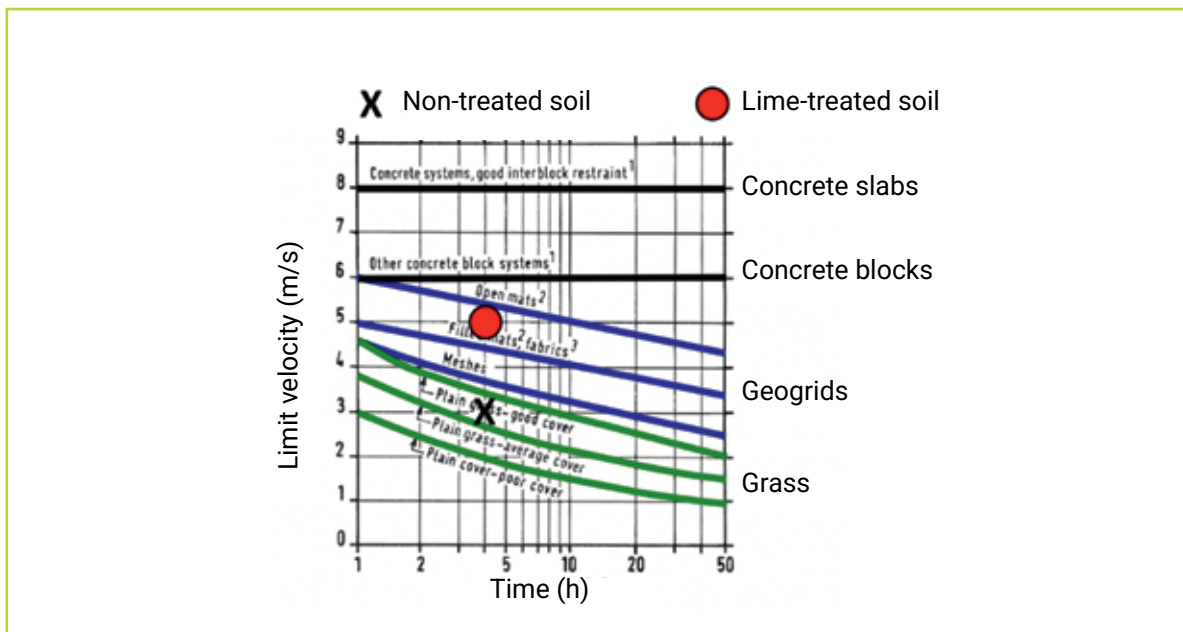


Figure 21: Classification of the soils used in the construction of the Vidourle demonstrator according to the CIRIA chart ([31] Figure 8.48, page 813)

6. Other properties of fine lime-treated soils

6.1 Influence of execution and curing parameters on the effects of the treatment

Not all soil types are equally suitable for lime treatment. Suitability largely depends on their mineral and clay composition. For a soil suitable for lime treatment, the percentage of lime added significantly influences the short- and long-term characteristics. The application of the reference method to determine the lime fixation point (LFP) of the soils—enabling medium- and long-term pozzolanic reactions and detailed in § 7.4.2—led to selecting lime dosages of 2 to 3% for most of the tests presented here.

Laboratory tests on F1, F2 and F3 soils [9] also demonstrated the influence of moisture content and compaction conditions on the permeability of lime-treated soils. However, the lime dosage seems to affect only partially the long-term evolution of this parameter.

Time is a major factor in the evolution of the mechanical properties in lime-treated soils, as it allows long-term pozzolanic reactions to develop, thereby improving the mechanical performance. Cohesion and tensile (or compressive) strength are the parameters most sensitive to curing time.

Several tests on the Rouen soil [32] and other F1, F2, and F3 soils [11] helped characterize the effect of temperature on the hardening rate of the soil-lime mixture. An increase in curing temperature accelerates the development of mechanical properties over time, particularly compressive strength and shear strength (Figure 22). Conversely, a decrease in curing temperature slows the development of mechanical properties in the soil-lime component.

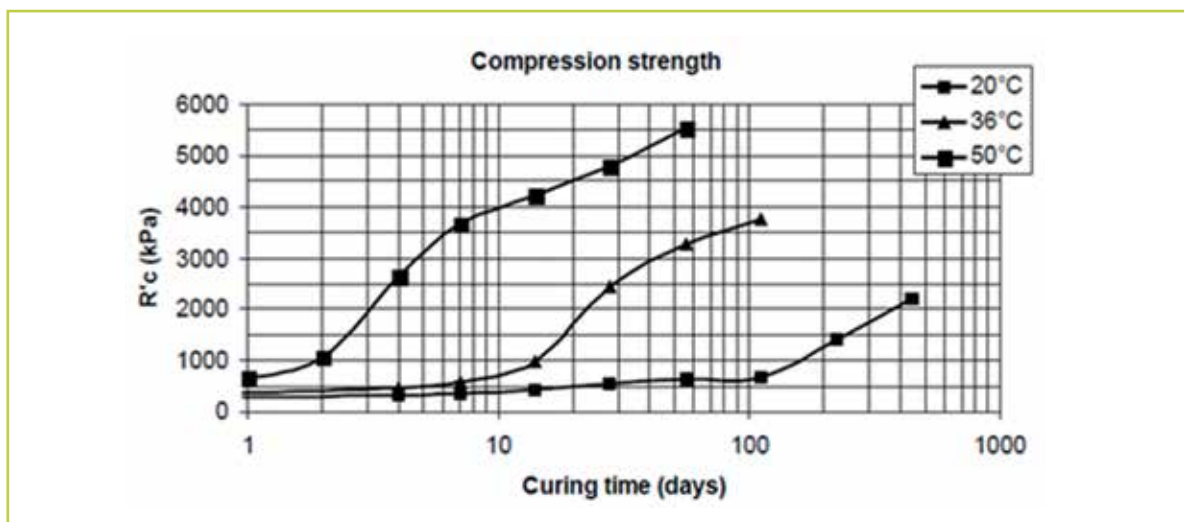


Figure 22: Effect of time and temperature on the compressive strength of a silt treated with 3% lime [29]

6.2 Mechanical strength of lime-treated soils

Direct tensile strength (R_t) is not commonly measured, but remains an important criterion in road construction and is frequently used for cemented materials. The results of the indirect tensile strength (R_{it}) tests generally allow the direct tensile strength to be estimated through the following correlation from the GTS [1]: $R_t \approx 0.8 R_{it}$.

Furthermore, tests on materials treated with different lime percentages [33] made it possible to assess the ratio between R_{it} and compressive strength R_c after various curing times. In general, $R_c/R_{it} \approx 10$. Tests were conducted on a French F1 soil and a Belgian clayey F2 soil [10], yielding the same trend for curing times ranging from 14 days to 1 year, with values between 8 and 14. The strong correlation of the results makes it possible to estimate the direct tensile strength as:

$$R_t \approx 0.8 \alpha R_c \text{ (with } \alpha \text{ between 0.08 and 0.12)}$$

This ratio also appears to remain relatively constant over the curing time.

6.3 Managing the cracking risks in treated and untreated fine soils

Cracking is common in earth structures, especially those exposed to hot and dry weather conditions (low humidity). Cracking may cause structural issues and is generally attributed to two main factors: soil drying and differential movement [34].

6.3.1 Shrinkage cracking

Drying results from a significant soil dehydration, which may lead to water shrinkage of the backfill mass. Constrained by geometry, this shrinkage may lead to cracking. The DigueELITE project allowed this issue to be studied at the Vidourle site, where specific implementation conditions favored the occurrence of this phenomenon in the both materials:

- significant addition of water, to bring the too dry natural soil to the moisture content required for implementation as determined by the studies
- daytime ambient temperatures reaching 35°C with moderate wind (highly drying conditions)
- application temperature of the treated soil above 45°C
- absence of a protective layer against drying external conditions: no topsoil layer was applied to the demonstrator

Cracks were indeed observed on the Vidourle demonstrator, both in the lime-treated and untreated soil areas (Appendix 2). A difference in the crack formation rate was observed: cracks appeared shortly after placement in the treated soil, and a few months later in the untreated soil.

Although cracks in the untreated soil appeared later, they worsened compared to those in the treated soil. Thus, the materials along the edges of the cracks showed rapid deterioration leading to erosion, and causing a widening of the cracks, which facilitated runoff water penetration into the backfill. No such development was observed in the treated soil: the material retained a durable appearance around the crack edges and no deterioration was recorded during the observation period.

Given the observed cracking in both soils, it was decided to initiate analyses and research to clarify the conditions leading to the crack formation. This work remains at the exploratory stage, as outlined in the box below.

DigueELITE insights into the risk of cracking in lime-treated soil embankments and in untreated soil

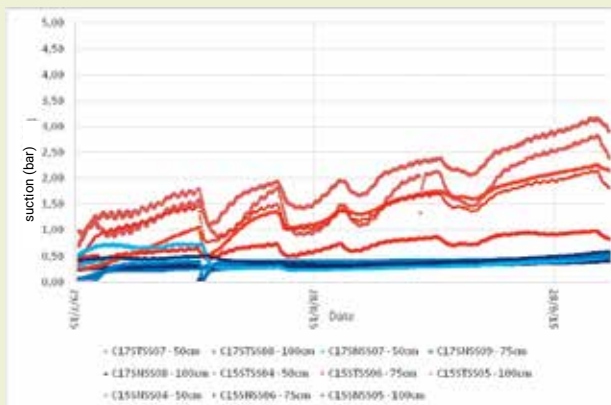
The Vidourle demonstrator helped to advance in the understanding of the shrinkage-induced cracking risk in lime-treated and untreated soil embankments, as well as how suction develops.

Factual data

On-site measurements: the lime-treated soil was applied immediately after leaving the mixing plant, at a relatively high temperature due to the exothermic reaction between lime and water ($T_{\text{soil}} > 45^{\circ}\text{C}$), thereby promoting evaporation.

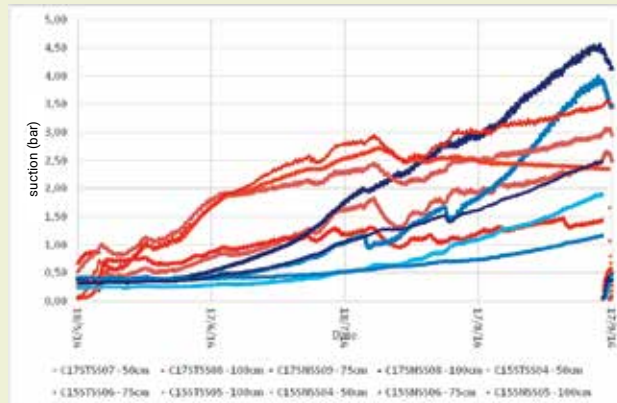
Instrumentation:

The Vidourle demonstrator was equipped with suction probes placed in the cover layer at depths of 50, 75, and 100 cm. The recordings show a rise in suction during the summer of 2015 while the lime-treated soil was still young, reaching around 200 kPa by late summer 2015 (figure on the right). The high suction that developed at an early stage in the lime-treated soil reflects the rapid evaporation of water from the mix, reaching water contents well below compaction targets (up to -7 points in ten days).



Suction trends in lime-treated soil (red) and untreated soil (blue) just after construction in summer 2015.

Meanwhile, suction values in the untreated soil remained fairly stable, reaching around 50 kPa by the end of summer 2015. During summer 2016, suction increased in both soils. By late summer 2016, suction levels in both the lime-treated and untreated soils were of the same order, between 100 and 350 kPa, with the highest suction recorded in the untreated soil (figure on the right).



Suction trends in lime-treated soil (red) and untreated soil (blue) in summer 2016.

DigueELITE insights into the risk of cracking in lime-treated and untreated soil embankments

Laboratory testing:

The initial results of the research conducted so far on the Vidourle material are as follows.

- The shrinkage limit of the lime-treated soil shifts significantly, reaching a water content 5 to 7% higher than that of the untreated soil, which confirms the short-term effect of lime treatment. Note that this “intrinsic” material property does not allow for direct conclusions on the shrinkage potential of the embankment material. Indeed, the conditions under which the shrinkage limit test is conducted differ from those of an embankment material: a saturated, uncompacted sample placed in an oven (with controlled and constant temperature and humidity).
- The bulk density has a significant influence on the tensile strength of lime-treated soils; the denser is the material, the higher is its strength.
- Restrained shrinkage tests indicate that cracking occurs in the lime-treated soil under higher suction stresses than in the untreated soil.

Discussion:

In general, and based on the variations in water content observed on the demonstrator, it appears that the drying shrinkage was more significant than the thermal shrinkage in the structure. Although the soil was placed at high temperature, the weather conditions (minor day/night temperature differences and high day-time temperatures during construction) prevented the structure from cooling abruptly.

Furthermore, the temperature sensors installed in the dike did not record any long-term exothermic phenomena (unlike concrete, for example, which undergoes an exothermic reaction during setting). Thus, thermal shrinkage during the curing phase was ruled out. However, since the shrinkage coefficient of the soil-lime component is not known (around 1×10^{-5} for concrete), the potential combined effect of early thermal and drying shrinkage is still under investigation.

The pozzolanic reaction in the lime-treated soil produces two competing effects in terms of resistance to cracking. The exothermic nature of the reaction appears to induce suction, but the hardening increases both the shrinkage limit and the tensile strength.

The lack of early suction development in the untreated soil does not protect it from later experiencing suction levels as high as those in the lime-treated soil when exposed to the summer climate of southern France. However, the untreated soil does not benefit from the increased shrinkage resistance provided by the lime treatment.

Lessons learned:

Although the lime-treated soil shows increased resistance to drying shrinkage cracking, the following precautions should nevertheless be taken during the execution in hot and dry weather conditions:

- set the target water content during the execution when aiming for a low microscopic permeability, which requires working on the wet side
- avoid exceeding the target water content to limit the risk of premature shrinkage, particularly before the tensile strength of the lime-treated soil has increased
- avoid the surface drying of the layer (systematic periodic watering, and covering the backfill before any period of inactivity – e.g. weekends or site shutdowns)
- allow the mixture to cool in storage when treated in plant to prevent the placement at high-temperature, which would accelerate the evaporation

The ICOLD Bulletin 195, “Cemented Soil Dams” [3], considers that cracking may affect several key design aspects, particularly due to the risk of water infiltration through the body of the embankment. Soil-lime mixtures provide good resistance to internal erosion, unlike untreated soils. However, potential water flow may be unacceptable in the case of structures subject to permanent loads, for which the Bulletin recommends upstream seepage control. In this way, the body of the structure is not in contact with water and does not serve a seepage control function.

6.3.2 Risks associated with foundation movements

Differential settlements may occur if the structure is placed on a foundation that is too compressible or if the foundation soil is heterogeneous across the structure footprint. Differential movements may also arise in inadequately compacted embankments.

For any structure built on a compressible foundation, the settlement limit state must be carefully assessed, especially in the presence of differential settlement risk. In the early stage, a lime-treated soil structure can accommodate settlements as effectively as an untreated soil structure, given their comparable modulus of elasticity. Once cured, the lime-treated soil becomes stiffer than the untreated soil and develops higher tensile strength.

Whether using lime-treated or untreated soil, the first step is to calculate the magnitude of the differential settlements and relate them to the length over which they will be absorbed, to assess whether they are acceptable for the structure.

In the case of lime-treated soils:

- if a limited leakage is acceptable (as with structures under non-permanent loads), and if the soil-lime compound is used to provide internal erosion protection (EI), it can be demonstrated that the resistance is sufficient and that additional devices (filters, sealing layers, etc.) may be unnecessary

- if the aim is to limit the risk of cracking, before considering, as with untreated soils, pre-loading or foundation soil reinforcement solutions, attention must be given to the rate at which settlements develop in the foundation, and to the rate of hardening and strength gain in the soil-lime compound. Indeed, for compressible fine soils, primary consolidation settlements are not immediate and typically occur over a variable period depending on permeability, drainage capacity, and thickness of the fine soil layer. However, the hardening and tensile strength development of lime-treated soils often occur on a comparable timescale. The engineer's task is therefore to study in parallel the kinetics of settlement in the foundation and the hardening and tensile strength development in the lime-treated soil.

6.4 Frost resistance

Although the frost-related stresses differ between hydraulic earthworks and road or rail infrastructure (such as backfill, upper earthworks, or lime-treated subgrade), the latter cases can serve as a reference for evaluating the frost performance of the constituent materials.

In France, the materials used in road and railway construction are classified as highly frost-sensitive (SGt), slightly frost-sensitive (SGp), or non-frost-sensitive (SGn). The frost heave test, as defined in the French Standard NF P 98-234-2 [35], is used to determine this classification. If such test is not planned, a conservative approach is to consider fine lime-treated soils as non-frost-sensitive when their compressive strength reaches 2.5 MPa.

In practice, it is important that the surface treatment operations on areas exposed to frost are completed well before its onset. In the event of frost risk, recently treated surfaces can be protected by applying a layer of untreated material, left in place throughout the entire frost period. The effects of frost do not manifest in the same way at the scale of the fully constructed structure as they do at the scale of implementation of a single layer. Frost generally affects only the superficial part of the structure (skin), whereas the body of the structure remains unaffected. Applying a topsoil cover layer on the slopes of the structure helps ensuring good performance against this risk.

6.5 Interstitial pressures

The stability of embankments built with fine materials depends on the interstitial overpressure induced, if any, during the construction. The generation of interstitial pressures within the structure depends on the degree of saturation, the compressibility of the compacted soil, the coefficient of consolidation, and the rate of construction. This also applies to lime-treated soil structures during the construction due to their slow setting and hardening kinetics. Interstitial pressure generation is less justified once pozzolanic reactions result in a gradual increase in modulus, coefficient of consolidation, and pre-consolidation stress.

For treated structures less than 15 m in height – therefore experiencing stress states lower than the compaction stress of 200 to 300 kPa – a simple stability verification can be performed. Slope failure along a circular slip surface is generally the most critical case.

Beyond 15 m, a potential development of interstitial pressure within the embankment body must be considered. Compressibility studies conducted in the laboratory on soils treated with 2.5% lime, along with calculations, have demonstrated that provided the initial degree of saturation after compaction is on average less than 90%, with no single value greater than or equal to 95%, the risk of interstitial pressure development at 14 days is almost negligible under a vertical stress corresponding to an embankment of 30 m high, or even 50 m depending on the case. Controls performed on a series of structures have shown that the aforementioned saturation conditions were met for a target density of $95\% \rho_{dmaxOMC}$, including implementation water contents between 1.05 and $1,15 \times w_{OMC}$.

