Lime Treatment: New Perspectives for the use of Silty and Clayey Soils in Earthen Hydraulic Structures

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Summary

This paper deals with the recent research results obtained through the SOTREDI project, "SOil TREatment for DIkes" undertaken by the Lhoist Group, a World leader in lime production, in collaboration with several research centers and universities. In a first part of the project, it was demonstrated that lime-treated soils could comply with several critical specifications for water retaining structures : low permeability level, mechanical stability, internal and external erosion, reduction of shrinkage risk and dispersive behavior of soils, etc.

Real-scale experimental dikes were built in September 2011, to verify the correspondence between lab results and the real-scale realization.

In parallel, elements about durability of lime-treatment will be reported by examples of more than 30 years old structures around the world.

1. Introduction

Lime treatment of soils is a technique widely used for soils improvement and stabilization for construction of roads, highways, railways, platforms [1],[2]… If the use of lime for transportation infrastructures is well-known, however the principles of lime treatment for hydraulic earthen structures remains barely applied or even forgotten (European case). Nevertheless, lime has been used for five decades for improving and re-using the soils in levees, earth dams, flood dikes, mainly in US and Australia. The treatment of soil with lime was reported to solve problems due to dispersive soils and internal erosion, to prevent shrinkage-swelling phenomenon coming from heavy plastic soils, and stabilize the slopes.

This paper describes the SOTREDI project, "SOil TREatment for DIkes", undertaken by Lhoist Group, a lime producer, since 2005. The aim of the project was to investigate the benefits of lime treatment of soils, to measure and describe the relevant properties of these materials for an application in hydraulic context.

2. Past field experiences

The best way to introduce the subject is to remember the existing testimonials as to the effectiveness and durability of lime-treated structures. It is reported that two different problematic soil types have been involved in these applications:

- highly plastic, expansive clayey soils, that are concerned by volume changes, water ingress through the cracks and slope sliding ;
- less plastic silty clays, also called dispersive soils : less cohesive, they are more subject to erosion.

2.1. The Friant-Kern Canal [3]-[7]

This irrigation canal located southeast of Fresno, California, was built between 1945 and 1951, mainly with highly expansive montmorillonitic clay. The canal earthen banks have suffered periodic damage from cracking, slipping and sliding, even in concrete-lined sections, coming from the volume variations of soils (PI from 23 to 50); moreover, erosion of soils at and below the water level was noticed. The US Bureau of Reclamation decided to rehabilitate several areas using soil-lime mix solution to stabilize the canal slopes, taking profit of the two known major effects of lime treatment at this time: improvement of the soil workability and increase of the soil strength. The rehabilitation operations were led between 1973 and 1977, according the following global procedure: soil treatment was carried out with 4 % quicklime, which reduced the PI from 47 to 12 % and increased the shrinkage limit from 7 to 26 %. The service

roads and the canal bottom were treated first, using in-place treatment methods. The bank lining material was treated in two sequences, first with a “bench method” on the slope in order to facilitate his moving to the bottom, and second with a dump truck spreading, and mixing with back rippers, angle and U-dozers, and graders. The treated soil was finally placed on the banks in 30-40 cm thickness layers and compacted with a vibrating sheepfoot roller that was winched up and down the slope by a crawler tractor (yo-yo fashion). Typical final thicknesses vary from 0.6 m (service roads and bottom) to approximately 1 to 1.4 m (banks). The final canal banks have 2:1 slopes.
Several evaluations of the results have been performed, no new slips, slides or sloughs have occurred. The viability and economical benefits of the solution were obvious. A recent visit (Figure 1) showed that the sheepfoot roller imprint was still visible both above and below the water surface, 35 years after the job [8]. The picture was taken during a maintenance phase, when the water level was below the normal one, one can see minor erosion along the water level, due to departure of small rocks or “untreated clay balls”, not mixed efficiently with lime due to the poor mixing quality at these ages. The maintenance operations are very limited on this section, considering the lime-treated part is durable and is significantly cost-saving.

Figure 1: Lime-treated section of the Friant-Kern Canal (taken in November 2010) on the left part; the right part consist of original, untreated slope covered with gravel.

2.2. Mississippi River Levees [3],[9]

Severe flooding on the Mississippi River in 1973 devastated some levees in Arkansas and Illinois, already weakened by slides in expansive clayey soil. The conventional repair method, including excavation and replacement of failed soil by stable one, building of a berm at the toe of the slope and flatten the slope, was not feasible in these cases because of the lack of good materials and the limited right-of-way. From 1974 and between 1985 and 1992, more than 150 slides were repaired, re-using the unstable soils after a lime treatment. The materials in the slide were excavated to just below the slip plane, after which scrapers transferred it to an offsite mixing area along the levee right-of-way. Successive lifts of treated soil (with 5 % hydrated lime) were placed in order to occupy the limited space of the right-of-way; slow setting characteristics permitted these operations. The treated materials returned to the slide excavation, and were compacted with heavy crawler tractors. Topsoil was added and fertilized for the completion of slide restoration.

