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G. Herrier, P. Leconte, N. Nerincx, Stéphane Bonelli, Florian Mercier, et al.. Lime treated soil as an erosion-resistant material for hydraulic earthen structures: state of the art and presentation of the french DigueElite project. South Baltic Conference on Dredged Materials in Dike Construction, Apr 2014, Rostock, Germany. pp.75-84. hal-01546925

HAL Id: hal-01546925

<https://hal.science/hal-01546925>

Submitted on 26 Jun 2017

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LIME TREATED SOIL AS AN EROSION-RESISTANT MATERIAL FOR HYDRAULIC EARTHEN STRUCTURES: STATE OF THE ART AND PRESENTATION OF THE FRENCH DIGUE.ELITE PROJECT

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Abstract. The treatment of silty and clayey soils with lime (calcium oxide or hydroxide) is a technique widely used for soils improvement and stabilization for construction of roads, highways, railways, platforms. However, the principles of lime treatment for hydraulic earthen structures remains barely applied or even forgotten (European case). If existing testimonials (levees, dams, mainly in US and Australia) are evidences that show effectiveness and durability of lime-treated structures, there was a necessity to evaluate a series of unknown characteristics and relevant properties of lime-treated soils for an application in hydraulic context, through laboratory studies and full-scale experiments.

Keywords: lime treatment, reuse of local soils, internal erosion, overflow, durability, dike design

1. Introduction

Lime treatment of soils is a well-know and widely applied technique for soil improvement and stabilization of infrastructure works (roads, highways, airfields, railroad beds) (Little, 1995). The use of lime treated soils in hydraulic context is less known, at least in Europe, and existing structures showing the relevance of this application are quite rare. However, several benefits of lime treatment for hydraulic structures construction or restoration were reported in the past (Gutschick, 1978): preventing softening while under-water (the lime-treated soil doesn't revert to mud), preventing the leakage and resisting erosion from flowing water, reduction of shrinkage and swelling movements of high plasticity index soils (heavy clays).

Testimonials of the application of this technique can be found in some places across United States and Australia, coming from several American and Australian authorities and offices for hydraulic earthworks restorations or reinforcement since the 1970's (Perry,

1977; ANCOLD, 1978; Gutschick, 1978; Gutschick, 1985; Knodel, 1987; Fleming, 1992; USBR, 1998; Stapledon, 2005; USACE, 2010).

In 2005, the Lhoist Group, a lime producer, launched a series of important research programs to identify the conditions and procedures for lime treatment and placement of soils in hydraulic earthworks. The research also sought to establish the relevant properties of materials for their use in earthen structures in contact with water.

Following this series of relevant acquired data, the next step was to build an experimental full-scale structure build using the specified methodology and technology that had to show on a lime-treated silty soil structure:

- the feasibility of the specific lime treatment and placement procedures at an industrial scale, using a dedicated mobile treatment plant and conventional earthworks equipment;
- the correlations between the laboratory observations on lime-treated soil properties and the real scale

- the benefits of lime treatment in terms of mechanical improvement and hydraulic behaviour over time, compared to natural (untreated) soil.

Recently and from these achievements, an ambitious French project called "DigueELite" was launched in June 2013, in order to establish innovations in the subject of flood protection levees.

2. Relevant properties of lime-treated soils: laboratory research programs

2.1 Materials

The limes used for soil treatment studies were a Lhoist Proviacal® DD calcic quicklime CL-90 Q (according to European Standard EN 459-1), with an available CaO content of 90.9 %, and a t60 (reactivity) of 3.3 minutes, and a hydrated lime (CL-90 S).

Six different fine soils with different Plasticity Indexes (PI), 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 (Mobile Jet) test.

2.2 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 (former LCPC) 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: clay fraction ($<2 \mu\text{m}$) = 23% ; silt fraction (between 2 and $50 \mu\text{m}$) = 59 % ; 88% particles $<80 \mu\text{m}$, PI=12.7, $w_{\text{OMC}}=15.8\%$, $\rho_d=1.81 \text{ g/cm}^3$.