If the doubt persists, the embankment stability should be verified using models that allow the designer to account for the progressive layer-by-layer construction in parallel with the increase in the mechanical properties of the treated soil and its stiffness, as measured by laboratory tests at different curing times.

6.6 Migration of Ca²⁺ ions in the medium and pH value in relation to the environment

Lime treatment of soils involves an effective mixing resulting in a significant increase in soil basicity, which can reach pH values greater than 12. This high pH, necessary for the development of pozzolanic bonds, is maintained for a long period, from several years to several decades. Consequently, certain questions may arise regarding the presence of calcium and hydroxyl ions in treated soil masses and their potential diffusion into the immediate environment of these structures, such as aquifers, groundwater, etc.

To address these questions, several multi-scale studies have been conducted. Thus, leaching experiments conducted in the laboratory on soils treated with 3% lime, a full-scale study on a trench filled with lime-treated materials and left in a saturated state for 2 months, as well as measurements taken at a construction site involving lime earthworks, lead to the same conclusions: the impact of lime treatment on the immediate environment of the structure, in terms of migration and diffusion of calcium and hydroxyl ions, is very limited. The presence of these ions and the impact of a pH increase are restricted to a few centimeters outside the treated material (5 to 6 cm for pH, up to 20 cm for calcium ions, which are more mobile).

During these studies, the calcium concentrations in the leachate, expressed as calcium oxide (CaO) content, remain well below the PNEC (*Predicted No Effect Concentration*) value mentioned in the REACH regulations (*European Union Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals, in force since June 2007*).

These results tend to demonstrate the "buffer" nature of the untreated soil in contact with the treated soil sections, acting as a barrier, and neutralizing the diffusion of ions outside the lime-treated material. These conclusions should be correlated with several bibliographical elements indicating the very limited mobility of lime-constituent ions outside treated soil columns used for structure foundations or for deep soil treatment. Furthermore, the pH and calcium ion concentration prove to be very stable over time, which confirms their availability for long-term "cementation" reactions.

In the event that the lime-treated soil is in permanent contact with water (e.g., a basin, a small retention dam, etc.), the question of lime migration and potential impact on the water may arise. As part of the DigueELITE project, a retention basin with a capacity of 200 m³ was constructed using local soil treated with 2% lime. This basin (Figure 23) was located below a berm and a platform, both also constructed with the same treated soil. The basin water consisted of rainwater mixed with water from pumping. Three months after the basin's construction, the measured pH values (7.2 to 7.3) were identical to those from samples taken from the Vidourle River, indicating no impact on the quality of the water contained within the basin.



Figure 23: Vidourle jobsite: view of the F1 soil basin treated with 2% lime after 6 months (INRAE photo taken on 04-02-2016)

6.7 Load-bearing capacity of lime-treated soils for foundation design

Fine soils treated with lime experience an increase in their mechanical performance immediately after treatment, which continues with curing. This property is useful and important for the construction of surface structures that may overlay hydraulic structures, which, in the most general case, consists of a service road reserved for the operation and maintenance of the structure, or more rarely, a pavement subgrade structure open to traffic.

In the first case, the uppermost layer of the structure constructed with treated soil must meet a minimum bearing capacity allowing for the compaction of the overlying access track layer, which is typically made of granular material (0/31.5 mm). The mechanical characteristics of the uppermost treated soil layer are not considered in the design of the service road but only address the feasibility of its construction. The interposition of a reinforcing geosynthetic at the structure/track interface is not necessary. A minimum bearing capacity of 35 MPa is recommended for the uppermost treated soil layer. If the service road is constructed immediately after the treated soil placement, achieving this criterion may potentially be conditioned by a slight overdosing of lime in the uppermost layer or an adjustment of its placement water content to fall within an average moisture state ($0,9 \times w_{OMC} \leq w_n \leq 1,1 \times w_{OMC}$) to attain the desired bearing capacity level. A protective layer, such as an emulsion with aggregates, is recommended before the construction of the service road.

In cases where a pavement structure is intended to cover the hydraulic structure and support road traffic, the usual road design methods apply. For the subgrade, the following elements must be determined:

- the embankment capping layer class
- the subgrade design (material, thickness)
- the subgrade bearing capacity class

The lime treatment allows to increase the bearing capacity of the treated soils and to reduce the thickness of the upper layer (capping layer). The modulus at the subgrade level (last embankment layer) must be 50 MPa (plate-load test) before the subgrade is placed. As in the previous case, a slight overdosing of lime in the uppermost layer or an adjustment of its placement water content may be necessary to achieve an average moisture state that allows for obtaining the desired bearing capacity.

Depending on the soil type and if the area concerned is not or minimally affected by frost, the subgrade may consist of the capping layer of the structure constructed solely with lime treatment.

Regarding the short-term bearing capacity performance achieved, the results obtained on the experimental Héricourt embankment within the framework of the TerDOUEST project can be cited as an example. The bearing capacities measured in the very short term (approximately 8 hours after placement) were as follows:

- 30 MPa(*) on the subgrade capping layer in F2 soil treated with 3% CaO with $w_n = 1,17 \times w_{OMC}$
- 68 MPa on the subgrade capping layer in F3 soil treated with 5% CaO with $w_n = 0,9 \times w_{OMC}$

(*) value < 35 MPa due to high water content ($w_n = w_{OMC} + 3.5\%$)

Bearing capacity measurements must be performed using static plate load tests (SPLT) or dynamic plate load tests (DPLT) (Figure 24).



Figure 24: Bearing capacity measurement with dynamic plate load tests on a subgrade capping layer in F3 soil treated with 5% CaO (experimental worksite RD438 at Héricourt), (TerDOUEST project photo)

C. DESIGN AND STUDIES

7. Deposit characterization and laboratory studies

7.1 Introduction

This section of the document details the important points to address regarding site investigations and studies for the construction of hydraulic structures using lime-treated soils. For elements considered known, reference is made to documents such as the GTS [1], standards, or publications.

7.2 Preliminary investigations

7.2.1 General principles

Generally, the use of lime-treated soil in a structure will be optimized to a greater extent if this technical option has been studied from the upstream phases of the project. Prior to initiating a project management assignment, the project owner who wishes to undertake a hydraulic structure project will perform or commission a diagnosis of the problem and feasibility studies aimed at determining a development program to be implemented by the project manager. It is desirable that the project owner inquires at this stage about the possibility and relevance of using lime treatment for soils, in order to specify in the project manager's specifications the integration of this technique at each step of the process. The scope of the preliminary studies for the project execution varies directly with the scale and complexity of the project.

7.2.2 Preliminary studies

During the preliminary study phase, the project manager investigates the feasibility of lime soil treatment from a technical, economic, and environmental perspective. To do this, the project manager relies on existing data, including geotechnical maps, available geotechnical data, and geotechnical reports from comparable nearby sites. The project manager identifies potential material deposits and the available material typologies.

Based on the analyzed data, the project manager assesses the possibility of considering lime treatment of soils to optimize the project from a technical, economic, and/or environmental perspective, taking into account the identified material quantities and their presumed affinity with lime.

7.2.3 Preliminary design

During the preliminary design phase, and provided that the preliminary studies related to lime soil treatment are conclusive, the project manager can confirm the feasibility and relevance of the soil treatment. It is responsibility of the project manager to define the specifications for the geotechnical studies related to lime soil treatment, which are entrusted to a geotechnical engineering firm specifically hired by the project owner. Based on the collected information, the project manager conducts a preliminary technical and economic study of one or more solutions involving lime soil treatment. The project manager justifies the functions (M, S, P, EI, ES) assigned to the treated soil and the project manager provides the preliminary technical and economic design elements for the project, taking into account lime soil treatment.

At the end of the preliminary design study, the project owner decides whether or not to proceed with the project design phase that includes lime soil treatment.

7.2.4 Final design

The role of the project manager is to specify the design parameters for the solution involving lime-treated soil, including volumes, lime dosages, costs, etc. At the end of the project design phase, the project owner has all the necessary elements to prepare a tender file, with a design based on lime-treated soil as the base solution.

The project manager defines the specifications for complementary geotechnical investigations, including a comprehensive treatment study. Based on the collected information, he conducts a comprehensive project study of the solution involving lime soil treatment, in accordance with the aforementioned requirements, and he justifies the functionalities (M, S, P, EI, ES) assigned to the lime-treated soils.

The project manager confirms the feasible execution methodology(ies) and specifies whether the level of knowledge regarding the construction conditions necessitates the execution of one or more testing plots and/or suitability tests, or even an experimental jobsite, indicating the phasing of their execution, their detailed description, and the corresponding objectives.

Depending on the site characteristics – including the intended functions, the project stakes, and the scale of the jobsite – the project manager defines the control requirements and the hold points. The controls to be foreseen include: topographical control (layer thicknesses, volumes), compaction quality control (continuous control or spot measurements), water content control, lime consumption control, etc. The project manager defines the corresponding hold points and specifies whether the control is internal, external, or third-party. Third-party control will be increasingly necessary, with a higher spatial and temporal density of in-situ tests, when quality requirements are high, especially if the functions P, EI, or ES are required.

Part E of this document outlines the general principles for site control involving lime soil treatment.

7.2.5 Support in the tendering and contract award process

If lime soil treatment is used, it is responsibility of the project manager to incorporate the chosen solution from the project phase into the technical document drafting, and, if applicable, all technical specifications related to lime treatment. Conversely, the project manager specifies whether lime soil treatment can be proposed as a contractor's alternative.

The project manager incorporates the necessary and sufficient conclusions of its studies into the tender documents for the consultation of contractors regarding the construction studies for lime-treated soil structures. Specifically, an indicative lime dosage may be provided, without contractual value. He specifies the requirements for testing plot(s) and suitability field tests to be conducted prior to the construction site. The project manager also specifies the requirements for internal, external, and third-party control, and the corresponding hold points.

In addition to the works contract(s), the project manager drafts the technical documents related to the consultation of external quality control offices for the execution of the controls defined in the final design phase.

During the tender phase, the project manager will pay particular attention to:

- the analysis of equipment resources and their suitability for the quality and productivity requirements of the jobsite
- the analysis of the treatment methodology
- the analysis of the control plan proposed by the contractor

7.3 Characterization of the material deposits

7.3.1 General principles

To construct a lime-treated soil structure, the necessary volume of material suitable for treatment must be available. Therefore, the geometry and capacity of the material deposit(s) must be defined, and their geotechnical characteristics, as well as homogeneity, must be evaluated. In the case of large structures requiring the use of multiple material deposits, each deposit must be studied separately.

The method for characterizing material deposits, as well as that for treatment studies, can be inspired by those presented in the GTS [3]. The objective is to provide zoning of the formations present in the material deposit, allowing for the collection of representative samples on which laboratory studies will be conducted.

Laboratory studies require the use of specific testing procedures that can only be entrusted to geotechnical laboratories equipped with the necessary equipment and experienced personnel: identification of components (soils, possibly lime), lime treatment suitability tests, compaction tests (Standard Proctor), immediate bearing capacity, permeability, mechanical strength, erosion resistance, etc.

The content of the laboratory studies, the quantity of material required, and the duration of the studies depend on the intended functions for the soil-lime component. The minimum quantity to be sampled also depends on the particle size distribution of the material. For a treatment study of a homogeneous family, approximately 200 kg of 0/20 mm equivalent material at its natural water content should be provided. The duration of the study can vary from 3 weeks to 2 months, or even longer if the long-term behavior of the soil-lime mixture is to be investigated.

The operations are based on the study phasing conducted by the project management and fall under its responsibility. The approach is progressive to avoid leading to hazardous improvisations or, worse, dead ends.

If the contractor proposes an alternative solution, the same procedure may apply.

7.3.2 Preliminary studies

This phase includes a preliminary geological study to identify areas likely to contain fine-grained clayey soils: silts, loams, loess, clayey sands, clayey gravels, clays, etc. It provides initial information on the homogeneity of the formation, as well as the possible presence of interfering elements such as gypsum, organic matter, significant proportions of micas, and coarse elements that could hinder the mixing.

7.3.3 Preliminary design and design

If the conclusions of the preliminary geological study are favorable, boreholes with representative sampling can be carried out for laboratory studies.

The preliminary design phase provides information on the availability and quality of the soils and assesses their suitability for treatment through simple tests. The design phase, being more detailed, must characterize the deposit more precisely in terms of its homogeneity, based on the boreholes cross-sections and the material identification. It must lead to localizing families of homogeneous material and defining the treatment procedures per family (lime dosages, humidification requirements if necessary, etc.).

In some simple cases, the preliminary and final design phases can be merged.

Table 10, extracted from [1], provides indications of the number of identification tests to perform according to the volume of the deposit to be exploited.

Table 10: Minimum number of tests required for the characterization of a deposit [1]

Volume (V) of capping layer to be constructed (m ³)	Geotechnical identification tests	Known and assumed homogeneous formation ◇	Known and assumed moderately homogeneous formation ◇	Unknown formation
V < 10 ⁴	Nature *	1	3	9
	Moisture content ⊕	2	4	16
10 ⁴ < V < 10 ⁵	Nature *	V / 10 ⁴	3V / 10 ⁴	9V / 10 ⁴
	Moisture content ⊕	2V / 10 ⁴	4V / 10 ⁴	16V / 10 ⁴
V > 10 ⁵	Nature *	10	30	90
	Moisture content ⊕	20	40	160

* The tests concerned here are those that allow the classification of the soil according to its nature, following the classification of EN 16907-2 [7]
 ⊕ Primarily assessed based on measurements of the natural moisture content, assumed to be representative of the construction season. If the construction period is unknown and this factor has an influence (e.g., for shallow deposits or those influenced by annual groundwater table fluctuations), a reflection supported as much as possible by measurements or observations is necessary to estimate, over an annual cycle, the possible extreme water content status.
 ◇ This assessment is expected to be provided by a geotechnical engineer with a good knowledge of local formations

Regarding the types of test to qualify the homogeneity of a material deposit, the proposal in document [8] may be adopted. This document proposes to consider the soil parameters (particle size analysis, V_{BS} , I_p) as homogeneity criteria. This provides a valuable alternative compared to the GTS [1], which recommends the Optimum Moisture Content (OMC) dry density, measured through a relatively heavy and material-consuming test, as homogeneity criterion.

Depending on the study level (preliminary design, final design) and the complexity of the deposit, the boreholes grid in the ultimate phase can typically vary between 200 m x 200 m and 50 m x 50 m. The grid size depends on several parameters, notably the conclusions of the preliminary investigation (e.g., geophysical study), the type of test to perform on the samples, and the function(s) of the soil-lime component in the structure, etc. It is recommended to perform the boreholes using a large-diameter auger or a hydraulic excavator to collect sufficient quantities of material for the laboratory testing. It is therefore essential to take into account the requirements expressed by the testing laboratory, otherwise the sampling campaign may need to be repeated.

A graphical representation of the geotechnical profiles is highly recommended to facilitate the exploitation of the deposit during the construction phase.

The conditions of the borrow material investigation campaign conducted as part of the DigueELITE experimental jobsite on the Vidourle River are summarized below.

Characterization of the deposit: The DigueELITE Example

In the case of the Vidourle demonstrator, as the borrowing area was imposed closed to the river, the deposit characterization was limited to mapping studies supplemented by site visits and a campaign of 14 excavator surveys down to an average depth of 3 m.

Visual observations during the boreholes allowed to judge the site as homogeneous, with the exception of two boreholes that revealed the presence of imported fill materials.



Exploratory surveys of the borrow area using an excavator



Bagged samples for laboratory study

39 disturbed samples were collected in 20 kg bags during the boreholes.

Initially, the samples allowed to perform the identification tests to confirm the homogeneity of the borrow material. Based on these results, and taking into account i) the geometry of the borrow pit and ii) the possibility of excluding certain materials (visually, they must be easily identifiable during earthworks, for instance, by a color contrast), the materials for the construction of the demonstrator were selected. The corresponding samples were mixed to form a reserve of material representative of the deposit for the laboratory treatment study.

The table below presents the identification characteristics and the associated standard deviation for all soils present in the borrowing area and then for the soils selected for the construction of the demonstrator. These values allow for verifying the homogeneity of the deposit used at the Vidourle site; it is also evident that once certain areas and soil layers are excluded, the parameters of the nature of the soil constituting the demonstrator are very similar. The mixing of these materials for the pre-construction laboratory treatment study is therefore technically justified.

Identification characteristics of soils from the entire borrowing area and of the selected soils for the construction of the Vidourle demonstrator, constituting the mixture for the laboratory treatment study

	Borrowing material				Soils selected for the construction of the demonstrator			
	mean	minimum	maximum	standard deviation	mean	minimum	maximum	standard deviation
< 2 mm (%)	100	99	100	0.2	100	100	100	0
< 80 μm (%)	85.4	65	97	9.7	84.6	67	92	7.7
< 2 μm (%)	24	16	32	4.7	23.3	20	27	2.7
V _{BS} (g/100 g)	1.85	1.5	2.5	0.41	1.67	1.50	2	0.29
w _L (%)	31.6	26	39.5	3.8	31.2	28	34	2.7
w _p (%)	25	21	31	2.6	25.2	23	28	1.9
I _p	6.6	4	9	1.8	6	4	9	1.8

Compaction behavior of the Vidourle soil

The soil exhibited low plasticity and a particle size distribution characteristic of a F1 soil (according to EN 16907-2 [8]). The chemical composition did not reveal any deleterious compounds (sulfates, organic matter), while carbonates were present in abundance (approximately 50% by mass of the material).

The compaction behaviors of the natural soil and the soil treated with 2% quicklime are illustrated by the following Proctor and IPI curves.