2.3. Earth Dams [3],[7]

Dispersive soils were identified as source of problems in the case of earth dams (Oklahoma, Mississippi, Texas, Arizona…). Lime was recognized as a relevant agent for improving and stabilizing it. Lime has been used for remedial treatment of existing dams, and the success of these jobsites has led to the extension of its use for new dam construction, as well as material for a protective blanket or shell to prevent erosion, as core material to minimize leakage and provide extra strength (Los Esteros Dam, New Mexico). For this last work, a portion of the impervious core was being treated with lime prior to the placement of the sandstone bedrock. Although the lime treated zone is quite small, the application can be regarded as significant. For the construction of the McGee Creek Dam (south-eastern Oklahoma) the defensive design measures incorporated to prevent dispersive clay erosion were e.a. the use of lime-treated soil with minimum required thicknesses of lime-treated soil were 0.7 m on the downstream slope (or 1.0 m if placed in horizontal layers), or 1.0 m underneath the core of the dam and dike, and in critical locations such as backfill around conduits.

3. Towards an advanced study of lime-treated soils for hydraulic uses

The relevant properties of lime-treated silty or clayey soils for a use in hydraulic earthen structures are barely described in the literature. The permeability of materials placed as impervious shells on the blankets, the erosion resistance, the mechanical characteristics, were not examined in the applications reported above. Moreover, some prejudices on lime-treated soils were mentioned, which will be covered in more details in the rest of the paper: increase of permeability, harmful for vegetation growth, materials heterogeneity after mixing, etc.

The design and conception of canals, levees and dams involves the knowledge of these properties and their evolution. This is why Lhoist launched an ambitious research program in partnership with Universities and Research Institutes, with the objective to establish the most appropriate procedures for lime treatment of soils, the relevant properties, performances and behaviour of the obtained materials for their subsequent use in hydraulic structures. The main results acquired in this context are now described.

4. Experimental

4.1. Materials

The limes used for soil treatment studies were a Proviacal® DD, calcic quicklime CL-90 Q (according to European Standard EN 459-1), with an available CaO content of 90.9 %, and a t_{60} reactivity of 3.3 minutes, and a hydrated lime Proviacal® DD (CL-90 S). Six different fine soils, from silty (PI=8) to clayey (PI=37) have been used to perform the following tests: permeability, isotropic compression, oedometric compression, shrinkage-swell, crumb test, hole erosion test and MoJET test.

4.2. Permeability

The construction of a hydraulic structure involves the control of its water permeability, that has to be the lowest possible to limit the water ingress through the bottom and the slopes. In the literature, few studies were concerned by permeability of lime-treated soils, and led to contradictory results. Moreover, preconceived idea is that permeability increases after lime treatment, due to the decrease of soil dry density. IFSTTAR realized an experimental study on the influence of the procedure of lime treatment and compaction of a silty soil on its permeability. This silty soil, coming from Moulin de Laffaux, Aisne department (France), had the following characteristics: 88% particles <80 µm, w_P=19.8%, w_L=32.5%, PI=12.7, w_{OPN}=15.8%, ρ_{d}=1.81g/cm³.

Two different moisture contents have been applied at compaction: the first around the water content at optimal Proctor normal density (w_{OMC}), and the second, a humid state equivalent to 1.2 times above this value (w_h). Untreated material, 2 and 3% quicklime-treated, and 2.65% hydrated lime-treated materials were compacted according two procedures:

Figure 2: Kneading compaction tool (a) and permeameter (b).

- classical Proctor dynamic compaction, to 95% of the OPN dry density ;
- kneading compaction, performed with a specific tool, simulating the geometry and surface ratios of a sheepfoot roller (Figure 2a) [10]. The specimens were compacted to the same final density as that of the Normal Proctor method. In the case of untreated silt, this last compaction procedure led to similar optimal values (ρ_d and w), but for lime-treated materials, the kneading led to higher optimal water contents.

The permeability tests were performed at LRPC Angers (France), according to the XP CEN ISO/TS 17892-11 Standard. The samples were directly compacted in the permeameters (Figure 2b). The set-up was similar to CBR moulds except that they were equipped with inox grids and pierced plates for the water entrance and exit. The permeability measurements were performed after 28 days curing at constant water content (after compaction), after 28d curing + 2 months immersion period and 28d curing + 5 months immersion. The following results were highlighted:

- kneading compaction led to the lowest permeability values (k) for a given mixture;
- for a given material with fixed compaction procedure, the humid state also gave lowest k values;
- the k values of lime-treated soils Proctor-compacted in the humid state, lied between 5.10^{-8} and 10^{-9} m/s;
- kneading compaction of lime-treated soils at high moisture content (humid state) led to k values below 5.10^{-9} m/s, even below 10^{-10} m/s.

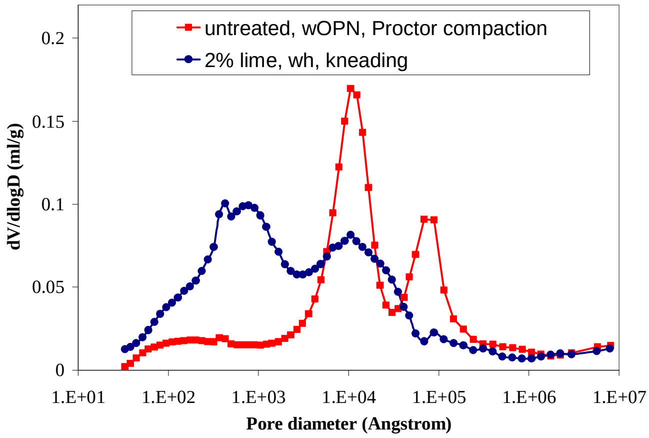

Figure 3: Mercury intrusion porosimetry of untreated (red curve) and lime-treated (blue curve) samples, as a function of water content and compaction procedure (silty soil from Moulin de Laffaux, France, PI=12.7).