Two different moisture contents have been applied at compaction: the first around the water content at the maximal density of Standard Proctor test (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:

- classical Standard Proctor dynamic compaction, to 95% of the maximal dry density at OMC;
- kneading compaction, performed with a specific tool which simulates the action of a sheepfoot roller (Fig. 1a) [Kouassi, 1998]. This tool allows respecting the following geometrical and surface characteristics given by a kneading compaction roller Caterpillar 825C:
- the surface ratio between a wheel and the compacted surface (ratio = 3.7)

- ratio between the thickness of a compacted layer and the foot height (ratio = 1.5).

The specimens were compacted to the same final density as that of the Standard 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 (Fig. 1b). When the kneading compaction was applied, the specific tool was pushed 8 times with a pressure equal to 1.25 MPa on the soil, with a gyratory movement. The specimen was obtained after the compaction of 3 layers of around 4 cm thickness each.

The permeameter 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 28 days curing + 2 months immersion period, and 28 days curing + 5 months immersion; in other words 3 months and 6 months after preparation, respectively. 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 gave lowest k values;
- the k values of lime-treated soils, Proctor-compacted in the humid state, was $5.10^{-8} - 10^{-9} \text{ m/s}$;
- 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 .

The k values remained constant with time, whatever the hydraulic loading application (constant or variable loading). This indicates 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 (Fig. 2). The biggest pores ($>3 \mu\text{m}$), and intermediate-sized (between 3000 \AA and $3 \mu\text{m}$) are considered as responsible for the water path. When

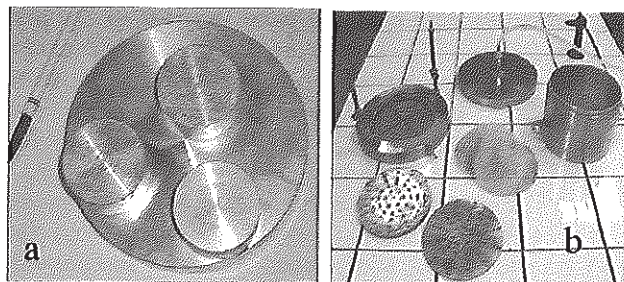


Fig 1. Kneading compaction tool (a) and permeameter (b)

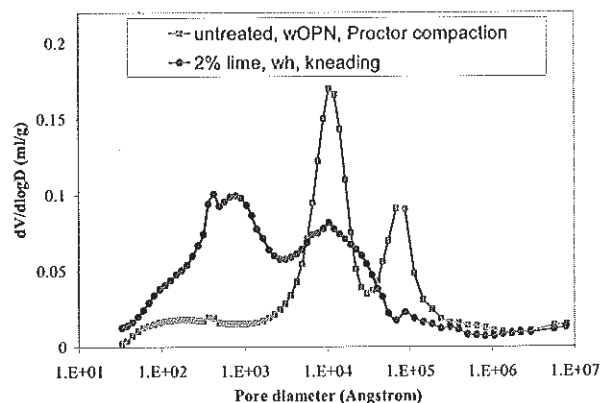


Fig 2. Mercury intrusion porosimetry of untreated (red curve) and lime-treated (blue curve) samples, as a function of water content and compaction procedure (silty soil from Moulin de Laffaux, France, PI=12.7)

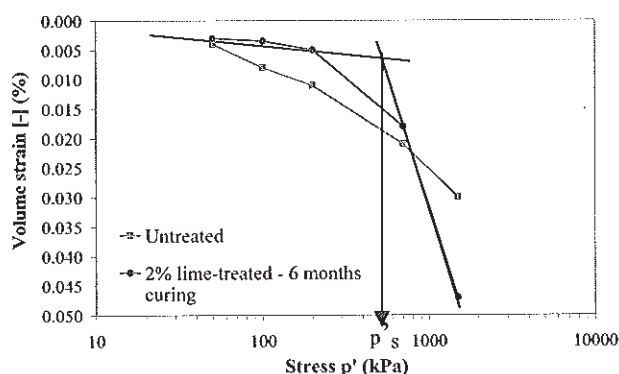


Fig 3. Isotropic compression of untreated and lime-treated silty soil from Moulin de Laffaux, PI=12.7 (6 month curing).

treated with lime, a third class of smaller pore appeared ($<3000 \text{ \AA}$). After lime-treatment in the humid state and kneading compaction, the amount of pores $> 3\mu\text{m}$ was strongly reduced in favour of the smallest pore size (Figure 2, blue curve), that do not affect the permeability. As a conclusion, the placement method of lime-treated materials is far more important than final density in the control of permeability (Cuisinier, 2011).