From the Standard Proctor curve of the natural soil, the following parameters are identified:

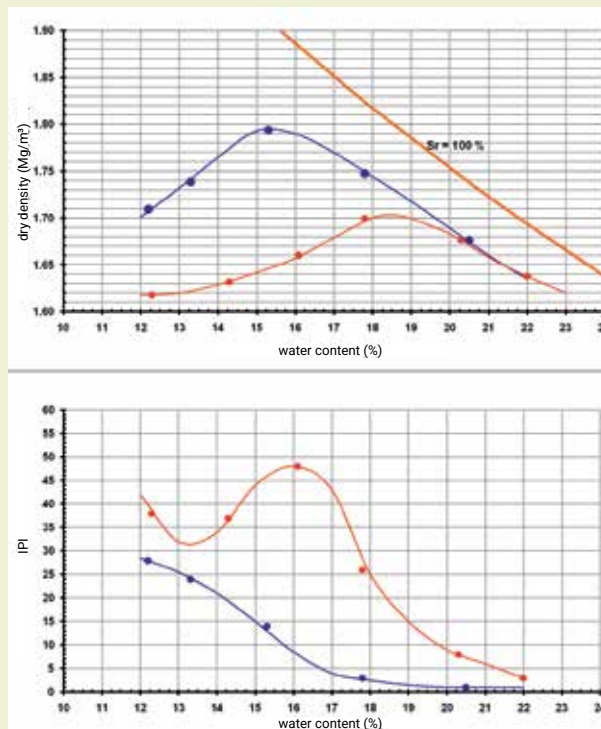
Maximum dry density = 1.79 Mg/m³ at w_{OMC} = 16%.

At this water content, the Immediate Bearing Index (IPI) is estimated at 10, but then decreases sharply (IPI = 3 at w = 17.8%).

In the case of soil treated with 2% quicklime, the maximum dry density is estimated at 1.70 Mg/m³ for a water content w_{OMC} = 17.8%. The Immediate Bearing Index (IPI) remains above 8 for water contents up to 20.3%.

It can also be noted that the intrinsic shrinkage limit of the soil shifts, moving from a water content of 15.6% (untreated soil) to 23.5% after the addition of 2% quicklime.

To be as representative as possible of the soil stock built up, these results, determined on soils extracted during the initial sampling campaign, were subsequently confirmed during a second sampling campaign that preceded the construction site. A few minor adjustments were decided upon with regard to the treatment and the on-site placement of the materials, particularly concerning water contents.



Standard Proctor (upper graph) and IPI (lower graph) curves of the soil extracted from the Vidourle dike construction site, for untreated soil (in blue) and soil treated with 2% quicklime (in red).

7.4 Treatment Studies

Appendix 3 presents a list of the relevant tests for characterizing the properties of soil-lime components. The tests to be carried out must be selected from this list based on the intended objectives.

The performance tests must be carried out on specimens whose characteristics are representative of the characteristics of the soil state at the time of implementation (water content, density): the laboratory study specifications must detail the water content and the compaction parameters to be adopted for the specimen preparation. Appendix 4 provides recommendations regarding the preparation of the specimens in lime-treated soil for laboratory studies.

7.4.1 Studies related to the workability (M)

When targeting the workability (M) function, the challenge lies solely in the difficulties of extraction and application. In addition to the usual parameters (characterization of the natural material), the parameters to study are therefore:

- the moisture content of the deposit, that is the distribution of natural moisture contents in relation to the Optimum Moisture Content w_{OMC}
- the immediate bearing capacity as a function of the natural water content, measured by the IPI (Immediate Bearing Index)
- the lime dosage to apply based on the natural water content to achieve an $IPI \geq 8$, compatible with proper implementation of the treated material, or any other value defined by the project manager

The methodology is clearly described in the GTS (Section B: Soil treatment in embankments) [1].

The expected results of the treatment study for the workability (M) function are presented in Figure 25. It is important to note that the moisture content of the deposit, assessed during the investigations, is likely to change with the seasons. Therefore, it is necessary to consider a wide range of moisture conditions to better understand the implications on the organization of the work at the time of its execution. The consequences on the lime consumption can be favorable (studies conducted during the wet season and work in the dry season: reduced lime consumption) or unfavorable (studies conducted during the dry season and work in the wet season: increased lime consumption).

Parameters measured during the laboratory study					
Parameters		Lime dosages (%)			
		0	1	2	3
<i>Soil w_n 18%</i>	IPI	4	20	30	35
	<i>Treated soil w (%)</i>	18	17,1	16,1	15
	<i>ρ_d (Mg/m³)</i>	1,73	1,73	1,70	1,60
<i>Soil w_n 20%</i>	IPI	2	10	20	21
	<i>Treated soil w (%)</i>	20	19	18,2	17,2
	<i>ρ_d (Mg/m³)</i>	1,70	1,71	1,71	1,64
<i>Soil w_n 24%</i>	IPI	0	2	7	12
	<i>Treated soil w (%)</i>	24	23,1	22,2	21,5
	<i>ρ_d (Mg/m³)</i>	1,50	1,55	1,55	1,66

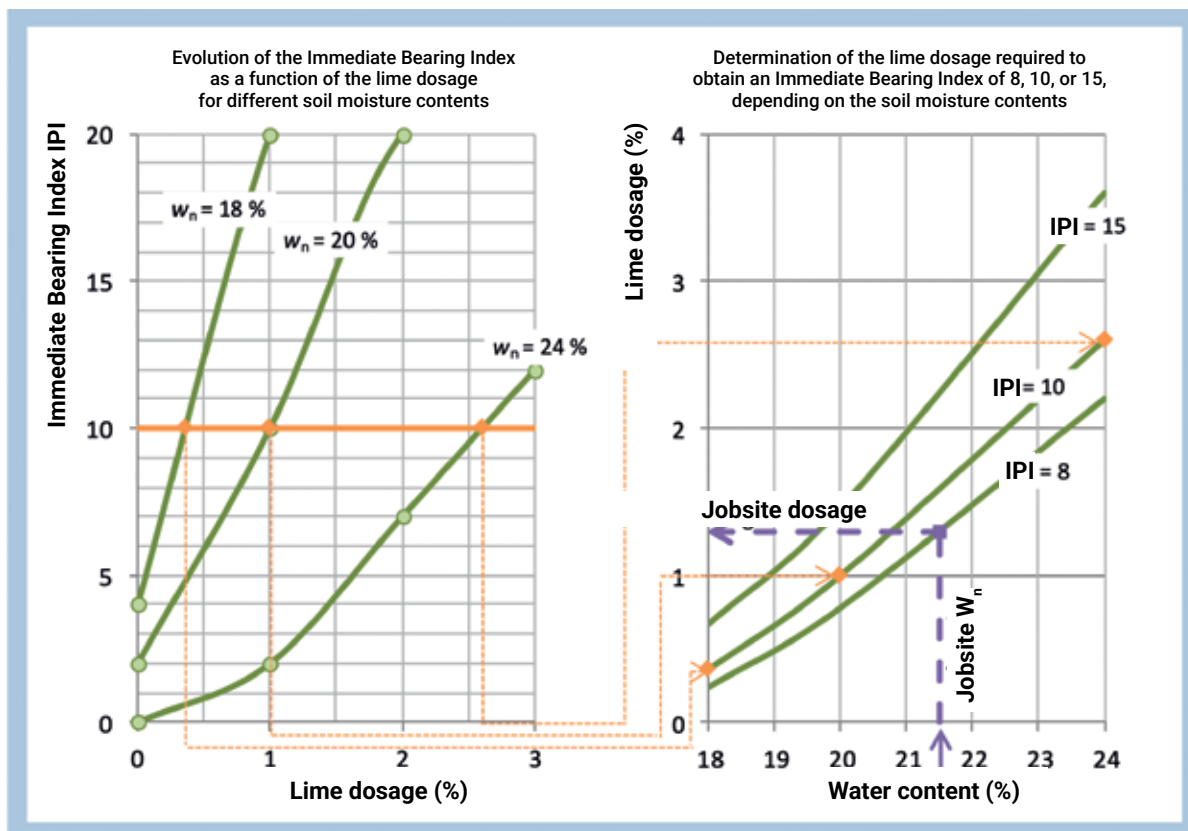


Figure 25: Results of a formulation study on a F1 silty soil treated with lime for the workability (M) function (extract from GTS [1])

7.4.2 Studies related to stability (S), watertightness (P), and resistance to internal erosion (EI)

Compared to the workability (M) function, the materials must satisfy requirements for mechanical performance, homogeneity, watertightness, or resistance to internal erosion. They may also need to satisfy several of these requirements simultaneously.

As in the case of the workability (M) function, moisture content of the deposit and immediate bearing capacity as a function of the soil water content need to be studied first.

The formulation study defines the water content and the lime dosage to apply for the targeted functions. The study includes:

- the determination of the Lime Fixation Point (LFP). This is the lime dosage at which the cation exchange phenomenon with the soil considered can begin, allowing the soil-lime reactions to proceed. The LFP is determined via a laboratory test according to ASTM D6276-19 [36], which consists of determining the amount of lime to be added to raise the pH of a soil dispersion in water to a value of 12.4 (see below). The amount of lime added to the soil exceeding the LFP constitutes a reserve available to initiate pozzolanic reactions and enable long-term gains in mechanical and hydraulic performance of the lime treated soil (the so-called stabilization reactions). The LFP thus serves as a reference for initiating studies on mechanical performance, permeability, and erosion resistance
- the verification of the treatment suitability by the accelerated swelling test, EN 13286-49 [5]. This test aims to detect the presence of elements that, if present in certain amount in the soil, can cause disturbances or hinder the action of the lime. It mainly concerns sulfates, which can generate swelling, or chemical elements (organic

matter, nitrates, etc.), or mineralogical elements (micas) that can slow down or alter the setting and hardening of the mixtures

- verification that the bearing capacity is maintained after 4 days of immersion in the soil treated with the selected lime dosage ($CBR_t/IPI > 1$)

Determination of the Lime Fixation Point (LFP)

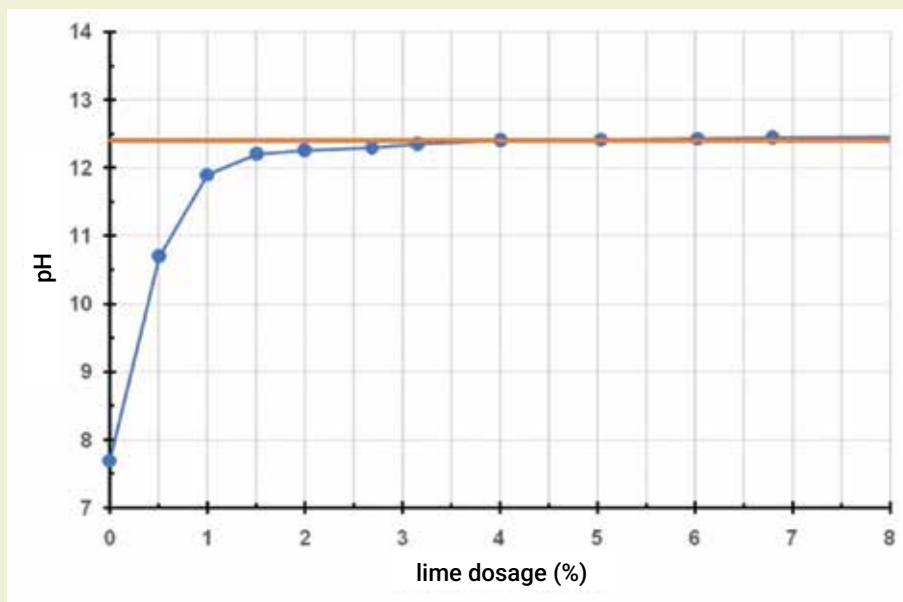
The LFP is determined by measuring the pH of the soil-lime mixture as described in ASTM D6276-19 [36]. This method determines the minimum lime dosage required for the lime-soil mixture to reach a pH of 12.4, this is the dosage considered as the transition between soil improvement and stabilization. Beyond this dosage, the quantity of lime added will be available for the pozzolanic reactions forming cementitious phases.

The test involves mixing the pre-dried soil with various lime dosages (generally 1% to 6%) and then adding distilled water. After a one-hour period of agitation, the pH of the solution is measured with a pHmeter.

The smallest dosage that allows a pH of 12.4 to be reached is the Lime Fixation Point (LFP).

In practice, the selected dosage should be higher than the LFP determined by the laboratory test. This accounts for the difficulty of precisely measuring high pH values with laboratory equipment and ensures that a reserve of lime is available for the pozzolanic reactions. Professional practice suggests that the dosage to be applied onsite should be $LFP + 1\%$.

The figure below shows an example of LFP determination.



LFP determination for a F3 soil In this example, the LFP is evaluated at 4%, so the suggested dosage for conducting the laboratory treatment study is 5%.

For conducting the tests, the laboratory study specifications must detail the conditions for the specimen preparation: water contents and compaction rates. Depending on the designer choices, these characteristics can be inspired by those recommended in the GTS [1], corresponding to implementation in embankment or capping layers.

Once the experimental plan is established, the performance of the mixture is studied for the targeted functions:

- for stability (S): the mechanical performance as a function of time and lime dosage (uniaxial compressive strength, tensile strength, if necessary, shear strength, compressibility and settlement). Tests are usually conducted at 28 and 90 days of curing, or even longer if the goal is to analyze the evolution of the mechanical characteristics over time
- for watertightness (P): the permeability of the mixture, measured in the laboratory under recommended conditions (water content, lime dosage, compaction rate and method, age)
- for the resistance to internal erosion (EI): the critical erosion stress measured according to the Hole Erosion Test method

The final lime dosage to adopt is the one that meets all the targeted functions.

Whenever possible, the performance measured on the treated materials will be compared to the performance measured on the same materials before treatment.

7.4.3 Studies related to resistance to surface erosion (ES)

Until recently, in the absence of laboratory tests capable of reliably characterizing the resistance to surface erosion of materials used in the design of hydraulic structures, full-scale studies were undertaken.

Since the DigueELITE demonstrator and the experimental plots at Salin de Giraud allowed for in-situ testing of the resistance to overflow erosion of an untreated and lime-treated F1 fine silty soil, it is possible, by reasoning analogously, to draw the following conclusions:

- under the manufacturing and implementation conditions conducted on the DigueELITE demonstrator and the experimental plots at Salin de Giraud (lime dosage, water content, homogeneity of the soil-lime mixture, compaction methods), a F1 soil, treated with lime at a dosage greater than or equal to 2%, exhibits resistance to surface erosion in the case of overflow that is significantly superior to that of the same untreated soil
- by comparison with the Class F1 soils in the cases of the DigueELITE demonstrator and the experimental plots at Salin de Giraud, it can be assumed that F2 soils behave identically to F1 soils in terms of overflow resistance

The description of the overflow tests performed on the Vidourle demonstrator and on the experimental plots at Salin de Giraud, as well as the quantified erosion results, are presented in the Part B of the document (§ 5).

It is premature to draw similar conclusions for other soil classes for which tests are necessary. Laboratory tests for measuring the resistance to surface erosion have been recently adapted to treated materials, such as the Jet Erosion Test (JET). These tests can provide indications on the properties of these other soil classes.

7.4.4 Studies related to resistance to overspill water (EV)

The overspill water function differs from the resistance to surface erosion function in terms of magnitude of the stress, particularly velocities and hydraulic stresses. It applies to dam spillways, but also to levee spillways that are designed to convey significant specific flow rates. The study of this function was not included in the objectives of DigueELITE. Nevertheless, discussions are underway in anticipation of future research programs.

While awaiting results, and in the event that stresses exceed the range of resistance to external erosion of lime-treated soil, the designer must consider conventional alternative solutions. However, the designer can exploit other functions of lime-treated soil (notably stability and resistance to internal erosion) in the design of the relevant system.

7.5 Experimental jobsites

Before building a structure, and depending on its intended use, it may be necessary to carry out an experimental jobsite (also referred to as a demonstrator) during the study phase and under a dedicated contract. This decision lies with the project owner, who may consider such an approach based on a technical, economic, and risk analysis.

Among the factors that may lead to the decision of conducting an experimental jobsite, the following can be mentioned:

- the use of soil(s) not yet employed for the specific intended function
- the need to clarify the state of knowledge or the results of previous studies
- the verification of actual mechanical and hydraulic performance obtained
- the precise definition of the desired objectives
- the terms of the works contract to be established

The primary objective of an experimental jobsite is to demonstrate the feasibility of using the selected soils, once treated with lime, for the intended applications, while ensuring that the required performance levels are met. The conclusions drawn from such a jobsite can lead the project owner to the definition of new construction conditions for the hydraulic structure. They can also lead to optimizing its design, which can have beneficial impacts on economic, environmental, and work schedule aspects.

Implementing an experimental jobsite, often associated with a substantial financial investment, is feasible for large-scale projects, particularly when aiming to achieve specific functions, such as low permeability or high resistance to erosion or overflow. It should be integrated into the upstream planning phase, prior to the works contract, and scheduled within a timeline that ensures its findings can be effectively applied to the final structure. This phase also enables a more accurate assessment of the cost of the structure.

In general, the project owner, supported by the project manager, should define all the conditions for executing the experimental jobsite within dedicated special technical requirements, which must include detailed provisions on:

- the desired objectives
- the site where the jobsite will be built
- the description of the structure
- the work execution procedures
- the quality control and monitoring procedures

All the useful elements for a proper execution, as well as the necessary material resources, must be planned during the experimental jobsite design phase. This includes quality controls, test methods, and resources to be deployed to ensure the monitoring of the execution and the evaluation of the achieved performance.

Several test sections can be built as part of an experimental jobsite to comparatively study various modalities that differ, for example, in the nature of the soils used (mineralogical composition, plasticity, particle size distribution), or in the chosen soil treatment methodology (lime dosage, material resources, phasing of operations), etc.

After the construction, the achieved performance are evaluated through in-situ tests. The resulting characteristics must allow for the validation and, if necessary, optimization of the methods used for the construction of the structure.

The following three recent projects can be cited:

- the experimental dike at the Rouen CER (Centre d'Études et de Recherches - Study and Research Center) (September 2011) – (Figure 26)
- the DigueELITE demonstrator on the Vidourle river (July 2015) – (Figure 27)
- the SYMADREM experimental plots at Salin de Giraud (November 2017) – (Figure 28)

These experimental jobsites have been the subject of several publications [10, 37-42] in which all the useful details regarding design, execution, and types of controls performed can be found.