The k values remained constant with time, indicating that the final permeability was already obtained after 1 month (curing done with constant water content). As a result, the preferred conditions for reaching low permeability values of the lime-treated silty soil (2 to 3% lime) are: (i) high moisture content and (ii) kneading compaction. These results were further explained by mercury intrusion porosimetry which highlighted the changes in the poral structure of treated soils. The biggest pores (>3µm), and intermediate-sized (between 3000 Å and 3µm) are considered as responsible for the water path. When treated with lime, a third class of smaller pore appeared (<3000 Å). After lime-treatment in the humid state and kneading compaction, the amount of pores >3µm was strongly reduced in favour of the smallest pore size (Figure 3), that is in favour of very small pores that do not affect the permeability. As a conclusion, the placement method is far more important than final density in the control of permeability.

4.3. Mechanical Behaviour of Lime-Treated Soils

4.3.1. Compressibility

Isotropic compression tests were performed on the same silt as the one used for permeability (Figure 4). The volume strain of the untreated sample is function of the logarithm of isotropic stress (log p'), which means that the yield strength is below the smallest applied stress. Once treated with 2% lime and after 6 months, 2 slopes can be distinguished on the graph, separated by the yield strength between 400 and 500 kPa.

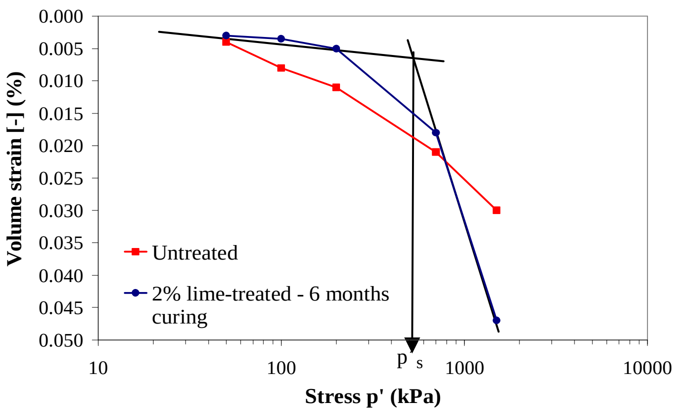

Figure 4: Isotropic compression of untreated and lime-treated silty soil from Moulin de Laffaux, PI=12.7 (6 month curing).

Oedometer tests were also performed at University of Brussels (ULB) on a clayey soil from Héricourt (Haute-Saône, France), untreated and 72 hours after a 5% quicklime treatment (dosage corresponding to the lime fixation point). This soil had the following characteristics: 94% particles <80µm, 75% <2µm, w_P=35%, w_L=72%, PI=37, w_{OPN}=27.5%, ρ_d=1.45g/cm³. Several observations were made: the swelling index was divided by 5 to 10 times after treatment (C_s between 0.005 and 0.010), the yield resistance (p'_s) was also multiplied by a factor 5 to 10 (p'_s values between 490 and 660 kPa for the treated specimen). The compressibility indexes were similar for the two series.

4.3.2. Shear resistance

The aim of the shear resistance measurements is to quantify the improvement of mechanical stability of embankments brought by lime treatment. The results were obtained at ULB, on two silty soils from Belgium (Soumagne soil, PI=16 and Marche-les-Dames soil, PI=11), treated with 3% quicklime [11]. Consolidated undrained triaxial tests were performed on samples of 3.6cm diameter and 7.2cm height, beforehand saturated. The untreated first silt (Soumagne soil) parameters are c'=5.8kPa and φ'=37.4°. The values obtained after treatment and at several curing times are reported on the Fig. 5. The friction angle stays stable with time, whereas the cohesion rises significantly: after 2 years, the c' value was multiplied by 25. Similar results were obtained with the silt from Marche-les-Dames (PI=11), which shows a c' value equal to 500 kPa at 450 days after treatment. The range of measured cohesion values was well above common stresses met on small hydraulic structures.

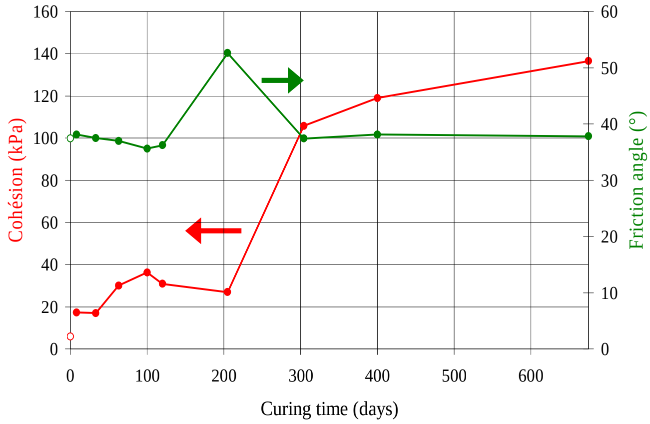

Figure 5: Evolution of the shear resistance parameters with time (treated silt from Soumagne,Belgium, PI=16). The white points at t=0 are related to the untreated specimen.