2.3 Mechanical behaviour of lime-treated soil

2.3.1 Compressibility

Isotropic compression tests were performed on the same silt as the one used for permeability (Fig. 3). 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.

Oedometer tests were also performed at Université Libre de Bruxelles (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 $<80\mu\text{m}$, 75% $<2\mu\text{m}$, $w_p=35\%$, $w_L=72\%$, $PI=37$, $\rho_d=1.45\text{g/cm}^3$ at $w_{OMC}=27.5\%$. 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.

2.3.2 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 (Verbrugge, 2011). Consolidated undrained triaxial tests were performed on samples of 3.6 cm diameter and 7.2 cm height, before-hand saturated. The untreated first silt (Soumagne soil) parameters are $c'=5.8 \text{ kPa}$ and $\phi'=37.4^\circ$. The friction angle stays stable after lime treatment, whereas the cohesion rises significantly: after 2 years, the c' value is 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.

2.3.3 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 cohesive bonds induced by the lime action. This new assembly has also a new stress resistance threshold; above this value, the assembly is destroyed and the behavior 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.

2.4 Water sensitivity and erosion resistance

2.4.1 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 $<80\mu\text{m}$, $PI=11$), treated with 2 to 3% quicklime. This improvement was still visible 3 years

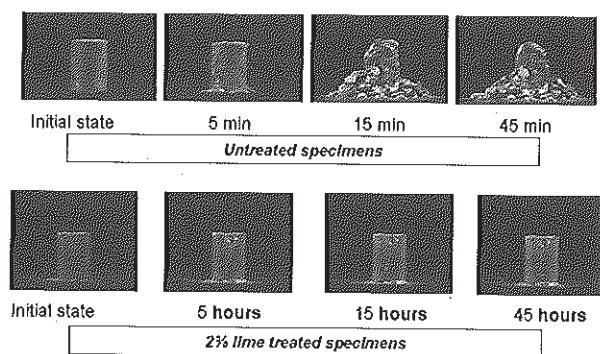


Fig. 4. Enhanced crumb-test performed on the silty soil from Héricourt (PI=11), untreated (above, scale in minutes), and treated with 2% lime (below, scale in hours).

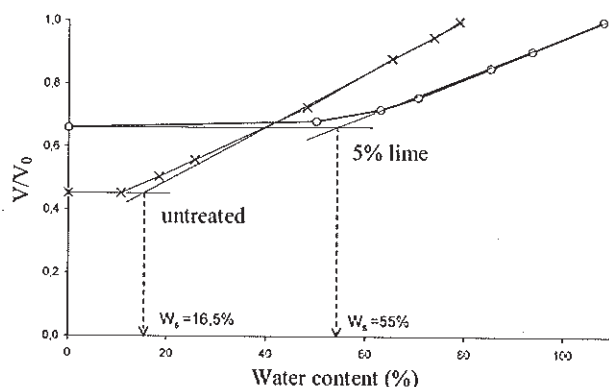


Fig 5. Free shrinkage curves of Héricourt clayey soil (PI=37)

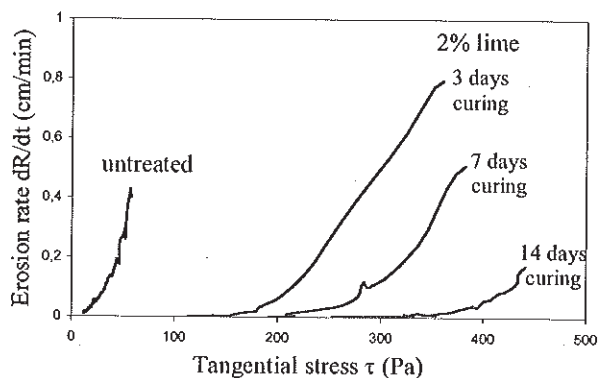


Fig 6. Hole Erosion Test: erosion rate vs tangential stress for untreated and 2% lime-treated clayey silt from a Camargue dike (PI= 11).