Figure 26: Experimental dry dike in Rouen – General view of the dike under construction (Photo: Lhoist)



Figure 27: DigueELITE demonstrator (Photo: DigueELITE)

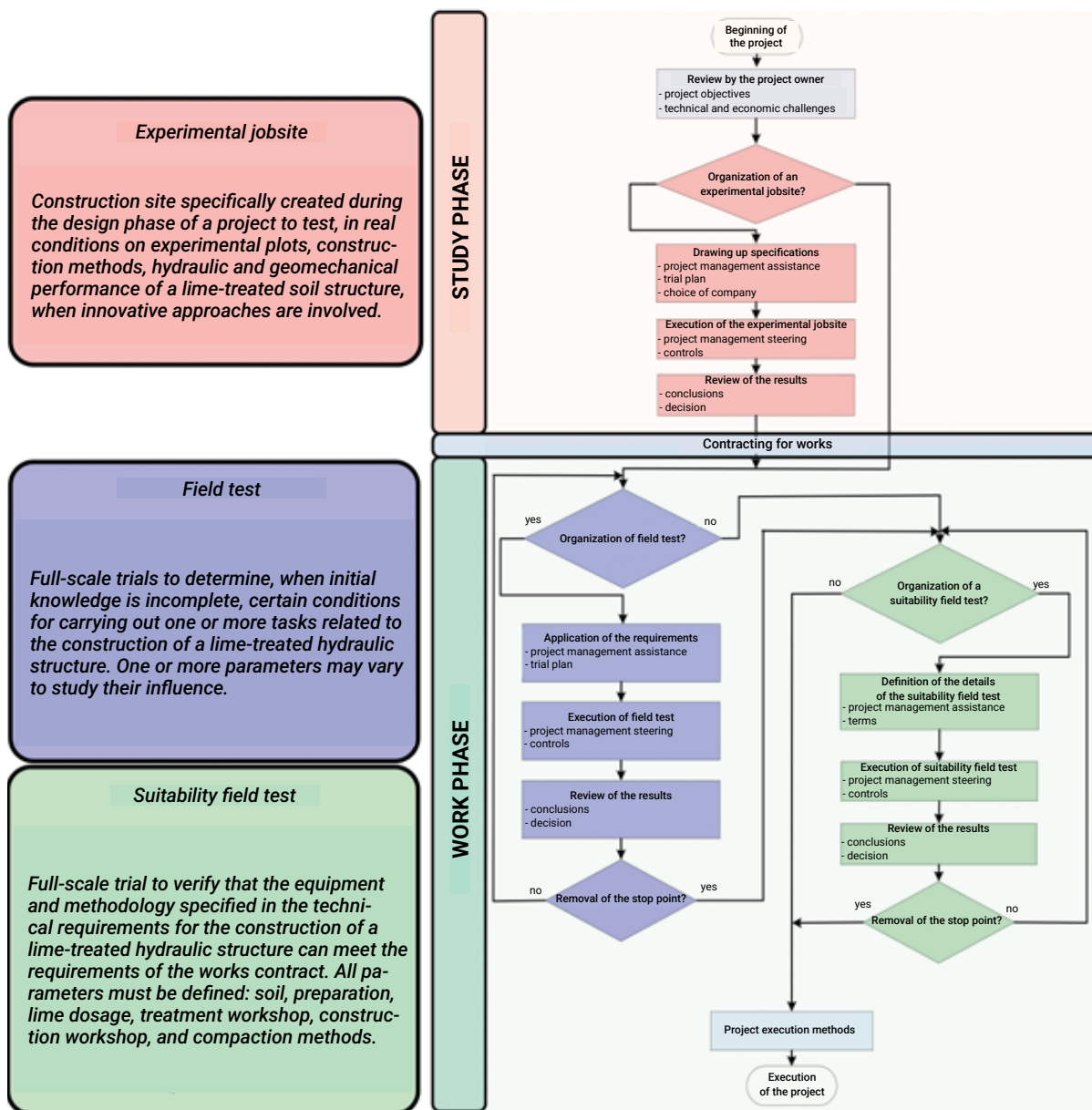


Figure 28 Experimental plots at Salin de Giraud – General view of the site (treated soil plot on the left and natural soil plot undergoing overflow tests on the right) (Photo: SYMADREM)

7.6 Experimental jobsites, field test, suitability field tests

To clarify the distinction between these different concepts, their definitions and a flowchart illustrating the progression of operations and decisions to be made by project owners and project managers are provided in the following.

As mentioned previously, an experimental jobsite should be conducted during the study phase and requires a dedicated contract, whereas a field test or suitability field tests should be carried out at the beginning of the works contract or whenever necessary.



8. Design considerations

These considerations apply to dikes and small dams with a height not exceeding approximately fifteen meters. These may be new structures or reinforcement of existing ones. The objective is not to replace established engineering practices, but to highlight the specific properties of lime-treated soils to support the structure design.

8.1 Design considerations related to workability (M)

The workability (M) function allows for the use of soils considered unsuitable, primarily due to their water content. When the range of water contents does not require systematic treatment of all the materials in the structure, it is important to consider whether the structure can tolerate heterogeneities, such as a random distribution of treated and untreated sections. Furthermore, while soil-lime embankments are accepted when compressible soils are present in the foundation of road or railway structures, it is crucial to verify that this practice is acceptable for the specific hydraulic structure under consideration.

8.2 Design considerations related to stability (S)

The stability (S) function makes it possible to leverage the improved mechanical performance of lime-treated soils. As a general rule, the use of lime-treated soils allows for significantly steeper slopes in structures. The mechanical characteristics of lime-treated soils also reduce the risk of failure in saturated or partially saturated embankments, for instance, during rapid drainage. The stability (S) function can also be required when reinforcing an existing structure. The implementation of lime-treated soils, either as a complement to or replacement for a part of an existing embankment with limited stability (upstream or downstream slope), can effectively improve the stability of a structure. However, this type of intervention must not compromise the drainage function, particularly on the downstream slope, where specific construction measures may be necessary to preserve existing drainage capabilities.

8.3 Design considerations related to watertightness (P)

Recent laboratory and full-scale studies have shown that lime treatment of silt-clay soils allows the achievement of low permeabilities—immediately after implementation—provided the mixture is compacted on the wet side of the Proctor curve through kneading compaction with a padfoot roller. The permeability is comparable to that obtained with the same untreated soil placed according to best practices. However, the overall permeability of the structure remains governed by construction heterogeneities, which could be the source of preferential flows. At this stage, it is therefore appropriate to exercise caution regarding the concept of overall permeability for a structure made of lime-treated soils, just as with untreated soils.

8.3.1 Structures subjected to permanent loads

Based on the current knowledge, lime-treated soil embankments cannot be considered capable of independently ensuring the watertightness function of a structure under permanent load, such as those retaining water over long periods (e.g., reservoir dams, canals). Additional features must be planned (e.g., seepage control and drainage system, impermeable upstream backfill, watertight cut-off).

8.3.2 Structures subjected to non-permanent loads

In this case, the level of watertightness provided by lime-treated soils is considered sufficient for this type of structure. In general, leakage is technically acceptable as long as it does not pose a risk of internal or external erosion. If the design includes safety barriers against erosion risks - such as using the EI and ES functions of lime-treated soils and/or a filtration and drainage system - then a structure under non-permanent loads is generally considered not to require additional watertightness measures.

8.4 Design considerations related to resistance to internal erosion (EI)

The resistance to internal erosion is demonstrated by laboratory tests, which are considered representative of the in-situ behavior of the material. Based on this observation, the systems for controlling the internal erosion can be fundamentally rethought. The following considerations can be useful when designing a structure with lime-treated soils:

- leakage is significantly uncorrelated with the risk of internal erosion
- filtration and drainage systems within the body of the structure can be simplified, considering the improved stability and resistance to internal erosion
- lime treatment of soils does not reduce the risk of erosion at the interface between treated and untreated material. In particular, the filtration and drainage systems at the interface with the foundation must be carefully designed. Similarly, in the case of a composite structure with a treated soil section and an untreated soil section, the interface between the two sections must be carefully studied
- although stability is ensured, the drainage of a shell structure must be carefully studied to control potential issues arising from permeability contrasts
- the risk of contact erosion at the interface with a crossing structure is significantly limited when lime-treated soil is used across the entire contact zone; however, the risk of leakage remains

Furthermore, external risk factors that could lead to a defect causing internal erosion are reduced.

- In the case of the Vidourle demonstrator, all attempts by burrowing animals to create tunnels in the lime-treated soil were unsuccessful. Conversely, in the untreated soil, burrowing attempts resulted in the creation of tunnels reaching depths of 80 cm. Given this observations and in similar contexts, implementing anti-burrower protections for lime-treated soils may be unnecessary.
- Lime-treated soil embankments are generally not conducive to deep root development. Shallow vegetation can develop on a topsoil layer, but tree growth is significantly inhibited on a structure made of lime-treated soil.

8.5 Design considerations related to resistance to surface erosion (ES)

Surface erosion may occur due to several physical phenomena encountered in hydraulic structures:

- a. overflow-induced erosion
- b. erosion due to wave action (wind, navigation)
- c. weather-related erosion
- d. longitudinal erosion caused by currents

The DigueELITE project contributed, for the first time at full-scale and in a quantitative manner, to determining the resistance to surface erosion caused by overflow. This study was supplemented by the same tests conducted on the experimental plots at Salin de Giraud, which led to the same conclusions. All the results obtained demonstrated the superiority of lime-treated soils compared to the equivalent untreated soils.

Based on this, and depending on the range of applied stresses, it is possible to consider designs that take advantage of this resistance. In particular:

- designing overflow-resistant dikes over long linear sections, as an alternative to heavily protected spillways over short sections. Lime-treated soils are usually covered with vegetated topsoil to ensure the material protection. As soon as the stresses exceed the erosion resistance of the vegetation, only the topsoil erodes, down to the treated embankment
- reducing the freeboard can be considered, assuming that the usual safety margin above the extreme high water levels is not entirely necessary, given the resistance to external erosion of the slope
- improving the resistance of a lime-treated soil embankment to erosion caused by precipitation (water runoff). It should be noted that this resistance is generally only required during the transitional phase, before covering the structure with topsoil, as this cover is recommended to protect the lime-treated soil from climatic exposure

The resistance of lime-treated soils to the wave action and longitudinal flows could not be tested within the scope of the DigueELITE project. Therefore, a certain degree of caution is required on this matter until further tests are conducted. However, feedback is available from the Friant-Kern irrigation canal in California, where the ceiling and the banks, protected with lime-treated soil, have withstood a current of 1.5 m/s for 50 years.

8.6 Design considerations related to overspill water (EV)

The EV function relies on the resistance to external erosion specifically within the context of flood discharge systems.

This function therefore differs from the resistance to surface erosion (ES) function by the magnitude of the stresses (water depth over the structure, flow velocities). The stresses can be significant, and the resistance of lime-treated soil could not be tested under such conditions.

Consequently, if the stresses exceed the range of resistance to external erosion of lime-treated soil, the designer must use conventional construction provisions. However, the designer can leverage other functions of lime-treated soil (notably stability and resistance to internal erosion) in the design of the flood discharge structure.

D. EXECUTION

9. Introduction

This part of the document focuses on the important aspects related to the construction methodology for hydraulic structures using lime-treated soils, which is based on the established methods used for conventional linear transport infrastructure. It provides supplementary information, in the form of proposals, inspired by lessons learned from recent construction site experiences.

10. Tender documents

The tender documents for a hydraulic structure project constructed with lime-treated soil must clearly indicate the structures or parts of structures to be built (or eligible for construction) using a soil-lime component, along with the specific functions that the soil-lime component must fulfill for each structure or part thereof. The functions are described according to the terminology defined in § 2.2. It is therefore appropriate to start drafting the requirements of the tender documents with a table summarizing which functions are required for the different parts of the structure.

Two versions of the tender documents are possible:

- option 1: an initial draft may be prepared in terms of obligations of means, with specifications set for lime dosage, suitability field tests, equipment, soil treatment, and execution methodologies, as well as quality controls
- option 2: the tender documents can be drafted in terms of results rather than obligations of means, with quantitative specifications of objectives to be achieved for each function required of the soil-lime component. The tender documents may then require the contractor to define the methods for achieving these objectives, subject to the approval of the project manager. The approval will cover characterization of the deposit, treatment study, program of the field tests, treatment procedures, homogenization, stock management, execution, monitoring, and quality control program proposed by the contractor

Regardless of the level of knowledge acquired before, and thus the chosen wording for the tender documents, the latter must include the following items in the requirements:

- a table of structures and parts of structures planned with the soil-lime components, and the function(s) required
- the content of the execution studies assigned to the contractor, particularly the characterization (or complementary characterization) of the deposits and the characterization of the performance associated with each function
- jobsite facilities and specific treatment equipment
- the origin and quality of the materials
- field tests and suitability field tests
- construction methods for entire structures or parts of structures
- quality controls

11. Field test

When the initial conditions for performing the works are not fully known, or when certain specific points need verification, the use of one or more field tests may be necessary. This phase, which can be crucial for the success of the construction site, generally applies to large-scale projects. The completion of each field test marks a stopping point in the quality management plan. The results must be presented in a detailed report submitted to the project manager, allowing the definition of practical execution conditions based on the targeted objectives, and enabling the decision to either lift or maintain the hold point prior to the beginning of the works.

The decision to use one or more field tests depends on several criteria, including:

- the jobsite size
- the choice between different soil types to be treated
- the development of a soil preparation or treatment technique
- the study of practical compaction methods if not predetermined
- alternative proposals by the contractor
- the economic impact of the approach

The field tests are constructed using all the resources that will be used by the contractor on the jobsite. They are carried out based on precise specifications detailed in the requirements and are subject to an established experimental plan. Unless authorized by the project manager, field tests are not an integral part of the project and are constructed outside the work area. It is recommended that the field tests be subject to execution plans prepared by the contractor and validated by the project management. The presence of a representative of the project manager during their execution is strongly recommended.

For very large construction sites that may require several field tests (e.g., soil preparation, development of the treatment plant, compaction methods), these can be carried out in separate phases.

For the construction of a field test, it is assumed that a prior stock of soil or a duly identified deposit is available. Before constructing a field test, it is necessary to adjust and/or check all the operating parameters of the equipment that will be used during the preparation, treatment, and execution phases. All useful information for the operation of machinery and for ensuring compliance with the prescribed values must be recorded and clearly communicated to the equipment operators.

Often, the construction of a field test aims at determining the compaction energy to be applied to achieve the desired densification objective. In this case, and although it resembles a suitability field test, it is sometimes referred to as a "*compaction field test*". In this scenario, all parameters are fixed except for the number of compactor passes, which is varied.

For each execution phase of the field test (natural soil preparation, lime soil treatment, implementation, compaction) and for the final control, a list of inspections and measurements to be performed must be established. The selection depends on the expected performance of the structure. While some parameters can be visually inspected during the execution, quantifiable factors must be determined using standardized measurements and procedures performed by a laboratory approved by the project manager, whether it is the contractor laboratory or an external party. The type and number of measurements to be performed, based on the factors to be quantified, must be specified in the experimental plan to ensure that reliable conclusions can be drawn. A field test report is then drafted.

Based on the analysis of the practical conditions under which the field test was executed and the results obtained, the project manager may decide to lift the hold point and authorize the beginning of the works, or alternatively, adjust one or more parameters that define the execution methods. In this last case, the project manager may or may not require another field test or a suitability field test to be carried out.

12. Suitability field test

In the most common scenario, when all conditions of execution are controlled and known, a simple suitability field test may be requested before the beginning of the works. This step, identified as a hold point within the quality management process, is essential to confirm that the selected products, deployed equipment, and execution methods are appropriate and sufficient to achieve the defined objectives. It serves to validate the proposed methodologies for carrying out the works and to verify the expected production rate.

The suitability field test is specified by the project manager, who defines the detailed conditions for its implementation in the requirements. It is a single action for which all parameters are defined in advance.

The scope of the suitability field test must be adapted to the size of the construction site. Its execution is carried out in the presence of a representative of the project manager. With the authorization of the project manager, the suitability field test may be integrated into the construction process and carried out on the initial layers of the embankment. The requirements detail all the conditions for carrying out the suitability field test, including geometry, number of layers, support soil, equipment verification and calibration, soil preparation and treatment, implementation and compaction of the treated soil.

To verify that the targeted objectives regarding grading of the soil-lime component, moisture content at implementation, compacted layer thickness, and level of densification are achieved, several measurements must be carried out during or after the suitability field test. These operations include:

- controls of soil preparation operations before treatment (homogenization, humidification, pre-mixing, moisture content)
- controls of soil treatment operations (lime spreading, mixing, achieving desired grading, water content, lime dosage, operation and output of the treatment plant)
- controls of implementation operations (supply, spreading, leveling, thickness, moisture content, compaction)

The controls and tests are performed according to the existing standards, test methods, or operating procedures referenced or described in the requirements. The laboratory responsible for the tests must be approved by the project manager.

At the end of the suitability field test and based on the results presented in a report, the project manager lifts the hold point. Failure to achieve the expected results may lead the project manager to request changes in the methodologies used or to resort to other processing or implementation equipment. In this case, a new suitability field test may be requested after modifying one or more parameters.

If the requirements have demanded one or more field test(s), the project manager may choose not to require a suitability field test. In this context, the verification of whether the targeted objectives have been met, as well as the assessment of practical implementation conditions, is based on the conclusions drawn from the field test(s).

13. Execution

13.1 Equipment inspection

The performance level of the equipment used must be appropriate for the intended function. Information on the technical characteristics of the equipment (treatment plant and compaction equipment) is provided to the project manager. Before the work begins, the various pieces of equipment (treatment workshop: sprinkler, spreader, mixer, treatment plant, and compactor(s)) must be inspected and calibrated to verify their morphological characteristics, working condition, and operating parameters. This equipment acceptance operation is generally carried out during the construction of the field test or the suitability field test. If any changes to the equipment are required during the execution of the works, the project manager must be notified and provide prior approval.

13.2 Construction of the structure

13.2.1 Soil excavation

In the context of hydraulic structures, typically built within a limited footprint compared to linear infrastructure projects, the frontal excavation method using an excavator is generally the preferred approach. This method allows for an initial mixing of the soil during the extraction, across the entire depth of the deposit. The assessment of the deposit is of fundamental importance prior to undertaking this task. In the case of reconstruction and reuse of soils from an existing structure, it may be necessary to sort the extracted soils during the demolition operation. In this case, the working area required for sorting must be planned, and similarly, if a mixture of different soil types is envisioned.