4.3.3. Interpretation of mechanical tests

The lime-treated soil can be considered as "cemented" material, in this sense that the particles assembly is realized by the adhesive forces developed by the lime action. This new assembly has also a new stress resistance threshold; above this value, the assembly is destroyed and the behaviour of the material becomes similar to an untreated soil. For isotropic and oedometric compressive tests, this threshold is not considered as a preconsolidation stress, but more as the yield strength of the new lime-treated material of low ductility, quantifying the resistance of the adhesive bounds created by the lime treatment. The rise in cohesion is also due to the so-called pozzolanic reactions between lime, dissolved silica and alumina species from clays and water, giving a material that is almost not compressible, and not subjected to deformations if submitted to stresses until several hundred kPa.

4.4. Water Sensitivity and Erosion Resistance

4.4.1. Dispersivity, swelling and shrinkage

The ASTM D 6572-06 Standard ("crumb-test") was used to demonstrate the non-dispersive behaviour of an initially dispersive silty soil from Marche-les-Dames (94% particles <80µm, PI=11), treated with 2 to 3% quicklime. This improvement was still visible 3 years after treatment. An enhanced crumb-test was also performed by IFSTTAR (France) [12],[13], on cylindrical specimens taken from moulded cylinders (same soil with 2% lime). The untreated cylinder collapsed after 15 minutes immersion, whereas no degradation occurs on the lime-treated sample, even after 45 hours immersion.

The consistency changes of clayey soils with moisture content are materialized by large volume changes (swelling and shrinkage). Laboratory tests on the Héricourt clayey soil (see 4.3.1.) showed that, after a 5% quicklime treatment, linear swelling of soaked CBR samples remained low and limited after the soaking step. In the mean time, the bearing capacity reached a value of 19, to be compared to the very low value of 1.3 obtained for the untreated sample.

Free shrinkage evaluation was also performed on this clayey soil according the German Standard DIN 18122-2. The principle consists in preparing a disc of soil (diameter 7cm, height 1cm) at very high water content (110%), and measuring its diameter vs water content when left to dry at room temperature. The shrinkage limit w_s is the inflexion point of the volume variation curve (Figure 6). At this water content, the shrinkage of the sample reaches the maximum amplitude; below this point, no volume variation is recorder. In other words, shrinkage/swelling risk exists for a soil if its water content is above w_s. Once again, natural Héricourt clayey soil was tested and showed a w_s of 16,5%, linked with a big volume variation (more than 50% shrinkage). Once treated with 5% quicklime, w_s is displaced towards higher water content (w_s=55%), well above the OPN conditions, ensuring the volume stability of the material.

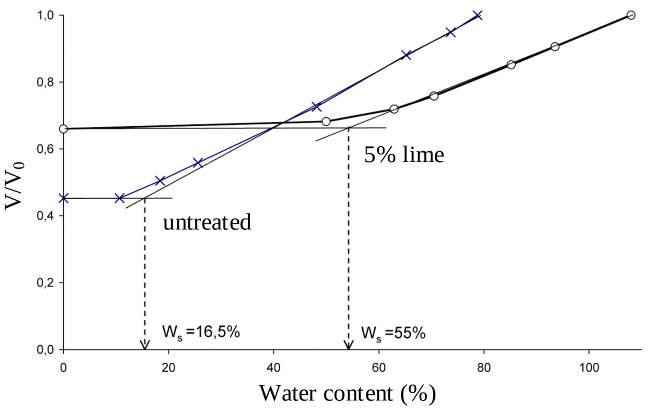

Figure 6: Free shrinkage curves of Héricourt clayey soil (PI=37)

4.4.3. Erosion resistance

Both internal (by Hole Erosion Test HET) and external (by Mobile Jets Erosion Test, MoJET) erosion resistance were studied, in order to evaluate the impact of lime treatment on the critical parameters of the materials. HET was performed at Cemagref (France) on a clayey silt taken from a Camargue Dike (France): 95% particles <80µm, 30% <2µm, PI=11. The erosion rates vs tangential stress are reported in Fig. 7 for untreated specimen, and 2% lime-treated after 3 curing periods.

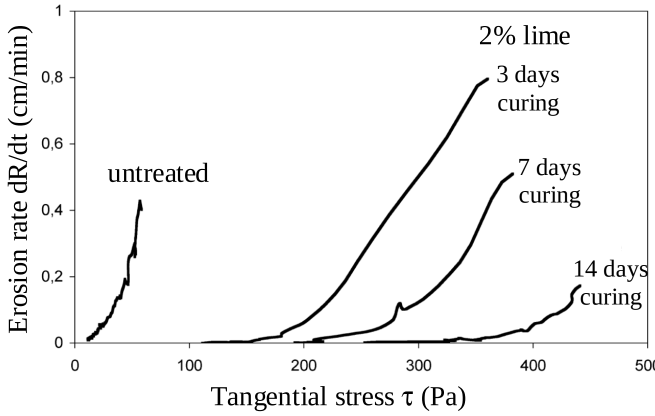

Figure 7: Hole Erosion Test: erosion rate vs tangential stress for untreated and 2% lime-treated clayey silt from a Camargue dike (PI= 11).