after treatment. An enhanced crumb-test was also performed by IFSTTAR (France) [Chevalier, 2011; Pham, 2008]. A thin wall sampler was used to cut out specimens from moulded cylinders (Héricourt silty soil, 67% particles $<80\mu\text{m}$, PI=11 untreated and treated 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 (Fig. 4).

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 showed that, after a 5% quicklime treatment, linear swelling of soaked CBR samples remained low and limited after the soaking step. In the meantime, 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 two tangents to the volume variation curve (Fig. 5). At this water content, the shrinkage of the sample reaches the maximum amplitude; below w_s , no volume variation is recorded. 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 OMC conditions, ensuring the volume stability of the material.

2.4.2 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 Irstea (France) on a clayey silt taken from a Camargue Dike (France): 95% particles $<80\mu\text{m}$, 30% $<2\mu\text{m}$, PI=11.

After lime treatment and 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. 6). For untreated clayey silt, the erosion threshold corresponds 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 (Benahmed, 2011; Bonelli, 2011). Additional informations can be found in (Bonelli, 2013; Herrier 2013a).

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, to recover the eroded particles and weight their dry mass. On a sample of Héricourt silty soil (67% particles $<80\mu\text{m}$, PI=11) treated 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.

Table 1. Identification characteristics of the silty soil from Marche-les-Dames (Belgium)

Clay fraction (<2 μm) (%)	12
Silt fraction (2 to 50 μm) (%)	82
Passing through 80 μm sieve (%)	99.5
Methylene Blue Value (g/100 g)	2.50
Plasticity index (%)	7 to 8
Moisture content at sampling (%)	17.9

3. An experimental full scale hydraulic earthen structure in lime-treated soil

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.

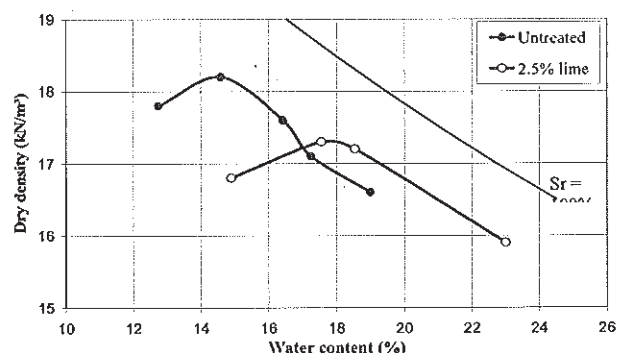
3.1 Chosen soil and its characteristics

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 reported in Table 1.

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. 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 (Knodel, 1987; Fleming, 1992).

3.2 preliminary lime treatment studies

The lime used for the soil treatment tests is a CL 90-Q quick lime according EN 459-1 standard, containing 90.9% of available CaO and a reactivity (t_{60}) of 3.3 minutes, supplied 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.

**Fig 7.** Standard Proctor compaction curves of untreated and 2.5 % Proviacal® DD-treated soil from Marche-les-Dames (Belgium).

The changes induced by the lime treatment on the compaction behavior of the soil are illustrated in Fig. 7. The optimal moisture content for Standard Proctor compaction of untreated soil is $\rho_d=18.2 \text{ kN/m}^3$ 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 $\rho_d=17.3 \text{ kN/m}^3$ at $w_{OMC}=17.8 \%$.

3.3 Mixing and compaction operations and equipment

The water permeability of a hydraulic earth structure must be managed during construction. Permeability must be sufficiently low to minimise water loss through the bottom and sides. The results from the Sotredi research program of the Lhoist Group (Herrier, 2012) showed that under specific treatment and placement conditions the permeability coefficient reached on a silty soil treated with 2 to 3 % quicklime was in the range of 5.10^{-9} m/s to 1.10^{-10} m/s and remained stable over time (Herrier, 2013).