Earthworks of an existing structure (Photo: INRAE)



Earthworks for a F2 soil deposit (Photo: DigueELITE)

Figure 29: Soil excavation

13.2.2 Temporary stockpiling of natural soil

The temporary storage of the extracted natural soil must be carried out under conditions that minimize moisture variations and, above all, exposure to weather. The storage pile is made on a platform above water, in successive layers spread, and lightly compacted over the entire surface of the platform. The slopes of the stockpiles are shaped and smoothed to promote the flow of rainwater. The crest of the storage pile is graded with a slope to prevent water stagnation on the surface and encourage its runoff. At the toe of the slopes, water drainage must be ensured by installing gutters and outlets. These measures help to maintain homogeneity and moisture content of the natural soil constituting the temporary stockpile, which can thus remain in place for several weeks, or even months, and be subject to as little variation in moisture conditions as possible.



Creation of a temporary stockpile (Photo: DigueELITE)



Soil recovery from a temporary stockpile (Photo: Lhoist)

Figure 30: Temporary storage of natural soil

13.2.3 Identification of natural soil moisture content

Controlling the moisture content of the soil-lime component during its implementation is a critical factor for the project success. Regardless of the treatment technique used, it is important for the moisture content of the natural soil to be as homogeneous as possible throughout the construction operations so that the settings of the preparation and treatment plants remain constant. It is therefore necessary to spatially identify the moisture content of the deposit or temporary stockpile. A campaign to identify the moisture state of the natural soil must be undertaken using appropriate methods. The sampling grid must be sufficiently fine to obtain a good resolution of the moisture content distribution over the concerned soil volume. It depends on the dimensions of the deposit or stockpile. As an indication, one sample may be taken for every 500 m³ of soil. For the workability function (M), monitoring the evolution of the moisture content of the natural soil is mandatory to adjust the lime dosage and ensure the respect of the planned implementation conditions.

13.2.4 Treatment of the structure foundation

After excavation and drainage, it may be necessary to treat the bottom of the excavation with lime in situ to ensure sufficient bearing capacity for the installation and compaction of the first layers of the backfill. Whether the excavation bottom is treated or not, it must be compacted under conditions adapted to the specific case. If a backfilled trench is constructed (e.g., anchor key, waterproofing) or if local deep excavation is required, the backfilling of these areas must be carried out under the same conditions as those selected for the main structure. Nevertheless, in certain cases, the presence of water at the bottom of the structure (e.g., outcropping groundwater, infiltrations) may require adaptations to the backfilling method for this part of the structure (e.g., reinforcement, soil nailing, dewatering).



Compaction of an excavation bottom (Photo: DigueELITE) Backfilling of an anchor key (Photo: Lhotellier company)

Figure 31: Excavation bottom and anchor key

13.2.5 Soil homogenization prior to treatment

For watertightness (P), resistance to internal erosion (EI), external erosion (ES), and overspill water (EV) functions, soil homogenization before treatment is necessary. Two solutions are possible depending on the initial degree of homogeneity of the deposit:

- if the natural homogeneity of the deposit allows it, vertical extraction over the entire depth of the deposit without creating a temporary stockpile. The soil is then loaded and transported to the platform designated for the treatment or to the treatment plant
- if the deposit heterogeneity is significant, vertical extraction over the entire height of the deposit with the creation of a temporary stockpile by layering (§ 13.2.2) In the case of in-situ treatment, this can be done directly on the temporary stockpile or on a dedicated platform after being piled up to the full height of the temporary storage area. For in-plant treatment, the soil must be recovered in ridges over the entire height of the temporary stockpile to supply the plant buffer feedstock.



Excavation of a deposit with an excavator with homogenization (Salin de Giraud jobsite November 2017 - Photo: INRAE)



Loading for temporary storage to supply a treatment plant (Photo: DigueELITE)



Reworking natural soil using an excavator on a temporary stockpile with homogenization (Salin de Giraud jobsite November 2017 - Photo: Lhoist)



Homogenization of natural soil using an excavator on a temporary stockpile (Vlassenbroek experimental jobsite - Photo: Lhoist)

Figure 32: Homogenization of natural soil before treatment

13.2.6 Soil moistening prior to treatment

In some cases, a more or less significant increase in the moisture content of the natural soil may be necessary. Depending on the amount of water to be added, several passes of a water sprayer may be justified. The watering equipment used for this operation must be volumetric dosing controlled by the forward speed. Traditional "carp-tail" sprinklers are not always suitable for this operation, and more precise machines (fine spray sprinklers or buried sprinklers) should be preferred.

Each pass of the sprinkler must be performed on soil that has been previously scarified or mixed. Each pass of the sprinkler must be immediately followed by mixing throughout the entire layer thickness, then by re-leveling the platform. Several passes of watering and mixing may be necessary to incorporate a significant amount of water into the natural soil. As an indication, a humidification sequence is generally considered to increase the moisture content of a soil by a maximum of approximately 3%. These operations can represent a significant amount of work and must be assessed in advance by the contractor.



Watering of a natural soil platform with a "carp-tail" surface sprinkler (Vlassenbroek experimental jobsite - Photo: Lhoist)



Buried sprinkler (Photo: INRAE)

Figure 33: Humidification of natural soil before treatment (watering)



Mixing of natural soil after watering (Vlassenbroek experimental jobsite - Photo: Lhoist)



Releveling of a natural soil layer with a GPS-guided Bulldozer after a watering and mixing sequence (Photo: Lhoist)

Figure 34: Humidification of natural soil before treatment (mixing and re-leveling)

13.2.7 In-situ soil treatment (watering, spreading, mixing)

In-situ treatment can be applied directly to the deposit without prior excavation for the workability (M) and stability (S) functions. For the workability (M) function, depending on the evolution of the moisture content of the natural soil during the execution, an adjustment of the lime dosage is possible. For all the other functions, the lime dosage must comply with the one specified in the study. For the watertightness (P), resistance to internal erosion (EI), surface erosion (ES), and overspill water (EV) functions, a homogenization phase is required before treatment. For the stability (S), watertightness (P), resistance to internal erosion (EI), surface erosion (ES), and overspill water (EV), functions if the moisture content of the natural soil did not require moistening before the treatment operation, an adjustment of the moisture content at the time of treatment may be necessary.

The treatment methodology must have been precisely defined and validated by a field test or a suitability field test before the beginning of the works. The main characteristics of the suitable equipment are:

- water spreaders equipped with volumetric dosing controlled by forward speed
- storage silos ensuring that lime is stored protected from air and moisture, with devices to limit dust emissions during tanker unloading and spreader loading
- lime spreaders equipped with volumetric or gravimetric dosing controlled by forward speed, ensuring a spreading coefficient of variation < 10% and spreading accuracy < 5%
- mixers equipped with horizontal shaft mixer (self-propelled or mounted equipment) with control and monitoring of forward speed and mixing depth

For each jobsite case, the quantity of lime to be spread Q (expressed in kg/m^2) is calculated according to the formula below, where d is the lime dosage determined by the laboratory study and expressed as a percentage of the mass of lime relative to the mass of dry products (soil + lime) contained in the mixture:

$$Q = e \times \rho_d \times \frac{d}{100 - d}$$

- Q : amount of lime to be spread (kg/m^2)
- e : thickness of the soil layer to be treated (m)
- ρ_d (*): dry density of the in-situ soil to be treated (kg/m^3)
- d : target lime dosage determined by the laboratory study (%)

(*): the dry density of the in-situ soil to be treated can be estimated or measured using a gamma densimeter

For soils requiring high lime dosages (generally $d > 3\%$), it is preferable to perform lime spreading in two passes, separated by at least one mixer pass (or more, depending on the clay content of the soil and its moisture content). A curing period (favorable to clay flocculation) between the different spreading phases may be necessary to achieve the desired grain size. Soils with high clay content (F3 and F4) require significant mixing energy to obtain the finest possible grain size (a total of 4 to 6 mixer passes may be necessary).



Figure 35: General view of a soil treatment jobsite with, from left to right, a binder spreader, two self-propelled mixers, and three compactors (Photo: Lhotellier Company)



Lime spreading on the dedicated soil treatment platform with a volumetric dosing spreader and weight control (Salin de Giraud jobsite, November 2017 – Photo: Lhoist)



Lime spreading on a dedicated soil treatment platform with a tracked volumetric dosing spreader and weight control (Vlassenbroek experimental jobsite – Photo: Lhoist)



Lime spreading on a wet F2 soil with a volumetric dosing spreader (Photo: Lhoist)



Lime spreading on a wet F2 soil with a tracked volumetric dosing spreader and weight control (Photo: Lhoist)

Figure 36: Lime spreading



Self-propelled mixer (Photo: Lhoist)



Tractor-mounted mixer (Vlassenbroek experimental jobsite – Photo: Lhoist)

Figure 37: Mixing



Figure 38: View of a treatment plant, including a self-propelled spreader and mixer, configured for road transport (Photo: Lhotellier Company)

Some equipment combines spreading and mixing functions, or watering and mixing functions, on the same machine. In the first case, the equipment is designed for medium-sized jobsites and to prevent lime dust emission. In the second case, combining the two functions ensures precise water dosing, enhances water diffusion within the soil-lime component, and can significantly improve the treatment plant output rate (as watering and mixing occur in a single operation).



Combined spreading and mixing functions: the equipment is towed by an agricultural tractor (Photo: Streumaster)



Combined watering and mixing machinery: the sprinkler is pushed by the self-propelled mixer, and water is incorporated directly into the mixer drum (Salin de Giraud jobsite November 2017 – Photo: Lhoist)

Figure 39: Views of soil treatment machines combining two functions (spreading and mixing on the left, watering and mixing on the right)

After the treatment, the soil is either collected with an excavator or loader, or pushed back at the end of the platform with a bulldozer and then loaded onto transport vehicles. Particular attention must be paid to the recovery operation of the treated soil to avoid picking up untreated soil, for example, by removing an excessive thickness or by including the edges of the untreated soil platform. This task is facilitated by GPS guidance equipment that can be fitted to machines (e.g., bulldozers, excavators), allowing for precise stockpiling and recovery operations. It is also possible to perform visual control by relying on the color contrast between treated and untreated soil, or, even better, by spraying the soil with phenolphthalein, a colorless basicity indicator that turns red in an alkaline environment.



Recovery of treated soil with an excavator on a platform with GPS guidance; note that the string in the foreground has not been included as untreated (Vlassenbroek experimental jobsite – Photo: Lhoist)



Recovery of treated soil with an excavator on a platform (Salin de Giraud jobsite November 2017 – Photo: Lhoist)

Figure 40: Recovery of treated soil

13.2.8 In-plant soil treatment

When the nature and moisture content of the soil allow it, this treatment method is particularly well-suited for the watertightness (P), resistance to internal erosion (EI), surface erosion (ES), and overspill water (EV) functions. It was used during the construction of the DigueELITE demonstrators at Vidourle and for the Rouen Dike. The soil is supplied from the deposit or temporary stockpile after undergoing homogenization, removal of coarse fractions, or preparation to adjust its moisture content prior to treatment. It is stockpiled near the plant at a sufficient height to allow for loading into the plant using an excavator positioned on the surface of the stockpile. This method allows the excavator operator to perform the loading operations with precision and avoid any unwanted clogging of the plant inlet hopper, which is equipped with trimming, screening, and lump breaker systems.

To limit clogging of the trimming system and limit the amount of soil reject entering the inlet screen and lump breaker, it may be necessary to prepare the natural soil in advance at the stockpile to crumble it as much as possible and separate any blocky elements that may be present.

For this application, the plants to be used are specifically designed for the recycling of fine, wet, and plastic soils. Their current actual capacity (50 to 240 t/h) must be in line with the expected production rate on the jobsite. The flow control system for incoming soil (untreated soil) can be volumetric or gravimetric. The lime storage system, with variable capacity depending on the machines, is incorporated into the plant. Lime dosing is generally gravimetric, allowing for precise dosing ($\pm 2\%$ of the required dosage). On some machines, dosing is volumetric and depends on the bulk density of the lime, which requires it to be measured beforehand. The installation of the plant alone requires a horizontal platform with an area of approximately 100 m². Its location must be planned to ensure good accessibility and circulation conditions for machinery.

The adaptation of the treatment plant to the incoming natural soil (type and moisture content) to achieve the desired moisture content, treated soil grain size, and production rate must be verified before the beginning of the jobsite. In particular, if a significant moistening is required, the treatment plant production rate may be limited based on its maximum achievable water addition rate. The quality of the treated soil grain size depends on both the clay content of the natural soil and the mixer characteristics (e.g., drum length, blade type, and mixer rotation speed). Generally, treating a low-clay soil (F1) in a treatment plant does not pose a problem. F2 soils can be processed in a treatment plant under certain conditions (e.g., low or medium moisture content, low clay content, no large clods).

For the treatment of F3 and F4 soils, the use of a treatment plant is not currently feasible with existing technology.



Temporary natural soil stockpile and mobile treatment plant (Vidourle jobsite July 2015) (Photo: DigueELITE)

Figure 41: General view of a treatment plant



100 t/h mobile treatment plant (Photo: DigueELITE)



200 t/h mobile treatment plant (Photo: Lhoist)

Figure 42: Details of a treatment plants

13.2.9 Grain size

The particle size of the treated soil depends, among other factors, on clay content and moisture content of the soil, type of mixer (in-situ or in-plant treatment), and mixing energy (number of mixer passes in the case of in-situ treatment). Therefore, attention will be given to the study of the capacity of the mixing equipment and the methodology used to achieve fine particle sizes compatible with the targeted objectives.

By convention, the agglomerate diameter used to characterize the particle size corresponds to the sieve mesh size allowing a passing > 95%.

For fine F1 and F2 soils, a particle size ranging from 20 to 40 mm is generally obtained during in-situ treatment after one or two mixer passes. The use of mixers with dual horizontal shafts in treatment plants generally allows for obtaining a grain size equivalent to that achieved with in-situ treatment equipment, but this must be verified before starting the jobsite. For wet, medium-to-high clayey soils, caution should be exercised when using a treatment plant, as it is not economically feasible to make several passes through the plant, whereas with in-situ treatment equip-

ment, several successive mixer passes can be performed to achieve the desired grain size. In this case, after each mixer pass, the platform must be re-leveled with a leveling machine to ensure the mixing depth for each mixer pass.

For finer, more clayey soils (F3 or F4), it is practically difficult to achieve a grain size of less than 50 mm when treating in-situ, despite a high number of mixer passes.

The mixing energy required to achieve the targeted grading of the treated soil must be taken into account, as it dictates the production rate of the treatment plant.



View of the grain size of F1 soil treated with 2% CaO after one mixer pass (Salin de Giraud jobsite November 2017 - Photo: Lhoist)



View of the grain size of F1 soil treated with 2% CaO at the treatment plant outlet (Vidourle DigueELITE project experimental jobsite)



Detail of the grain size of F1 soil treated with 2% CaO after one mixer pass (Salin de Giraud jobsite November 2017 – Photo: Lhoist)



Detail of the grain size of F1 soil treated with 2% CaO at the treatment plant outlet (Vidourle DigueELITE project experimental jobsite)

Figure 43: Grading of F1 soil after lime treatment



View of the grain size of F2 soil treated with 4% CaO after one mixer pass (Photo: Lhoist)



Detail of the grain size of F2 soil treated with 4% CaO after 3 mixer passes (Photo: Lhoist)

Figure 44: Grading of F2 soil after lime treatment

13.2.10 Implementation of lime-treated soils

For embankments, the classic “excess meter” method is adopted: an extra width of about 1 meter allows the compactor to work safely while ensuring the quality of compaction at the edge of the embankment. The excess soil is removed with an excavator equipped with a cleaning bucket at the end of construction. Depending on the jobsite size, the volume of soil corresponding to this extra width can be significant. After re-cutting, this treated soil can be used as backfill soil in the same way as that already placed, provided it is not too aged and has been properly disaggregated. An adjustment of its moisture content may also be necessary (e.g., watering and mixing, or re-passing through the treatment plant without adding lime). Adjustments are preferably done using a bulldozer.

Regarding the adjustment, the use of equipment with automatic altimeter adjustment device is highly recommended to minimize the time required to adjust layer thickness and to achieve effective control over the thickness applied. The use of such devices also makes it possible, thanks to the recordings that can be made, to provide useful data for inspections and for the as-built documentation of the structure.



Supply of treated soil by dumper and spreading of a layer with a bulldozer (Salin de Giraud jobsite – Photo: Lhoist)



Simultaneous execution of implementation and compaction operations (Vidourle jobsite – Photo: DigueELITE)



Spreading a layer of treated soil on a field test with a bulldozer equipped with an altimetric GPS system (Vlassenbroek experimental jobsite – Photo: Lhoist)

Figure 45: Operations for the implementation of treated soil on hydraulic structures

In the case of partial reconstruction or reinforcement of an existing structure (e.g., shell, bank protection), the new embankment is supported by the existing structure by means of pre-formed terraced benches. If the terraced bench technique is not feasible, the new embankment is supported directly by the slope of the existing structure. The compaction of these interfaces is a delicate point requiring careful considerations on the methodology and resources to be deployed, to avoid the presence of fragile and poorly compacted areas that could be detrimental for the strength of the structure. In the case of a terraced bench, it must be moistened if necessary and compacted with a heavy vibrating padfoot roller (the size of the compactor must be adapted to the bench) to ensure sufficient bearing capacity for the treated soil compaction and good adhesion of the treated soil layer, thanks to the impressions left by the compactor feet on the bench surface. If an embankment is placed against an existing structure, the latter must be moistened if necessary, and the compaction of the treated soil layers should rely as much as possible on the slope of the existing structure.

In both cases, the type and size of the compactor will be adapted to the available space for machinery movement, which may require adjusting the elemental layer thickness and, consequently, the implementation methodology.



Structure with terraced benches (Photo: Lhoist)



Compaction of an embankment without terraced benches, supported by the slope of an existing structure (Photo: DigueELITE)

Figure 46: Rehabilitation of existing structures

In the same scenario of repairing or reinforcing an existing structure, the different layers can potentially be implemented by completely covering the slope of the existing structure. While this technique does not appear to pose any particular problem for adjusting and leveling operations using a bulldozer, compaction must nevertheless be carried out in the direction of the slope of the embankment. This technique is limited by the slope gradient and by the traction capabilities of the compaction equipment. In practice, it must be verified before the beginning of the works, based on the slope working capability declared by the compactor manufacturers. However, this methodology appears less suitable for slopes steeper than 25% (4H:1V). When implementing soil according to this methodology, compaction of the existing slope using a heavy vibrating padfoot roller, possibly accompanied by watering, is necessary before the implementation of the lime-treated soil layers.