After 14 days curing, the critical stress was increased by a factor 20, and the erosion coefficient divided by 10. The device didn't allow the erosion initiation of the 28 days cured samples. HET results can be used to estimate the threshold water velocity that induces erosion (Fig. 8). For untreated clayey silt, the erosion threshold correspond to a water velocity of 2 m/s, whereas for lime-treated material, the value rises up to 10 m/s. These results are important elements for the problematic of internal erosion, main origin of hydraulic earthworks failures [14],[15].

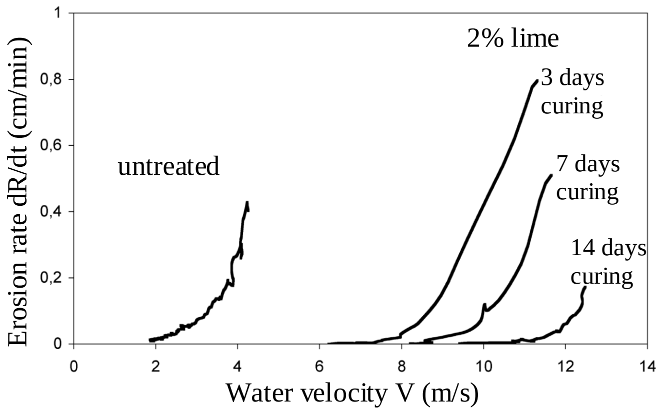

Figure 8: Hole Erosion Test: erosion rate vs water velocity for untreated and 2% lime-*treated* clayey silt from a Camargue dike (PI= 11).

The surface erosion was also tested by the mean of MoJET test, performed at IFSTTAR. The procedure consists to spray 6 rotating water jets perpendicular to a sample surface, with a water flow of 600 ml/min, recover the eroded particles and weight their dry mass. On a sample of Héricourt silty soil (67% particles <80µm, PI=11) with 2% lime and cured 90 days, the erosion could not be initiated, even with an increase of water flow to 2 l/min, when the same conditions gave 500 g of dry particles eroded from the untreated soil.

5. Experimental full-scale hydraulic earthen structure in lime-treated soil [16]

Following the series of relevant acquired data, the next step was to build an experimental full-scale structure with three important objectives:

(1) proving the feasibility of the specific lime treatment and placement procedures at an industrial scale, using a dedicated mobile treatment plant and conventional earthworks equipment;
(2) correlating the laboratory observations on lime-treated soil properties at a real scale
(3) evaluating the benefits of lime treatment in terms of mechanical improvement and hydraulic behavior over time, compared to natural (untreated) soil.

5.1. Materials, equipments and procedures

A silty soil with a low plasticity index was used for the construction of the experimental dry dikes. This soil was imported from Marche-les-Dames (Belgium). Its main characteristics are : clay fraction (<2µm) = 12% ; silt fraction (2 to 50 µm) = 82 %; 99.5 % < 80 µm ; PI = 7 to 8 ; moisture content at sampling = 17.9 %.

A crumb-test, performed according ASTM D 6572-06 standard on a compacted sample of this soil, showed qualitatively its dispersive character, a priori unsuitable for a use in a hydraulic context. A dispersive soil is defined as one that will easily and quickly disperse (deflocculate) in water, with no mechanical intervention. Such materials generally have a tendency to shrink-expand, have a little resistance to erosion and a low permeability if they remain in this condition.

The lime used for the soil treatment tests is a Proviacal® DD, a CL 90-Q quick lime according EN 459-1 and provided by Lhoist. The lime fixation point of the soil, determined according the Eades and Grim test (ASTM D6276-99a), was between 1.5 and 2%. A lightly higher dosage of 2.5 % was selected to ensure the development of middle to long-term mechanical resistance.
The changes induced by the lime treatment on the compaction behavior of the soil are illustrated in Figure 1. The optimal moisture content for Standard Proctor compaction of untreated soil is ρ_d=18.2 kN/m³ at w_{OMC}=14.5 %. It is known that lime treatment leads to a displacement of the w_{OMC} towards higher moisture contents and a reduction of the maximal dry density: the specific compaction characteristics of the Marche-les-Dames silty soil treated with 2.5 % quicklime are ρ_d=17.3 kN/m³ at w_{OMC}=17.8 % (Figure 9).

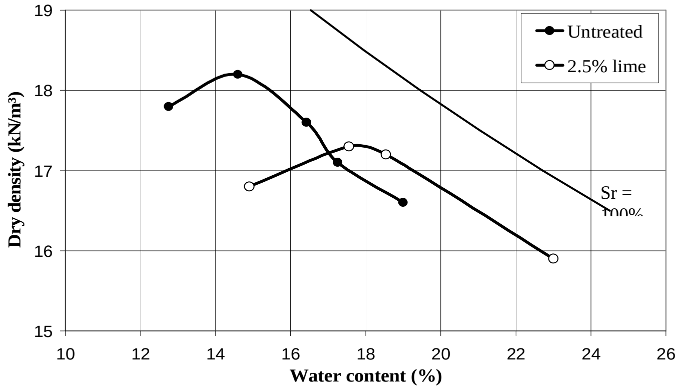

Figure 9: Standard Proctor compaction curves of untreated and 2.5 % Proviacal® DD-treated soil from Marche-les-Dames (Belgium).