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/m^3).

The equipment used for lime treatment was a mobile soil mixing plant (Fig. 8a), 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 parti-

cle 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 (Fig. 8b).

3.4 Experimental dikes conception

3.4.1 Dike built with lime-treated silty soil

The biggest of the two experimental dikes was entirely built with the 2.5 % lime-treated silty-soil from Marchelles-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 (Fig. 9a and b, 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.

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 (Fig. 9a). 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 (Fig. 9b). Pictures of each step can be viewed in Fig. 8. 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

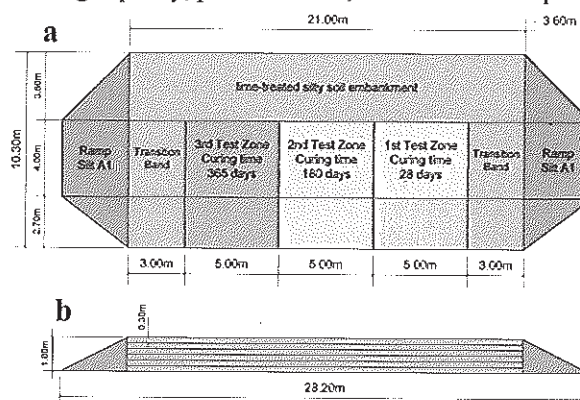


Fig 9. Top view (a) and longitudinal section (b) of the lime-treated silty soil experimental dike.