Figure 47: Compaction of a layer along a 3H:1V slope (Vlassenbroek experimental jobsite – Photo: Lhoist)

13.2.11 Compaction of backfill layers

Unless otherwise specified, the practical compaction methods outlined below are adapted according to the functional requirements of the intended structure.

- For the workability (M) function, the practical compaction procedures are usually those applied for the use of materials in embankments. The required densification objective is $\rho_{dm} \geq 95\% \rho_{dmaxOMC}$ on average.
- For the stability (S) function, the practical compaction methods are those applied for the use of materials in capping layers. The required densification objective is $\rho_{dm} \geq 98.5\% \rho_{dmaxOMC}$ on average, and the moisture content of the treated soil must be close to OMC.
- For the watertightness (P) and resistance to surface erosion (ES) functions, in the absence of available feedback from the experience, the choice of usable soils is currently limited to fine F1, F2, and potentially F3 soils, with the moisture content of the soil-lime component at the time of compaction that must be above OMC, approximately $1.10 \times w_{OMC}$. The maximum recommended thickness of compacted layers is 30 cm. Compaction is preferably carried out using heavy vibrating padfoot rollers (Figure 48). This equipment is chosen to both apply the necessary compaction energy, overcome the lamination phenomenon, and provide a kneading action during compaction that is beneficial for achieving the desired level of permeability. The required densification objective is $\rho_{dm} \geq 98.5\% \rho_{dmaxOMC}$ on average.
- For the resistance to internal erosion (EI) function, in the absence of available feedback from the experience, the choice of usable soils is currently limited to F1, F2, F3, and F4 soils, which must be compacted under the same moisture content conditions as those for the watertightness (P) and resistance to surface erosion (ES) functions, approximately $1.10 \times w_{OMC}$. Similarly to the watertightness (P) and resistance to surface erosion (ES) functions, for the resistance to internal erosion (EI) function, compaction will be performed using heavy vibrating padfoot rollers (Figure 48). The use of F3, and especially F4, soils should be considered with caution. Indeed, the clay content and plasticity of these soils make them difficult to treat and to obtain a grain size compatible with the function in question. Laboratory tests have proven the good resistance of these soils to piping erosion, and the jobsite carried out as part of the TerDOUEST project demonstrated that F3 soils could be implemented under correct

conditions of moisture content and a particle size of approximately 0/50 mm after treatment. Nevertheless, if the use of F3 or F4 soil is being considered, it is advisable to at least verify the treatment, implementation, and compaction conditions for these two soil types through field tests. For this function, the compaction conditions are identical to those recommended for the watertightness (P) and resistance to surface erosion (ES) functions. These conditions must be established on a case-by-case basis through the execution of compaction field test, based on the specific jobsite.



Figure 48: Compaction with a heavy vibrating padfoot roller for a F2 soil structure treated with 3% lime (Photo: Lhoist)

13.2.12 Layer adhesion

In earthwork operations, the most frequently used compactors are heavy vibrating padfoot rollers and smooth drum rollers. The use of heavy vibrating padfoot rollers is preferred to ensure a good mechanical inter-layer adhesion. The footprints left by the compactor pads on the underlying layer (a layer already placed and compacted) act as anchors, allowing the interlocking of the superjacent layer (the layer currently being applied) into these points of adhesion. The use of smooth drum rollers does not allow for this arrangement between layers.

Furthermore, the movement of transport equipment affects both the compaction and the surface condition of a layer after its compaction. For these reasons, the practical implementation procedures must be defined jointly by the contractor and the project owner during the jobsite preparation phase.

Two scenarios are possible.

- **Sections of the structure where transport vehicles do not travel on the underlying layer**

When the moisture content of the soil is sufficiently high ($w \geq 1.1 \times w_{OMC}$), compaction performed with a heavy vibrating padfoot roller creates well-formed footprints on the layer surface, approximately 0.10 m deep, with well-compacted soil. If the moisture content is too low, the superficial part of the layers may experience significant shearing of the visible portions of the footprints (Figure 49). In this case, the layer adhesion is of poor quality, due to insufficient water content and density. Furthermore, once covered by the superjacent layer, this poorly compacted soil fringe adds to the thickness of the next layer and can lead to poor compaction quality in this inter-layer zone.



Well-formed and compacted padfoot roller footprints on F1 soil treated with 2% CaO at $w=w_{OMC} +4\%$ (Lhoist photo)

Friable padfoot roller footprints due to insufficient water content on F1 soil treated with 2% CaO at $w=w_{OMC}$ (Lhoist photo)

Figure 49: Footprints left by a padfoot roller on F1 soil treated with 2% CaO

In the case of high temperature and wind, the moisture content of the superficial part, corresponding to the depth of the footprints ($\approx 0.10\text{m}$), can rapidly decrease by a few percentage points (2 to 3%, or even more). To avoid such a situation, the surface of the compacted layer can be slightly moistened (2 to 5 l/m²) and additionally compacted before the application of the superjacent layer.

Conversely, if a compacted layer that is not yet covered by the next layer is subjected to precipitation during jobsite downtime or during a thunderstorm, the compactor footprints will retain water. In this scenario, the simplest approach is to remove the affected part by scarification and perform a new compaction. Alternatively, a new lime treatment can be considered for the surface, to a depth of approximately 0.10 m, followed by an additional compaction to restore moisture content and densification level of the soil-lime component to the expected values.

If in-plant soil treatment is used without in-situ treatment equipment available, it is advisable to remove the upper fringe of the layer and reshape the padfoot impressions with one or two passes of a heavy vibrating padfoot roller.

During a scheduled jobsite shutdown (night or weekend), it is advisable to close the surface of the layer using a smooth drum roller. When work resumes, it is recommended to scarify the upper part of the layer to a thickness of approximately 0.10 m. This operation may be supplemented by watering or adding milk of lime, and by creating impressions with one or two passes of a vibrating padfoot roller.

- **Sections of the structure where transport vehicles travel over the underlying layer**

In this case, the upper part of the underlying layer, compacted by the movement of transport vehicles, exhibits a closed surface condition. The footprints left on the underlying layer, which was compacted with a heavy padfoot roller, disappear under the action of transport vehicles, preventing layer interlock. Furthermore, depending on the moisture content of the soil-lime mixture, more or less pronounced rutting may appear (Figure 50). Rutting is a function of the type of transport equipment and the contact pressure exerted on the soil by the wheels. For this reason, the use of articulated dump trucks is preferred, while the use of tipper trucks, which leads to significant rutting, is not recommended. Before implementing the superjacent layer, a surface scarification, potentially

preceded by reprofiling and accompanied by watering to compensate for moisture content loss due to aeration, must be carried out on the part of the underlying layer that has experienced transport vehicle traffic.

As far as possible, the movement of transport equipment on the surface of the underlying layer should be limited by defining traffic zones. The surface condition of these areas must be restored before the implementation of the superjacent layer.

One solution to improve bonding when vehicles are circulating is to spray a small amount of milk of lime suspension on the surface of the underlying layer before it is covered by the superjacent layer. This requires effective jobsite traffic management on the surface to be covered, access to milk of lime, and a suitable sprayer.

Furthermore, the rutting caused by transport vehicles can promote preferential flow and localized concentration



of stormwater on the structure. Measures must be taken to prevent this phenomenon, which could lead to the formation of gullies on the slopes of the structure.

Figure 50: Closure and rutting of the underlying layer caused by transport vehicle traffic (Photo: DigueELITE)

13.2.13 Difficult-to-access areas

These zones correspond, for example, to the connection of ramps between an existing structure and the one under construction, to a section with a complex geometry and reduced dimensions, to the surroundings of masonry structures, or to backfilling near pipelines.

In these areas, smaller compaction equipment, such as vibratory plates, vibratory tampers, or small compactors (Figure 51), are preferable. The use of these small compaction devices needs reduced the layer thicknesses and requires a significant number of passes.

Other compaction equipment, such as vibratory plates, hydraulic hammers, or padfoot rollers, mounted at the end of an excavator arm, are also usable. The efficiency of these machines depends on the contact force exerted on the excavator arm; therefore, it is impossible to define general compaction procedures applicable to all jobsite scenarios. The operating conditions for this equipment must be defined based on prior experience gained from tests that verify the actual compaction quality achieved.



Compaction with a vibratory tamper around a manhole
(Photo: DigueELITE)



Small vibrating padfoot roller (Photo: Lhoist)

Figure 51: Compacting difficult-to-access areas

13.2.14 Trafficability of construction machinery

The supply of treated soil for the embankment is preferably carried out using tractors equipped with trailers or dumpers. Transport using dump trucks is not recommended because their high ground contact pressures risk to cause significant rutting and a detrimental increase in pore water pressure in fine, wet soils, in addition to superficial shear in curved or turning areas. Rutting of approximately 5 cm is acceptable, it becomes problematic for greater values, generally leading to the appearance of creep phenomenon. To limit these risks, if the length of the structure allows it, it is advisable to prioritize the unloading at the end of the platform and to push the soil as far as possible with a tracked grading machine that develops lower contact pressures.



Movement of a dumper on F1 soil at the Vidourle jobsite
(Photo: DigueELITE)



Example of creep caused during transport by a 6x8 dump truck on F1 soil at the Vidourle jobsite (Photo: DigueELITE)

Figure 52: Rutting on lime-treated soil

13.2.15 Weather conditions

The execution conditions for building a hydraulic structure with lime-treated soil, in terms of weather conditions, are similar to those for a typical earthwork project.

Nevertheless, particular attention must be paid observing the following precautions:

- no temperature limitations for the workability (M) function
- temperature > 5°C for the stability (S), watertightness (P), resistance to internal erosion (EI), surface erosion (ES), and overspill water (EV) functions
- measures to prevent the exposure of treated and mixed, but uncompacted, soil to precipitations must be implemented

13.2.16 Environmental protection measures

The primary concern regarding environmental protection is related to dust emission in the presence of wind. As a general rule, rather than referring to a specific wind speed threshold, it is preferable to recommend the suspension of the in-situ soil treatment (lime spreading and mixing) if lime dust is observed dispersing outside the jobsite boundaries or into sensitive areas within the jobsite perimeter. It should be noted that construction sites for hydraulic structures can often be classified as "sensitive sites", due to their location (e.g., natural parks, nearby dwellings, cultivated lands).

To prevent dust dispersion, technical solutions can be implemented, such as using reduced-dust lime. In-plant soil treatment eliminates almost entirely the risk of dust emissions. Certain in-situ treatment equipment, which combines both lime spreading and mixing in a single operation, also helps prevent dust dispersion. This point must be addressed during the study phase, and the technical specifications must detail precise rules for environmental protection management. It should be noted that the risk of dust dispersion applies not only to soil treatment tasks but also to the supply, storage, and transfer phases of lime. To that end, the location of the lime storage silos must be chosen based on the potential risk, and natural or artificial protective measures should be considered. Equipment must be fitted with operational devices designed to limit dust dispersion. This point must be checked during machinery acceptance procedures.

The geographical locations of some jobsites are more sensitive than others, particularly in areas exposed to prevailing winds and require the utmost attention.

13.3 Structure instrumentation

In some cases, structure instrumentation is planned and must be detailed during the study phase. If sensor installation (e.g., probes for measuring moisture content, temperature, settlement, pore water pressure) must be carried out during the construction, these tasks may require downtime for installation operations, which should be anticipated in the phasing of implementation operations. Construction provisions must be considered by the designer to limit the risk of deterioration and to ensure the identification of buried systems (sensors, cables) during the embankment implementation operations due to equipment traffic, compaction, or slope trimming work. A centralization of cables connecting the various devices (sensors, recorders, transmitters) is generally implemented, involving the installation of underground access chambers. At the end of the jobsite, boreholes may be drilled for the installation of certain sensors such as piezometers, inclinometers, etc. It is preferable to install this equipment promptly once the contractor has completely finished the work, as the material begins to harden immediately after its implementation.



Drilling for a piezometer installation (Photo: DigueELITE) Installation of moisture content probes (Photo: DigueELITE)

Figure 53: Instrumentation of the demonstrator at the Vidourle jobsite

During the installation, it is advisable to perform a 3D topographic survey of each device installed within the structure.

13.4 Finishing work

Aside from the installation of specific devices (e.g., geotextiles, geogrids for layer adhesion), the finishing work includes:

- slope trimming (preferably from the toe of the slope, using an excavator equipped with a ditching bucket)
- earthworks for trenches and basins
- application of topsoil on exposed surfaces (thickness of 0.20 to 0.30 m), or any other protective measure to prevent significant variations in the moisture content that could lead to desiccation cracking
- vegetalization on slopes covered with topsoil



Figure 54: Trimming of slopes for a hillside retention structure (Photo: Entreprise Lhotellier)

E. CONSTRUCTION WORK INSPECTION

14. Introduction

This section of the document focuses on the controls to perform for structures built with lime-treated soil. The compaction control is detailed here, as the quality achieved determines the stability and durability of the structures.

15. Implementation control

In its quality assurance plan, the contractor presents the work execution procedures it commits to implement, along with their control methods, to achieve the required quality. This document enables the project owner to size the external control and establish the control plan, which defines the control actions to be carried out and their distribution between internal control (contractor) and external control (project owner). During the progress of the jobsite, the planned tests must be conducted according to applicable standards or operating procedures defined in the technical requirements by the project owner. Test results are verified and validated by the project owner.

The functional quality of a structure, according to its functions (workability (M), stability (S), watertightness (P), resistance to internal erosion (EI), surface erosion (ES), overspill water (EV)), is translated into the required quality and necessitates verification of its achievement through measurable parameters.

The nature and frequency of the controls to be carried out must be defined based on:

- service function of the structure
- jobsite size
- treatment method
- technical and economic challenges

All control actions must be detailed in the Control Plan, specifying the representative number of measurements for each type of test to be conducted. Some actions that require the provision of laboratory facilities or the use of specialized laboratories must be stipulated in the Control Plan.

Certain types of controls are performed "post-process," after the work has been completed, either in whole or in part. If a non-conformity is detected, a partial or total rework of the operations may be requested, which is often unrealistic or impractical. Therefore, to prevent potential deviations or the appearance of defects detected too late, it is preferable to apply other in-process control methods, such as:

- monitoring the evolution of the moisture content of the deposit as work progresses
- continuous monitoring of lime soil treatment operations
- continuous compaction control
- preparation of execution tracking documents
- unannounced inspections conducted at the request of the project owner

For structures constructed with lime-treated soil, the following points must be subjected to appropriate controls.

15.1 Water content

The water used onsite for lime soil treatment must undergo a physico-chemical analysis to ensure it does not contain any interfering elements. This analysis must be repeated if the water supply source changes. Reference samples can be taken in chemically neutral, sealed containers.

Controlling the water content of the soil before and after lime treatment is critical because it allows for:

- organizing the humidification or aeration phases of the natural soil under controlled conditions
- ensuring compliance with the target moisture content of the treated soil, as determined by laboratory studies, to achieve the expected results after compaction

Several methods for measuring gravimetric water content are available and standardized. If the oven-drying method is used, a 24-hour delay should be anticipated between sample collection and result availability, while in the case of a microwave desiccation process, only a few minutes are required. These factors must be considered when defining the organization of control operations.

Measurements taken with devices equipped with a neutron absorption system do not always concur with measurements obtained by drying. If such devices are used, it is advisable to calibrate the values obtained using a standardized oven-drying measurement method.



Taking samples for water content measurement on a field test (Photo: Lhoist)



Jobsite laboratory for water content measurement with a microwave oven (Photo: Lhoist)

Figure 55: Jobsite water content controls

15.2 Lime characteristics

The quality of the lime used (type, reactivity, particle size) impacts the final performance of the treated soils. Standard EN 459-1 [4] defines the characteristics and requirements for the limes usable in civil engineering and building construction. Therefore, when referring to this standard, it is necessary to explicitly designate the product to be used. For applications in hydraulic structures, laboratory studies and demonstrator tests recommend high-purity quicklime conforming to standard EN 459-1 [4] with the designation CL 90-Q (R5, available lime $\geq 88\%$).

- Reactivity class: R5 (temperature greater than 60°C in less than 10 minutes during the water reactivity test)
- Granulometric class: The particle size distribution must be chosen between class P1, P2 or P3, in accordance with the local lime requirements for soil treatment, and following EN 459-1 [4]
- Free lime content: $\text{CaO}_{av} \geq 88\%$

Characterization tests are described in standard EN 459-2 [43]. The reactivity of lime and its particle size distribution by dry sieving can be easily checked on site. The free lime content is measured by the producer and can also be measured in laboratories equipped for this purpose. Reference samples can be taken and stored in sealed, chemically neutral containers.

As a construction product, lime is a certified material subject to CE marking, which attests to its conformity with standard requirements. The CE mark must appear on the delivery note and on the packaging when using bags or big bags. Delivery notes must be submitted to the project owner and verified.

15.3 In-Situ treatment

The first action to take is to inspect the condition and operational status of the treatment equipment:

- lime storage silo
 - visual inspection of the silo
 - visual inspection of the anti-dust system during initial filling
- sprinkler
 - visual inspection of the machine
 - inspection of the spraying system (actuators, valve, transverse distribution of spraying)
- spreader
 - provision of the technical data sheet and machine serial number
 - visual inspection of the machine
 - inspection of equipment (indicators, printing of weighing tickets if available)
 - inspection of the anti-dust systems fitted on the spreader
- mixer
 - provision of the technical data sheet and machine serial number
 - visual inspection of the machine
 - inspection of the mixing tools (type and state of wear)
 - inspection of the equipment (mixing depth and speed indicators, ejection hatch operation)



*Visual inspection of the mixer rotor's condition
(Photo: Lhoist)*



*Inspection of the mixing depth indicator installed
on the mixer (Photo: Lhoist)*



Visual check of spreader loading without dust emission
(Photo: Lhoist)



Visual check of lime spreading without dust emission
(Photo: Lhoist)

Figure 56: Example of visual inspections for an in-situ treatment plant

If a "carp-tail" type sprinkler is used, it must be calibrated by determining the average flow rate obtained during a complete tank emptying (tank volume/watered area in l/m²). This operation can be repeated several times to ensure the reproducibility of the resulting average flow rate. It can also be performed at various forward speeds to define the sprayer operating point based on the quantity of water to be added.