Besides improving immediate workability, facilitating placement and enhancing mechanical properties in the medium term, lime treatment is known to control the soil particle dispersion, due to the cationic exchange and flocculation/agglomeration effects [7],[9].

For the construction of the experimental full-scale embankment, the most beneficial placement conditions and processes producing the lowest permeability of lime-treated compacted materials were determined as follows:

- after lime and soil mixing, the final materials must be humid, e.g. wet of optimum conditions. In the case of Marche-les-Dames soil that means that water must be added to obtain a final moisture content above 18 %, once treated.
- the compaction must be performed with kneading operations (sheepfoot roller). The objective in terms of density level is to reach at least 95 % of the maximal dry density (17.3 kN/m³).

The equipment used for lime treatment was a mobile soil mixing plant, able to precisely control the lime dosage through a continuous weighing of soil passing through the band, and offers a regular addition of water directly in the mixing bell. The particle size of the treated soil is very fine and ranges between 0 and 20 mm.
The compaction equipment is a VP5 sheepfoot roller, according the French Standard NF P 98-736 (Figure 11b).

5.2. Experimental dikes conception

Dike built with lime-treated soil
The biggest of the two experimental dikes was entirely built with the 2.5 % lime-treated silty soil from Marche-les-Dames (Belgium). For this purpose, approximately 1000 tons of soil were brought to the site of CER (Experimentation and Research Center), close from Rouen (France).
The dimensions of the embankment are 28.2 m long and 10.3 m wide at the bottom, 21 m long and 4 m wide at the crest (Figure 10a and 10b, upper and longitudinal views). The final height of the structure is 1.8 m, with different slopes on each

longitudinal side, 3:2 and 2:1 (horizontal:vertical) respectively, obtained by cutting compacted bands.

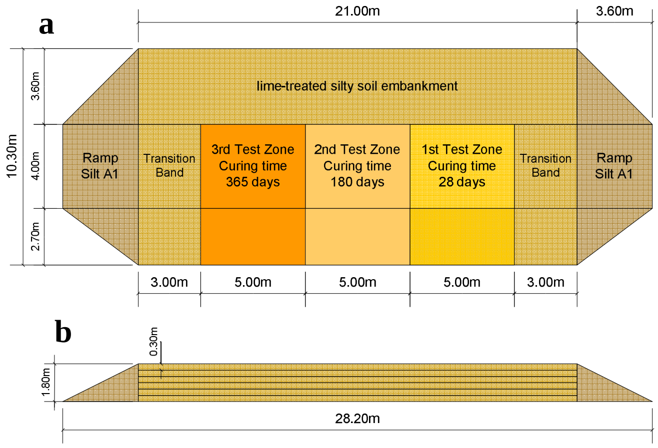

Figure 10: Top view (a) and longitudinal section (b) of the lime-treated silty soil experimental dike.

The dike is virtually divided into 3 sections of 5 m long, corresponding to the 3 successive measurements periods of 28 days, 180 days and 1 year (Figure 10a). The access ramps were built with another silty soil, in order to save the first one for the bulk of the dike, whereas a transition band of 3 m lime-treated soil was added to ensure the constant speed of the compactor on the 3 measurements zones.
The 2.5% lime treatment with a controlled water addition in the mobile mixing plant, produced a granular, fine material at a humidity level above OMC. This material was transported directly to the jobsite, and then taken by a shovel for the placement of 50 cm thick layers prior to compaction. The compaction step was performed with a kneading compactor in 6 passes at a speed of 3 km/h, producing a final thickness of 30 cm for each layer. Finally, the embankment was constructed in 6 layers, giving a total height of 1.80 m (Figure 10b). Pictures of each step can be viewed in Figure 11.
The top of the dike is divided in 2 parts longitudinally, one side is reserved for measurements of placement and mechanical properties such as density, water content, bearing capacity, pressuremeter, collection of samples for triaxial testing, and hole erosion testing. The other side is reserved for permeability measurements. *In situ* surface erosion measurements will be performed on the slopes.

Dike built with natural (untreated) silty soil
The second smaller embankment was built using the same initial silty soil, but without lime treatment. The structure consists of 3 layers with a compacted height of 30 cm. The total length and width at the bottom are 13.6 m and 5.6 m respectively. The crest is 10 m long and 2 m wide. The slopes have a 2:1 value.
The material was placed at the same humid state as the lime-treated dike and was compacted using the same kneading equipment. The compaction level was 95 % of the maximum dry density at the natural state (1.82 g/cm³ according Standard Proctor compaction). A single measurement section is foreseen, because the material properties can be considered unchanged over time. The same measurements were foreseen as for lime-treated sections.

Figure 11: Lime-treated material production (a), application and compaction with a sheepfoot roller (b), global view of the lime-treated dike (c) and of the two dikes (lime-treated and untreated, on the right) (d).

5.3. Results

5.3.1. Dike built with lime-treated soil : efficiency of mixing and placement procedures
The treatment and placement objectives were to produce a 2.5% lime-treated material, with a moisture content above OMC of the Standard Proctor; to compact this material by kneading, and achieve a compaction level at least equal to 95 % of the Standard Proctor density at OMC. Table 1 presents the measured values of water content, lime addition, and compaction level, on several layers during the placement, along with the top layer after the leveling operation.