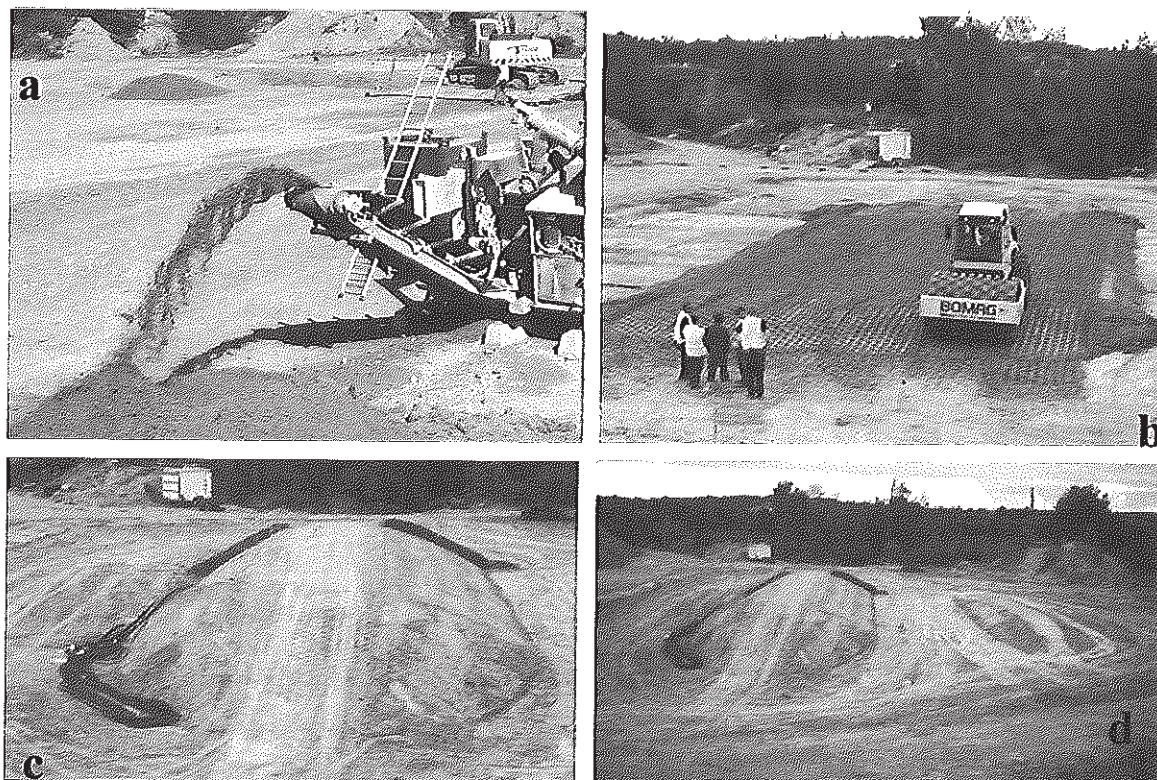


Fig. 8. Lime-treated material production (a), application and compaction with a sheepfoot roller (b), global view of the lime-treated dike (c) and of the two dikes (lime-treated and untreated, on the right) (d).

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.

3.4.2 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.

3.5 Results

3.5.1 Efficiency of mixing and placement procedures

Dike built with lime-treated soil

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 2 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.

Table 2. Measurements 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)

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.

Dike built with natural soil

In order to compare the properties of the lime-treated structure and their evolution over time, the second experimental embankment was built using the same soil and construction procedures, but without lime treatment. The measured properties are reported in Table 3.

3.5.2 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 (Sedidril 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, 6 months and 1 year after the construction of the experimental dikes, and are reported in Table 3.

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_i^* between 5 and 8), lime treatment and conservation after placement produce an important

Table 3. Pressuremeter measurements

Structure	Measurement period	p_i^* (MPa)	p_i^* (MPa)	E_M (MPa)	E_M/p_i^*
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
	12 months		≈ 6	≈ 80	≈ 13

Table 4. Triaxial tests results (CD, residual values).

Structure	Measurement period	c' (kPa)	ϕ' (°)
Untreated dike	28 days	≈ 0 (<10)	34.6
Lime-treated dike	28 days	41 (after 75 days)	39.2
	6 months	61 (after 195 days)	39.2
	12 months	75	39

strength increase, making the soil consolidated (ratio $E_M/p_1 > 10$). 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 41 kPa after 75 days and to 75 kPa after 12 months (Table 4).

3.5.3 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 Fig. 10a) 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 (Fig. 10b). Finally, the vertical permeability was also measured using the triaxial test under saturated conditions. Table 5 reports the recorded permeability values on the two structures.

Very low permeability values were obtained for both structures, in the range of 1.10^{-9} m/s. 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.

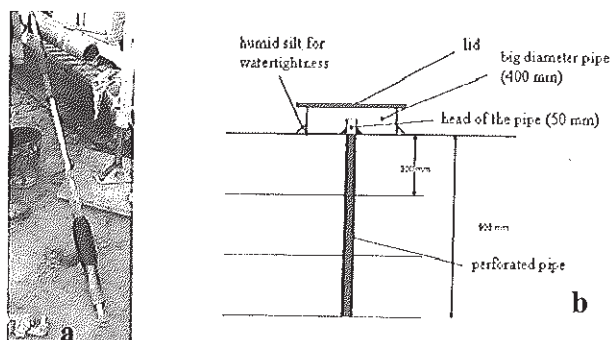


Fig. 10. Double-packer probe used for variable head Nasberg test (a); schematic view of the constant head Nasberg method (b).

Table 5. Results of permeability measurements.

	Untreated dike	Lime-treated dike		
Measurement period	28 days (in m/s)	28 days (in m/s)	6 months (in m/s)	12 months (in m/s)
In situ tests :				
Variable head	-	$0.8 \cdot 10^{-9}$	$4.5 \cdot 10^{-9}$	$8.5 \cdot 10^{-9}$
Constant head	$3.2 \cdot 10^{-9}$	$1.2 \cdot 10^{-9}$	-	-
Tests on cored specimens :				
Triaxial (CD)	$1.0 \cdot 10^{-9}$	$1.4 \cdot 10^{-9}$	$1.0 \cdot 10^{-9}$	$1.0 \cdot 10^{-9}$