For in-situ treatment, the lime dosage is translated into the quantity of lime to be spread per unit area, expressed in kg/m². The actual quantity of lime spread must be verified during spreader adjustment by carrying out measurements using tarp or pan weighing methods. Using the same method, spot measurements are recommended during jobsite operations or whenever the spreader setting is changed. For spreaders with an integrated onboard weighing system, issuing a weighing ticket after each spreading sequence allows for controlling the average quantity of lime spread, based on the amount of lime discharged and the area covered by the spreader during the spreading sequence.

In the case of treatment on a dedicated platform, the recovery phase of the lime-treated soil, performed with an excavator or by bulldozer, must be visually controlled, with the aid of phenolphthalein if necessary. This ensures that natural soil from the platform (maintaining the required thickness of the lime-treated soil layer) or untreated soil from typically remaining side windrows is not mixed with the treated soil.



Control of spread lime surface mass by pan weighing
(Photo: Lhoist)



Display of an onboard weighing system of a spreader – display of remaining lime weight in the spreader
(Photo: Lhoist)

Figure 57: Control of lime dosage

15.4 In-plant treatment

The descriptive and detailed technical data sheet of the treatment plant must be provided. The use of a treatment plant with volumetric or gravimetric dosing requires calibration before the production phase. Control weighings must be performed on both inputs: natural soil and lime. For natural soil, a double weighing per dump truck allows for controlling the actual flow rate of "wet natural soil." For lime flow control, a suitable system (e.g., pan, big-bag) should be provided to receive and weigh the lime. These controls must be repeated for every change in the nominal flow rate of the plant (soil and lime). Some equipment allows for recording the plant operating parameters during production, such as average soil, lime, and water flow rates, the quantity of treated soil produced, etc. These records, which allow for tracking the production history, are useful for controls.

After the plant adjustment phase, it is advisable to conduct an operational check during which a representative quantity of treated soil is produced (approximately 10 to 25 tons, depending on the plant flow rate). The resulting stock allows for controlling the water content and particle size of the lime-treated soil.

15.5 Grain size of lime-treated soil

The grain size control of the lime-treated soil is performed at the beginning of the jobsite during the testing plot, suitability field test, or the plant operational check. The achieved fineness of grading may require to modify the treatment methodology to achieve the target objective.

This parameter is generally assessed visually, but can be controlled by direct manual dry sieving of a sample through sieves with mesh sizes of 20, 31.5, and 40 mm. The minimum mass of soil to be sieved must be 3 kg for a 20 mm grain size and 12 kg for a 40 mm grain size. The factor D characterizing the grain size corresponds to the sieve mesh size that allows 95% passage. Grain size control can be repeated during the jobsite operations if a deviation is visually observed.

As an example, Figure 58 shows a grain size result obtained after in-plant treatment of a F1 soil with 2% lime. The particle size distribution curve shows 87% passing through the 20 mm sieve and 95% (D_{max}) through the 30 mm sieve. The grain size in this example is 30 mm.

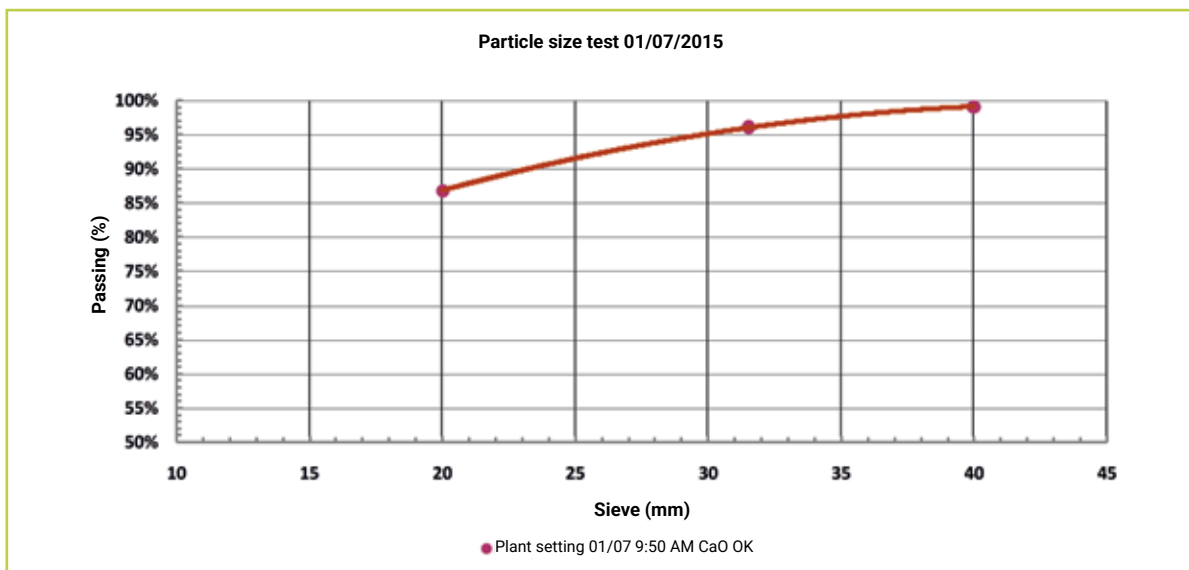


Figure 58: Particle size of F1 soil after in-plant treatment with 2% lime

16. Compaction control

Compaction control first involves the acceptance of the compactors, checking their specifications, ensuring they are in good working condition, and adjusting them if necessary.

The quality of compaction can be verified using two methods:

- Continuous control method
- Spot check method

16.1 Acceptance of compactors

The compaction equipment used on site must be inspected and verified. The technical data sheets for the machines, including characteristics that allow verification of their efficiency class, must be provided. The effectiveness of compaction depends on the operating speed of the compactor, and the presence of a calibrated speed indicator on the machines must be verified. For continuous compaction control, the equipment of a calibrated and properly functioning tachograph-type device must also be verified. Recently, new GPS-based driver assistance and continuous compaction control systems have emerged. These systems, which provide complete and reliable results, are expected to rapidly gain prominence and should be favored.

Note: It is important to verify during the compaction field test plot or at the beginning of the works that the use of smooth drum compactors does not generate layering due to vibration.

16.2 Continuous control method

There are several methods for performing continuous control. Each country that uses this approach has developed its own method. The European standard EN 16907-5 [44], focused on quality control and presents two main methods:

- Continuous Compaction Control (CCC) using vibrating compactors
- Compaction using the Q/S method

If continuous compaction control is chosen, and no proven local method is available, one may refer to the standard and choose one of the two methods, provided it is suitable for the context (materials, moisture content, etc.). Otherwise, it is preferable to adopt a spot check method.

16.3 Spot check method

This type of control is carried out measuring density in situ or the resistance to the penetration of a penetrometer tip at the end of a compaction operation.

Density measurements must be performed using gamma densimeters compliant with current standards. The investigation depth of the measuring equipment used (Figure 59) must correspond to the thickness of the placed layers. The maximum investigation depth of the measuring equipment is currently 0.40 m. To control the compaction level of a layer, a series of at least 6 measurements should be taken to evaluate the mean value and its dispersion. These measurements are generally accompanied by destructive soil sampling to determine the water content. The measurement results are expressed as a compaction ratio with reference to the Optimum Moisture density of the treated soil, allowing for the assessment of the compaction quality achieved over the average thickness of a layer. It is not possible with these devices to access the density at the bottom of the layer.



Figure 59: In-situ density measurement using a gamma densimeter (Photo: DigueELITE)

17. Final topographic survey

It is advisable to conduct a final topographic survey of the structure (Figure 60). The topographic surveys must allow for the reproduction of the spatial dimensions of the as-built structure.

This data can be provided in the form of a digital terrain model (DTM), which will allow for monitoring the evolution of the structure over time (settlements, slope stability, etc.). In this model, it is advisable to include all singular points (chambers, sensors, boreholes, drains, etc.) whose knowledge is important for any future work (maintenance, repair, etc.).



Figure 60: Final topographic survey by GPS (Vlassenbroek experimental jobsites – Photo: Lhoist)

18. Construction monitoring records

The establishment of a register compiling all the elements related to the construction of the structure and the control operations is strongly recommended. This register is updated daily by the contractor, who records all useful data, such as:

- weather conditions
- observations and visual examinations (notes, dated photographs with legends)
- any changes to the methodologies used (soil preparation, treatment, compaction)
- precise identification of the work carried out and its location within the structure (excavation, backfill, layer, work on an existing structure, etc.)
- daily volumes of soil treated and implemented
- any replacement of treatment or implementation equipment
- results of continuous compaction monitoring
- control operations performed (operator, type of control, etc.) along with their results
- location of in-situ controls performed
- hazards and incidents encountered

The complete jobsite register is periodically reviewed by the project management and submitted at the end of the jobsite. This register is an important source of information and is useful for preparing the as-built documentation to be provided at the completion of the work.

Regardless of its size, every completed jobsite (new construction, reinforcement, or structure repair) requires an as-built file. This file is a key component in the transfer of responsibility from the contractor who performed the work to the project owner, and then to the manager.

All documents related to the construction of the structure (execution plans, surveys, jobsite log, instrumentation), its control (location, nature of controls performed, and test results), and its final acceptance ensured by external control must be included in the dossier of the structure. These documents enable:

- updating and completing databases of existing structures
- preparing and organizing future maintenance operations

F. STRUCTURE MONITORING

19. Monitoring methods

19.1 Visual inspection

Periodic visual inspection of dikes currently plays a predominant role in structure monitoring.

The DigueELITE example showed that treated soil structures must be observed in the same way as untreated soil structures: the observation points (serving as a checklist) are identical. Based on DigueELITE experience, the differences relate to burrowing animals and vegetation: burrowing animals cannot dig into the treated soil, and vegetation struggles to establish itself spontaneously. However, the observer will focus on checking for the presence of burrows in the untreated soil sections (foundation).

19.2 Instrumentation

The monitoring of a treated soil dike using sensors and instruments should not differ from that of an untreated soil dike; there are no specific characteristics of treated soil that require particular monitoring. The Vidourle demonstrator was subjected to specific instrumentation for research purposes with sensors installed within the structure for suction characterization. This provision should not be deployed in common cases of flood protection dikes.

It should simply be noted here that, as with any large linear structure, the development of fiber optic monitoring is relevant and that there is no contraindication to the installation of these fibers in treated soils. Simply it is important to check with the supplier that the protective sleeves and/or geosynthetics covering them are compatible with the high pH conditions of treated soil.

19.3 Monitoring by sampling and testing

Similar to an untreated soil structure, there is no reason to plan for long-term monitoring of the dike through subsequent geotechnical borings and tests. The laboratory and in-situ studies (and potentially the execution of an experimental jobsite), along with control and acceptance operations, ensure that the desired characteristics are obtained. Such sampling and testing should only be considered in cases of disorders or damages to determine their cause, similar to an untreated soil structure.

20. Application to the Vidourle experimental structure

A summary of the observations made during the monitoring of the DigueELITE demonstrator is presented in Appendix 2. For research purposes, a significant investment was made in the monitoring; therefore, it is not an example of the typical monitoring that would be carried out on an in-service structure. Visits were frequent (once a month after construction, then spaced out) and detailed. Furthermore, a particularity of the demonstrator is that it is not covered with a layer of topsoil, unlike in-service structures. This allowed for direct observations of the evolution of the embankment exposed to external agents, without the risk of attenuation or masking by a cover, which is exceptional.

Appendix 2 presents a summary of the monitoring by specific points observed, and for each of these points, the evolution over time and seasons, as well as the behavioral differences between untreated and treated soil. This informational document aims to show examples of observations that can be made during the monitoring, their interest, and the visible particularities of a treated soil structure compared to an untreated soil structure.

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Annex 1

List of hydraulic structures built in France using soil treatment with calcic aerial lime:

Structure	Location	Type of structure	Construction date of lime-treated areas	Description	Comments
Torcy-Neuf Dam (Canal du Centre)	Torcy-Neuf (71)	Dam	1883–87	2% hydrated lime (or milk of lime) in the clayey soil per 10 cm layer (compacted to 7.5 cm)	
Bief de Humes (Marne - Saône canal)	Humes (52)	Canal dam	1889	0.5% hydrated lime in the clayey soil per 10 cm layer (compacted to 6.7 cm)	
Michelbach	Michelbach (68)	Dam	1982	Purpose of treatment: seal the banks and ensure stability. Silty soil, with variable clay content and high moisture content, treated with varying lime dosages based on the moisture contents.	30 cm of lime-treated soil protection, in two 15 cm layers (3% lime for the first, 2% for the second)
Gast dam	Le Gast (14)	Dam	1985–86		
Fond Pignon dam	Sangatte (62)	Storage dam for excavation sludge from the English Channel tunnel	1987–1990	Objective of the treatment: re-use of wet chalks via in-place treatment with 2.5% quicklime	38 cm of lime-treated soil protection, covered with 10 cm of topsoil
Structures in Normandy	Normandy	Flood protection dams/ small dams	1990–2014		Protection with lime-treated soil, covered with 15 cm of topsoil
Estey d'Eyrans	Montesquieu (33)	Dike	2011	Garonne tributary subject to fluvial-maritime floods. Site material treated in-place in a Natura 2000 zone	
Overflow basin (ADP)	Roissy-en-France (95)	Dike	2013	Site silts lime-treated to form the basin dikes	
Borre dike	Borre (59)	Dike	2013	La Bourre floodplain. Site materials treated with 2-3% quicklime	38 cm of lime-treated soil protection, covered with 8-15 cm of topsoil

List of hydraulic structures constructed abroad using soil treated with calcic aerial lime

Structure	Location	Country	Type of structure	Construction date of lime-treated areas	Comments
Lyndon Johnson LBJ Ranch	Johnson City, Texas	USA	Basin	1960	
Lavon Lake Dam – Santa Fe railroad	Dallas, Texas	USA	Dam	1960	
US SCS Frogville Creek Dams 1 and 2	Oklahoma	USA	Dam	1968	30 cm of lime-treated soil protection, applied in two 15 cm layers (3% lime for the first, 2% for the second)
Reservoir Bottom Stabilization – Southern Illinois University.	Edwardsville, Illinois	USA	Reservoir bottom	1968	
US SCS Middle Clear Boggy dam	Oklahoma	USA	Dam	1970	38 cm of lime-treated soil protection, covered with 10 cm of topsoil
US SCS Squaw Creek canal	Oklahoma	USA	Canal dam	1972	Protection with lime-treated soil, covered with 15 cm of topsoil
Friant-Kern canal	California	USA	Irrigation channel (reconstruction of part of the channel)	1972–74	
1975–77	Stabilization of damaged areas (slippage, shrinkage) using 4% quicklime treatment of local soil ($I_p \sim 23-50$) to a depth of 1.2 m on the banks and 0.6 m at the canal bottom				
US SCS Mississippi dams (18 sites)	Mississippi	USA	Dam	1973	38 cm of lime-treated soil protection, covered with 8-15 cm of topsoil
West Memphis	Arkansas	USA	Dike	1974	Bank treatment with homogenization
US SCS Union City dam	Tennessee	USA	Dam	1974	30 cm of lime-treated soil protection, covered with 15 cm of topsoil

List of hydraulic structures constructed abroad using soil treated with calcic aerial lime (Cont.)

Structure	Location	Country	Type of structure	Construction date of lime-treated areas	Comments
US SCS Upper Lake Fork 1 – McKinney	Texas	USA	Dam	1974	30 cm of lime-treated soil protection, covered with 10 cm of topsoil
Dike network between Alton and Gale (on the Mississippi river)	Illinois, Missouri	USA	Dike	1975–1992	Treatment of damaged areas (slips, shrinkage cracks) of clayey local dikes ($I_p \sim 50$) with 4-5% hydrated lime, homogenized as a protective shell
Bog Hole Waterfall	Arizona	USA	Dam	1976	75 cm of lime-treated soil protection
Dam	New South Wales	Australia	Dam	< 1977	
Canada		Canada	Dam	< 1977	
US SCS Upper Lake Fork dam 2 and 3	Texas	USA	Dam	1977	30 cm of lime-treated soil protection, covered with 10 cm of topsoil
Dam 1 (Lamchieng?)		Thailand	Dam	< 1978	Upstream slope protection
2Huay Saneng dam?)		Thailand	Dam	< 1978	Asphaltic concrete sealing layer
Kilmore Dam	South Australia	Australia	Dam	< 1978	Protection of drains and slopes
Bungal Dam		Australia	Dam core	< 1978	Vertical layer of lime-treated clay on the downstream side of the core
US SCS dams 1 and 2	Tennessee	USA	Dam and Core	1978	30 cm of lime-treated soil protection and a lime-treated soil core

List of hydraulic structures constructed abroad using soil treated with calcic aerial lime (Cont.)

Structure	Location	Country	Type of structure	Construction date of lime-treated areas	Comments
US SCS Upper Lake Fork 4 – Paris	Texas	USA	Dam	1978	
USACE Los Esteros dam	Santa Rosa, New Mexico	USA	Dam core	1979	1.5 m lime-treated soil core
McGee Creek dam	Colorado	USA	Dam	1982–87	Zoned dam, 50 m high and 600 m long (crest). Materials with varying plasticity (I_p between 1 and 35), of which 30% have $I_p > 20$, treated with 1.5-3% hydrated lime
Mnjoli Dam		Swaziland	Dam core	1987	Downstream portion of the core treated with lime
Mun Bon Dam		Thailand	Dam	1994	
Chobot Lake dike	Milevsko	The Czech Republic	Dike	2003	
Hvezda lake dike		The Czech Republic	Dike	2003	
Javor reservoir		The Czech Republic	High-altitude water reservoir for artificial snow production	2009	Dike body treated with 2% quicklime, with slopes stiffened by geotextile reinforcement

List of hydraulic structures constructed abroad using soil treated with calcic aerial lime (Cont.)