The measured lime and water contents and the calculated standard deviations of the mixture composition show the high level of homogeneity of the treated soil, and therefore the consistency of the production using the mobile plant. The objectives in terms of water content > OMC, trafficability and density level are reached. This last value exceeds on every layer the 95 % of maximal dry density measured according the Standard Proctor test.
The issue of homogeneity for treated soil is always raised when discussing this treatment for hydraulic structures, because that parameter is closely related to the permeability gradient. The issue is crucial because an unforeseen permeability gradient may result in abnormal and localised flows. It seems that this objection is a reaction from geotechnicians, and that the suspicion has two probable origins. On the one hand, it is always very difficult to obtain homogeneous soil in civil engineering, notwithstanding the question of treatment. In addition, past treatments (with lime

or any other treatments) have probably not reflected the importance of that parameter. Consequently, they may have been performed with inappropriate methods and unsuitable controls, leading to a conclusion that the treatment itself makes it impossible to obtain a sufficiently homogeneous material. This full-scale test has shown the feasibility of using the process on an industrial scale, and the benefits of processing the soil in a central unit, which ensures an excellent level of homogeneity.

TABLE 1: MEASUREMENT PERFORMED ON THE LIME-TREATED DIKE AFTER PLACEMENT

	Water content (%)	Lime dosage (%)	density level (% ρ_d at OMC)
objective	above OMC (>17.8%)	2.5	equal or above 95%
average	**19.4** ($w-w_{OMC}$ = 1.6 %)	**2.5**	**96.7** (layers 2-4-6) **98.5** (top layer, leveled)
# measurements	118	6	18 (layers 2-4-6) 24 (top layer, leveled)
standard deviation	0.72	0.19	1.1 (layers 2-4-6) 1.1 (top layer, leveled)

5.3.2. Mechanical performances

Mechanical properties of the test embankment materials were performed *in situ* by pressuremeter measurements, and on cored samples using triaxial testing. The cores were obtained using a CETE NC soil investigation rig (Sedidrill 500), on a rubber tracked crawler equipped with a double core barrel. Using that kind of equipment, the core is not in contact with the rotating core barrel and the drilling fluid. Two coring diameters were used, 116 mm and 80 mm.

Pressuremeter test (Menard) is a static loading test performed by means of a cylindrical swelling probe introduced within a vertical drilled hole. The values were obtained 28 days and 6 months after the construction of the experimental dikes, and are reported in Table 2.

TABLE 2: PRESSUREMETER MEASUREMENTS.

Structure	Measurement period	p_f* (MPa)	p_l* (MPa)	E_M (MPa)	E_M/p_l*
Untreated dike	28 days	0.15	0.25	1.6	6.5
	6 months	0.15	0.36	2.0	5.5
Lime-treated dike	28 days	2.53	3.77	38.6	10.2
	6 months	2.51	4.23	52.7	12.5

The increase of strength and cohesion is demonstrated through these last measurements. Pressuremeter values indicate that from a natural underconsolidated soil (ratio E_M/p_l^* between 5 and 8), lime treatment and conservation after placement produce an important strength increase, making the soil consolidated (ratio E_M/p_l^* >10). In the same time, triaxial tests identify the initial, untreated soil as non- or little-cohesive (cohesion value is arbitrarily 0), whereas the cohesion after lime treatment increased to 61 kPa after 75 days and 102 kPa after 6 months (Table 3).

TABLE 3: TRIAXIAL TESTS RESULTS (CD)

Structure	Measurement period	c' (kPa)	ϕ' (°)
Untreated dike	28 days	≅ 0 (<10)	34.6
Lime-treated dike	28 days	61 (after 75 days)	39.2
	6 months	102 (after 195 days)	39.2

5.3.3. Permeability level and erosion resistance

In situ and laboratory permeability measurements were recorded using several methods. Two *in situ* methods were used. First, using a double-packer probe (see Figure 12a) at a depth between -0.5 and -1.1 m, the device passing then through at least 2 interfaces between successive layers. For this test, an 18-hour saturation step was applied under a hydraulic head of 1.5 m, and the measurement was done by following the decrease of water level vs time (variable head Nasberg test). The second *in situ* method used was a constant head Nasberg test, where a perforated pipe is pushed into the structure, to a depth of 0.90 m. The head of the pipe comes out of the surface and is covered by a lid that does not contact the pipe (Figure 12b). Finally, the vertical permeability was also measured using the triaxial test under saturated conditions. Table 4 reports the recorded permeability values on the two structures.

Very low permeability values were obtained for both structures. The similar orders of magnitude can be seen as evidence that the lime treatment produces equivalent permeability levels as the natural soil if the treatment and placement methodologies are applied. Finally, *in situ* horizontal permeability values show that kneading compaction using a "sheepfoot" roller can guarantee a good overlapping of the successive layers, avoiding water movement through interfaces.