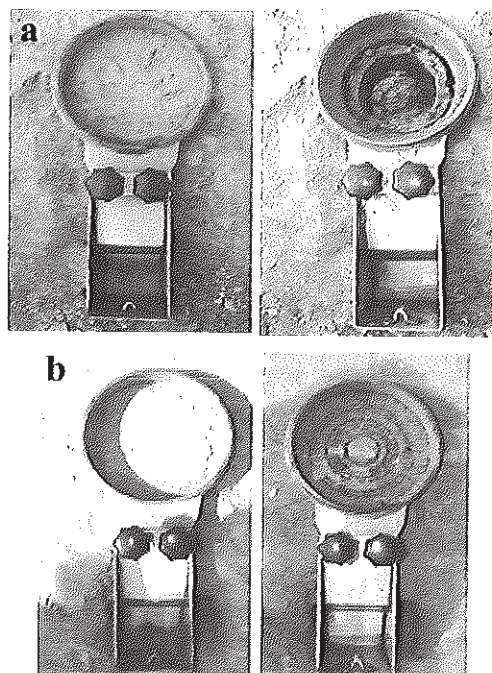


Fig. 11. MoJet external erosion tests performed on untreated soil (a, according usual parameters) and lime-treated embankment slope (b, increased flow to 2 l/min). The left pictures of each series are taken before the test, the right ones at the end of the test.

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 11a and b.

4. The French "DigueElite" project

Recently and from these achievements, an ambitious French project called "DigueELite" (which could be translated by "Elite Dike") was launched in June 2013 (logo on Fig. 12), in order to establish innovations taken

from the lime treatment technique and technology in the field of flood protection levees.

This project is sponsored by "Pôle Risques" and "Axelera" competitiveness hubs, and includes the following partners : ISL, (a hydraulic engineering office, project leader), Irstea (French Research Public Institute), Lhoist France (Lime Producer), EDF (French electric power company and owner of hydroelectric structures) and Arcor Technologies (monitoring systems).

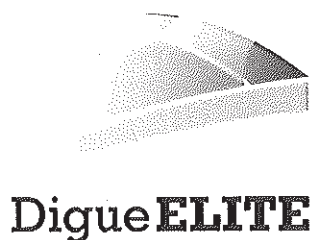


Fig. 12. Logo of the French DigueElite project.

The lime treatment is relevant in the field of flood protection levees construction and renovation, first because constitutive raw material is soil. Quality materials are rarely available on the site and their delivery involves significant costs. Conversely, a priori poor materials, available in quantity, are difficult to recycle. Since the late 90s, regulatory constraints of French national scope impose a rational and strictly controlled natural resource exploitation. These considerations show that the use of local materials, namely the existing soil or sediment for the implementation of hydraulic structures is a major challenge in the years to come.

The project aims to propose a solution to improve the resistance of protection dikes, as well for new structure as for existing ones, through developing an innovative and economically attractive dikes resistant to all failure mechanisms concept: DigueELITE. This concept is based on the development of a range of new materials, CONDYMAT (concept for new materials Dyke), based on the treatment of soils with lime. This treatment gives the soil, including local soil of poor quality, remarkable properties. At present, the performance of soil-lime material in hydraulic structures are fragmented and mostly limited to laboratory scale. That is why the formulation CONDYMAT, conditions for its manufacturing site and its limitations must be defined and works full-scale must be designed and tested to address all issues related to dikes and levees:

- The goals of the project are within 3 years:
- reduce the breaching risk due to external erosion (overflow), internal erosion and sliding;
- propose a new way to design overflow resistant zones, acting as spillways for flood control
- allow the reuse of local materials with poor engineering properties, also sediments
- reduce the overall construction and maintenance costs of a levee

- ensure the aesthetic, ecological and landscape continuity.

To meet these goals, all the stages of a civil engineering project of great magnitude have to be controlled and managed :

- control of the materials themselves, taking into account all materials included in the term 'soil', and its interaction with various elements ;
- the establishment of a concept, resolutely innovative compared to the conventional design of a dam, to assess the characteristics of the material, focusing on the efficacy and safety of the work;
- control of implementation, monitoring and maintenance.

The possibility of extending the applicability of the concept to the sea dikes will be studied throughout the different phases of the project.

These technical aspects must be accompanied by broader considerations related to both a civil engineering project and an innovation project.