Structure	Location	Country	Type of structure	Construction date of lime-treated areas	Comments
USACE Los Esteros dam	Santa Rosa, New Mexico	USA	Dam core	1979	1.5 m lime-treated soil core
McGee Creek dam	Colorado	USA	Dam	1982–87	Zoned dam, 50 m high and 600 m long (crest). More or less plastic materials (I_p between 1 and 35), of which 30% $I_p > 20$, enriched with 1.5-3% hydrated lime
Mnjoli Dam		Swaziland	Dam core	1987	Downstream portion of the core treated with lime
Mun Bon Dam		Thailand	Dam	1994	
Chobot Lake dike	Milevsko	The Czech Republic	Dike	2003	
Hvezda lake dike		The Czech Republic	Dike	2003	
Javor reservoir		The Czech Republic	High-altitude water reservoir for artificial snow production	2009	Dike body treated with 2% quicklime, with slopes stiffened by geotextile reinforcement

Annex 2

Monitoring of the DigueELITE Demonstrator

Several inspections were conducted on the experimental structure after its construction. The methodology followed the usual recommendations: single observer to limit subjectivity, sometimes accompanied by a second observer for cross-checking opinion; numerous referenced photographs to compare observed points; a checklist serving as a guide during the inspection; observations conducted from a distance and then up close, from all accessible points, including crest and toe of the slopes.

Key points related to this monitoring and observations include:

- the demonstrator comprises a lime-treated soil section and an untreated soil section. As part of the research project, the monitoring was specifically focused on comparing the behavior between the treated and the untreated sections
- the intensity and detail of these inspections are not reproducible in the case of an operational structure
- since the structure is not covered with a topsoil layer, the observer has direct access to the embankment without any risk of masking or attenuation

The main specific points identified during these inspections are presented below, with emphasis on their evolution over time and the comparison between treated and untreated soil.

Cracks

Cracks are observed on the demonstrator. They are visible on both the crest and the slopes. These cracks are both longitudinal (parallel to the crest of the structure) and transverse. On the lime-treated soil section, these cracks appeared immediately after the construction. A precise mapping confirms that over time (after 1.5 years from the construction) there is no change in the number or location of the cracks. The cracks are more or less visible depending on the season: hidden in winter by fine sediments and rain-induced surface reshaping, but clearly visible in summer. The material at the edges of the cracks retains a healthy and resistant appearance; there is no visible degradation such as crack widening or material degradation.

On the untreated soil section, cracks were observed several months after the construction, particularly immediately after it was subjected to overflow tests. These cracks are also both longitudinal and transverse to the structure. The most visible longitudinal crack is a continuation of the one identified on the lime-treated soil section. Similar to the lime-treated soil section, they are more visible in summer when the surface soil is dry.

Although they appeared later than on the treated soil, a rapid deterioration was observed in the cracks of the untreated soil section. The edges of the cracks show altered soil, eroded by runoff. This leads to a widening of the cracks, which promotes water and atmospheric penetration, accelerating the degradation process.



Transverse cracks in lime-treated soil (left) and untreated soil (right) - Photo taken on 09/16/2016, construction + 422 days (DigueELITE photos)

In the immediate vicinity of the cracks, the material behaves differently: in the lime-treated soil, it remains sound and compact, in the untreated soil, the material is altered and friable, crumbling under the fingernail of the observer.



Material degradation near the cracks on the untreated soil - Photo taken on 24/02/2017, construction + 583 days (photo DigueELITE)

At the time of writing this document, experimental and modeling efforts are underway to understand the origin of the cracks in the specific context of the demonstrator, as the construction occurred during an exceptionally hot period. Recommendations regarding the implementation method may be proposed based on the conclusions of these studies.

Rabbit Burrows

No anti-burrowing device was installed on the demonstrator. Observational monitoring included counting and precisely locating rabbit burrows. On the structure, burrowing animals dig their burrows on the slope facing the Vidourle (the most sheltered side) and exclusively in the untreated soil. Five months after the construction of the structure, 17 burrows were identified on the untreated soil slope, while none were found on the lime-treated soil. However, burrowing animals attempted to dig in the lime-treated soil, as evidenced by scratch marks and numerous feces, but without success.



Attempted burrow in the lime-treated soil on the left: scratch marks and numerous feces are visible. Burrow in the untreated soil on the right (DigueELITE photos)

Based on these observations, it appears unnecessary to plan for anti-burrowing devices on lime-treated soil embankments.

Resistance to external erosion by weathering agents

Observing the demonstrator immediately after construction provides valuable information on the resistance of the soil to adverse weather conditions.

The demonstrator experienced severe thunderstorms in the months following its construction. As soon as the first rains fell, signs of erosion (gullies) appeared on the untreated soil, some of which formed preferential pathways for runoff water. Regressive erosion phenomena then appeared, with some gullies reaching penetration depths of up to 1 m at the crest. Such phenomena were absolutely not observed on the lime-treated soil slope, which maintained a smooth appearance despite the rainfall. The contrast in the surface behavior against weathering is particularly noticeable at a specific point on the demonstrator, where layers of lime-treated soil are overlaid by layers of untreated soil. On the slope, gully erosion phenomena are visible in the upper part (untreated soil) and disappear upon contact with the lime-treated soils.



Erosion gully in the untreated soil on the left and behavioral contrast between lime-treated soil (smooth slope) and untreated soil (gullied slope) on the right (construction + 3 months) (DigueELITE photos)

The lime-treated embankment exhibits better resistance to weathering agents, which is beneficial for long-term performance and also offers significant short-term advantages. Indeed, during earthworks for long linear structures, it can take some time before the embankment is covered with topsoil. Embankment slopes, often fragile right after their construction, frequently show superficial damage that requires rework. Treating the embankment to enhance its resistance to precipitations helps avoid this type of costly rework.

Basin

A water retention basin was built at the base of the demonstrator to facilitate hydraulic testing as part of the research project. The basin was built with lime-treated soil, using the same formulation and implementation method as the lime-treated dike.

The basin filled up with the first rains. During subsequent visits, including periods of drought, the water level decrease remained minimal and could be attributed to evaporation. This confirms the effectiveness of the lime-treated soil layers, compacted under the specified conditions, in ensuring seepage control.



Water retention basin sealed by 2 compacted layers of lime-treated soil (DigueELITE photo)

Annex 3

Laboratory testing: standards, operating procedures, and publications

Characterization of the deposit

Enseignements de TerDOUEST - Propositions de compléments au Guide Traitement des Sols, IDDRIM, décembre 2015, <https://www.idrrim.com/publications/4055.htm> - French document

Granulometric analysis

EN 933-1, Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. January 2012

EN ISO 17892-4, Geotechnical investigation and testing. Laboratory testing of soil. Determination of particle size distribution. December 2016

Determination of the Atterberg Limits

CEN ISO/TS 17892-12, Geotechnical investigation and testing. Laboratory testing of soil - Determination of liquid and plastic limits. June 2018

Methylene blue value

EN 933-9, Tests for geometrical properties of aggregates Assessment of fines. Methylene blue test. March 2022

Sulfate and sulfide content

ISO 11048, Soil quality – Determination of water-soluble and acid-soluble sulfate. July 1995

Water content

ISO 17892-1, Geotechnical investigation and testing – Laboratory testing of soil. Part 1: Determination of water content. December 2014

Compaction behavior

EN 13286-2, Unbound and hydraulically bound mixtures Test methods for laboratory reference density and water content. Proctor compaction. April 2013

Laboratory tests for the workability (M) function

EN 13286-47, Unbound and hydraulically bound mixtures - Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling. November 2021

Laboratory tests for the formulation

Verification of suitability for treatment

EN 13286-49, Unbound and hydraulically bound mixtures - Part 49: Accelerated swelling test for soil treated by lime and/or hydraulic binder

Formulation study

ASTM D6276-19, Standard test method for using ph to estimate the soil-lime proportion requirement for soil stabilization.

Refer to annex 4

Laboratory tests for the stability (S) function

Sample preparation

EN 13286-50, Unbound and hydraulically bound mixtures - Part 50: Method for the manufacture of test specimens of hydraulically bound mixtures using Proctor equipment or vibrating table compaction. December 2004

EN 13286-53, Unbound and hydraulically bound mixtures - Part 53: Methods for the manufacture of test specimens of hydraulically bound mixtures using axial compression. January 2005

Uniaxial compressive strength

EN 13286-41, Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures. November 2021

EN ISO 17892-7, Geotechnical investigation and testing – Laboratory testing of soil Part 7: Unconfined compression test. November 2017

Tensile strength

EN 13286-42, Unbound and hydraulically bound mixtures - Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures, March 2003

EN 13286-43, Unbound and hydraulically bound mixtures - Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures. July 2017

Shear strength

EN ISO 17892-9, Geotechnical investigation and testing – Laboratory testing of soil Part 9: Consolidated triaxial compression tests on water saturated soils. February 2018

EN 13286-43, Unbound and hydraulically bound mixtures - Part 43: test method for the determination of the modulus of elasticity of hydraulically bound mixtures

EN ISO 17892-8, Geotechnical investigation and testing – Laboratory testing of soil Part 8: Unconsolidated undrained triaxial test. February 2018

EN ISO 17892-10, Geotechnical investigation and testing. Laboratory testing of soil Direct shear tests. January 2019

Compressibility and settlement

EN ISO 17892-5, Geotechnical investigation and testing – Laboratory testing of soil Part 5: Incremental loading oedometer test. February 2017

Laboratory tests for the watertightness (P) function

Determination of permeability (hydraulic conductivity)

EN ISO 17892-11, Geotechnical investigation and testing - Laboratory testing of soil - Part 11: Permeability tests. March 2019

Laboratory tests for the resistance to internal erosion (EI) function

HET (Hole erosion test)

XP P94-065, Sols : reconnaissance et essais - Hole Erosion Test - Principe et méthode d'essai en laboratoire pour la détermination des caractéristiques de résistance à l'érosion de conduit, November 2023 – French document

Investigation of rate of erosion of soils in embankment dams. C.F. Wan, R. Fell, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 130, No. 4, pp. 373-380, 2004

Investigating concentrated leak erosion behaviour of cohesive soils by performing hole erosion tests. N. Benahmed, S. Bonelli, European Journal of Environmental and Civil Engineering, 16(1), pp. 43-58, 2012

Investigation of erosion of soils in embankment dams. C.F. Wan and R. Fell, Journal of Geotechnical and Geoenvironmental Engineering, 130(4): 373-380, 2004

Laboratory tests for the resistance to surface erosion (ES) and overspill water (EV) function

The tests recommended here evaluate the erosion resistance of the surface locally and do not replace full-scale tests for determining overflow resistance.

JET test (Jet erosion test)

ASTM D5852-00. Standard test method for erodibility determination of soil in the field or in the laboratory by Jet Index Method, 2017

Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. G.J. Hanson, K.R. Cook, Applied engineering in agriculture, pp. 455, 2004

Pinettes P., Haddad H., Picault C., Bonelli S., Courivaud J.-R., Mallet T., Two erosion tests to quantify resistance to erosion during overflow: the jet erosion test and the overflow test, 28th ICOLD Congress, Chengdu, 2025

MoJet test (Mobile erosion test)

Erodibility diagnostic of existing hydraulic earthworks by Mobile Jets Erosion Test. P. Reiffsteck, I. Haghighi, C. Chevalier, 6th International Conference on Scour and Erosion, Paris, France, 2012

EFA test (Erosion Function Apparatus)

SRICOS-EFA method for complex piers in fine-grained soils. J.L. Briaud, H.C. Li, P. Nurtjahyo, Journal of geotechnical and geoenvironmental engineering, 130(11), pp. 1180-1191, 2004

SRICOS : Prediction of scour rate in cohesive soils at bridge piers. J.L. Briaud, F.C. Ting, H.C. Chen, R. Gudavalli, S. Perugu, G. Wei, Journal of Geotechnical and Geoenvironmental Engineering, 125(4), pp. 237-246, 1999

Erosion charts for selected geomaterials. J.L. Briaud, A. V. Govindasamy, I. Shafii, Journal of Geotechnical and Geoenvironmental Engineering, 143(10): 04017072, 2017

The EFA, Erosion Function Apparatus: an overview. J.L. Briaud and H.-C. Chen, Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, 2005-2006

Annex 4

Production of test specimens of treated material

Introduction

This annex provides recommendations concerning the preparation of specimens of lime-treated materials for laboratory studies. It is based on the Annex A of EN 16907-4, Earthworks - Part 4: Soil treatment with lime and/or hydraulic binders. It covers sampling, homogenization, binder addition, mixing, compaction, and curing conditions.

Sampling

Collected soil samples must be representative of the deposit to characterize.

The selection criteria and location of sampling points, as well as the method of preparation before testing, will be recorded in a test report. This data depends on:

- the objectives of the study and the project phase
- preliminary information available
- on-site conditions

Adequate precautions will be taken to ensure, as far as possible, that the samples do not undergo any changes between sampling and testing. The materials must be stored in labeled airtight bags or containers to prevent any change in moisture content.

Samples will be characterized by appropriate identification tests and grouped into material families with similar properties for the treatment study.

Water content

The natural water content of the material before treatment will be measured and recorded in the test report.

Maximum Particle Size

The materials selected for the specimen preparation must comply with the dimensions indicated in the following table.

Maximum particle size permitted in the specimen versus specimen size and compaction method according to the test to be performed

Parameter	Compaction method	Mold Diameter (d) and Height (h) (mm)	Maximum particle size permitted in the specimen (mm)
CBR _i /IPI EN 13286-47	Proctor EN 13286-2	d 150 ± 1 h 120 ± 1	22.4
R _c EN 13286-41 R _{it} EN 13286-42 E _c and E _{it} EN 13286-43	Proctor equipment or vibration compaction table EN 13286-50	d 100 ± 1 h 120 ± 1	16 (or 22.4)
		d 150 ± 1 h 120 ± 1	31.5
	Vibrating hammer EN 13286-51	d 100 ± 1 h 100 ± 1	22.4
		d 150 ± 1 h 150 ± 1	31.5
	Vibrocompression EN 13286-52	d 100 h 100 or 200	22.4
		d 160 h 160 or 320	31.5
Static compression EN 13286-53	d 50 h 50 or 100	11.2	
	d 100 h 100 or 200	22.4	

NOTE: - A slenderness ratio of 2 is preferable when measuring R_c
- A slenderness ratio of 1 is preferable when measuring R_{it}

Treatment

General information

The quantities of soil and binder are determined by weighing. The binder dosage is calculated based on the dry weight of the components (soil + binder) using the formula:

$$d \% = 100 \times Q / (Q + M_{dr})$$

where:

d: dosage

Q: mass of the binder

M_{dr}: mass of dry material

Mixing

A sufficient quantity of soil to prepare the required number of specimens is placed in the mixer.

The mixing process must result in a uniform and homogeneous mixture. The mixing equipment must be capable of achieving the same mixing quality across different material batches. The time spent on mixing must be recorded in the test report.

Details of the preparation method, such as the type of mixer and mixing tool, the power and rotational speed of the mixing machine, the mixing duration, etc., are not specified. These will be chosen based on the local experience and the available equipment.

NOTE: A fixed mixing time cannot be specified due to the wide range of soil types, binders, and mixers. The most reliable method for checking the homogeneity of the mixture is a visual inspection. This inspection must be carried out by qualified laboratory personnel.

Prior to the binder addition, two samples shall be taken to determine the initial water content of the soil. Once treated, the mixture must be protected from desiccation before its use in specimen fabrication.

Mellowing and compaction of the treated material

After lime treatment, the mixture shall be held for a minimum of 1 hour in sealed bags or an airtight container prior to compaction. Depending on the application, a longer mellowing period before compaction for the lime-treated material may be appropriate. Compaction must be completed 30 minutes after the end of the mellowing. The applied mellowing period shall be recorded in the laboratory test report.

Compaction procedures (EN 13286-50 to 53) are dependent on specimen dimensions, desired objectives (density or energy), and the characteristics to be measured in accordance with the corresponding standards (refer to the table).

The compaction method used shall be recorded in the laboratory test report.

Curing and storage

General information

Depending on the material and the tests to be conducted, specimens are either cured within a mold or removed from their mold after compaction.

NOTE: Generally, no load is applied during the curing period. However, the strength of the treated material typically increases if a load is applied during the curing.

A curing period, which may be necessary between specimen fabrication and testing, involves maintaining the specimens for a specified duration under one of the following conditions:

- a) conditions preventing significant evaporation and mass loss,
- b) conditions allowing for the complete immersion of the specimens in water,
- c) conditions preventing evaporation (as in a), followed by the complete immersion of the specimens in water.

In each case, the type of curing, average temperature, and storage duration shall be recorded in the test report.

Curing by preventing water loss

Curing by preventing water loss due to evaporation is achieved using one of the following methods:

- a) storage in a climatic chamber or a room with a relative humidity $\geq 90\%$, unless specific values are prescribed in the relevant test standard
- b) coating the ends of the specimen with wax when specimens are stored in molds
- c) wrapping the specimen in plastic film
- d) any other appropriate method

Specimens shall be stored at a temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ or at any other specified temperature.

NOTE: The selected temperature influences the curing kinetics.

Curing in conditions of full immersion

When a specific immersion procedure is included in the relevant test standard (e.g., CBR test), that procedure shall be followed.

In other cases, the specimen, whether stored in or out of the mold, shall be carefully immersed in water at $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ or another specified temperature.

Curing by preventing evaporation followed by full immersion

Curing by preventing evaporation followed by full immersion shall be performed combining the two curing methods previously described. However, the protection applied to prevent evaporation must be removed before immersion.

Specimen removal from the mold

After curing, the specimen height relative to the mold ends shall be recorded, and the surface roughness at the specimen ends shall be noted. Specimen removal from the mold must be performed with minimal disturbance. For example, in the case where split band molds have been used, remove the band from the split and open the split to allow the sample to be removed. In the case of cardboard molds, peel off the cardboard.

Reporting

A comprehensive report shall be provided on the sample preparation conditions. This report shall include:

- soil classification
- soil source and quantity
- characteristics of the mixer and mixing tool used (power, rotational speed, mixing time, maturation and storage conditions and times)
- water content of the homogenized soil
- diameter of the selected mold
- standard, type, class, specifications, etc., of each binder as provided by its producer or supplier
- binder dosage
- maturation conditions and times
- type of molds used
- description of the compaction press, if applicable: platen diameter and geometry, applied pressure, etc.
- water content of the lime-treated material after mixing
- storage conditions (temperature, humidity, duration) and variations during curing
- etc.

The following details will be recorded for each test specimen:

- density after compaction and cutting condition within the mold
- height of the specimen relative to the mold after curing
- roughness of the ends of the specimen after curing
- any difficulty encountered in removing the specimen from the mold after curing
- any irregularities in the specimen (e.g., holes, voids, uneven ends)
- any surface treatment of the ends performed before conducting further tests
- density after removal from the mold
- etc.

If necessary, photographs of the specimen before and after curing, and/or before and after testing, may be included in the test report.