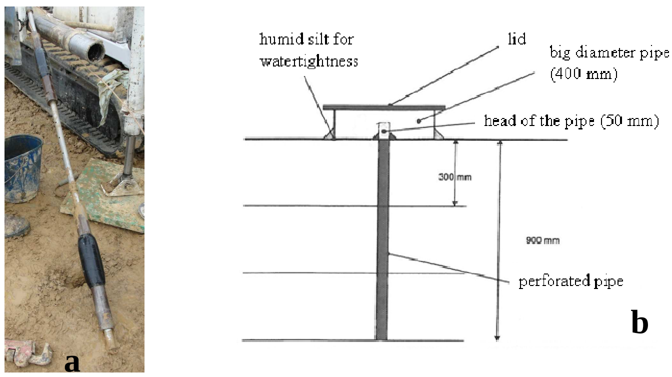

Figure 12: Double-packer probe used for variable head Nasberg test (a) ; schematic view of the constant head Nasberg method (b).

TABLE 4: PERMEABILITY VALUES

	Untreated dike	Lime-treated dike	
Measurement period	28 days	28 days	6 months
In situ tests : Variable head Constant head	- $3.2\ 10^{-9}$ m/s	$7.7\ 10^{-10}$ m/s $1.2\ 10^{-9}$ m/s	$4.5\ 10^{-9}$ m/s -
Tests on cored specimens : Triaxial (CD)	$1.0\ 10^{-9}$ m/s	$1.4\ 10^{-9}$ m/s	$1.0\ 10^{-9}$ m/s

Erosion studies have been led by IFSTTAR and Irstea. Interpretation of Hole Erosion Test (HET) results identify a significant increase in the critical stress with lime treatment. 30 days after construction, the value was multiplied by at least 7 orders of magnitude to more than 800 Pa. The same tendency is observed for *in situ* MoJet (Mobile Jets) erosion tests performed on the slopes of the dry dikes. The amount of soil recovered after the test is divided by 25 times (normal flow of 600 ml/min during 15 min) or by 12.5 times (modified protocol: 5 min at 2 l/min), as it can be seen on Figures 13a and b.

a

b

Figure 13: a : MoJet external erosion test performed on a slope of the untreated embankment (usual parameters).
b: test performed on a slope of the lime-treated embankment (increased flow to 2 l/min).

6. Present and potential applications for hydraulic structure, future prospects

6.1. Relevant Properties, Recommended Methodology

The above results indicate that through lime treatment, the properties and behaviour of the resulting materials can meet 3 key factors insuring the construction, design, durability and limited maintenance of a hydraulic earthen structure: permeability, mechanical and volume stability, internal and external erosion resistance.

The homogeneity of the treated soil is an issue in order to limit permeability gradients that can be the origin of abnormal local flows. Moreover, the difficulty to obtain a homogeneous material in Civil Engineering works is a permanent issue. The way the lime treatment was performed in the past (see examples of Friant-Kern canal and Mississippi levees, pt 2.), with treatment methods and devices that did not follow the current recommendations (i.e. kneading compaction of a plant-treated soil in the humid state) gave nevertheless materials with good performance and durability. Real-scale trials of treatment in a mobile plant followed by kneading compaction performed in 2008, showed the feasibility of the recommended procedure at industrial scale. Moreover, it allowed for a precise control of lime content, moisture content (by controlled water addition), fineness and homogeneity of the treated soil. Feasibility of this method was again demonstrated in September 2011 during the full-scale dry dike construction in CER (Rouen, France).

6.2. Present Applications (US Case)

The Mississippi River dikes network from Ashton to Gale is an example of present uses of lime treatment for restoration or reinforcement. Several techniques are considered using lime [17],[18]

- excavating the entire levee embankment, lime treatment and backfilling of these materials and compacting in place;
-excavate the upper levee embankment down a minimum of 2m, mixing it with lime, backfilling of these materials and compacting in place;
- use of injection of a lime/fly ash slurry into the levee side slope. Note that the issue of fly ash ecotoxicity and composition is still debated.

On the New Orleans dikes network, it has been decided to rise up the height of the dikes after Katrina storm [19],[20]. The design takes into account the mechanical improvement brought by lime addition, because the dike height is raised by 1m without changing the base width of the dike, thanks to a steeper slope.

6.3. Potential Uses in the Future

Thanks to the mechanical improvement, erosion resistance and permeability levels conferred by a lime treatment using the specific conditions described in this paper, it is possible to foresee future uses in a lot of diverse hydraulic applications:
- reuse of heavy clays in dike or dam foundation, thanks to the absence of differential settlement, creep and the stability;
- homogeneous embankments in lime-treated soils for warm and dry countries, thanks to the reduction of shrinkage cracks, the improved workability and easier compaction procedures;
- construction of overtopping resistant and erosion-resistant dikes and dams spillways, external blankets of levees.

7. Conclusions

Lime treatment of soils was applied from the 70's, mainly in US, in hydraulic structures restoration and construction. It seems that this technique was forgotten in Europe. The design of canals, levees and dams can only be done with the proper knowledge of the adequate properties of lime-treaded soils and their evolution. This paper described the corresponding results obtained in a research program launched by Lhoist in partnership with Universities and Research Institutes (Irstea, IFSTTAR, LRPC angers, CER Rouen, Université Libre de Bruxelles). A series of relevant mechanical, stability, permeability and erosion-resistance properties of lime-treated soils was measured, which allows the development and the control of this technique, according to a specific method of treatment and compaction.

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