The first jobsites of dikes construction, in South of France, and dike reinforcement (along the Schelde River in Belgium), will be achieved in Q2 – Q3 2014.

5 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.

6. 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-treated 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.

The laboratory experiments were followed by the

construction of a full-scale dike experiment achieved using the specified methodology and technology, that showed, on a lime-treated silty soil structure:

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

Recently and from these achievements, an ambitious French project called "DigueELite" was launched in June 2013, in order to establish innovations in the subject of flood protection levees. This project is sponsored by "Pôle Risques" and "Axelera" competitiveness hubs, and includes the following partners: ISL, (a hydraulic engineering office, project leader), Irstea (French Research Public Institute), Lhoist France (Lime Producer), EDF (French electric power company and owner of hydroelectric structures) and Arcor Technologies (monitoring systems). The goals of the project are within 3 years:

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redgDikes

Proceedings of the

South Baltic Conference on Dredged Materials in DiKE Construction

Rostock, Hohe Düne
10-11 April 2014

Organised by:

Universität Rostock
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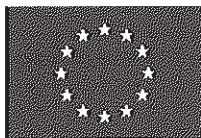
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Part-financed by the European Union
(European Regional Development Fund)



Proceedings of the South Baltic Conference on Dredged Materials in Dike Construction

Edited by:

Prof. Dr.-Ing. Fokke Saathoff and Dr.-Ing. Stefan Cantré
Universität Rostock
Chair of Geotechnics and Coastal Engineering
18051 Rostock
www.auf.uni-rostock.de; www.dredgdikes.eu

CIP-Short Title:

Proceedings of the South Baltic Conference
on Dredged Materials in Dike Construction
Universität Rostock
Chair of Geotechnics and Coastal Engineering
Rostock, 2014

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Digital PDF versions of the conference papers are available online on www.dredgdikes.eu.

ISBN: 978-3-86009-409-9

Published by Universität Rostock
www.uni-rostock.de

Printed on 100% recycling paper with carbon neutral printing technology.



Foreword

Dredged materials research has been developing rapidly during the past decade. Although sediments that are taken on shore are generally considered a waste according to European legislation, the materials prove to have a good potential to be re-used in a variety of applications. Also the European Waste Framework Directive demands recycling rates for wastes; for dredged materials taken on shore a recycling rate of 70% shall be achieved until 2020. This implicates research and development in all fields of sediment management. In the framework of a growing environmental awareness all around the Baltic Sea also strategies are discussed on how to reduce the amount of dredged sediments to be dumped at sea.

The Chair of Geotechnics and Coastal Engineering at the University of Rostock has been investigating the issue of dredged materials as replacement materials for dike construction since 2007. The topics of dikes, particularly with the focus on geosynthetics used in dikes and the determination of hydraulic design values, have been subject to research for a much longer time. This knowledge base of combined subjects in Geotechnics and Coastal Engineering finally lead to the project DredgDikes which was developed together with the Department of Geotechnics, Geology and Maritime Engineering at Gdansk Technical University and the Steinbeis Innovation Centre for Applied Landscape Planning in Rostock with nearly 30 years of experience in dredged material research. Two more partners, the Hanseatic City of Rostock with its dredged materials containment facilities and the Water and Soil Association "Untere Warnow – Küste" in Rostock are responsible for two pilot investments in Germany.

The project has three main objectives: The application of fine-grained dredged materials as a replacement for standard dike cover material or in homogenous dikes, the use of geosynthetics to address different weaknesses of the ripened dredged materials which are not additionally improved and the use of composites of ash and dredged sand to be used as dike core and dike cover materials. Therefore, three large-scale dike constructions have been built in the frame of the project to investigate installation and performance of the replacement materials. After the construction of the two research dikes in Rostock and Gdansk in 2012 one year of field experiments have now been evaluated to be presented to the interested public.

The South Baltic Conference on Dredged Materials in Dike Construction is the first of two project conferences with strong focus on the application of rather fine-grained dredged materials in dikes and other geotechnical constructions. The papers presented on the conference with authors from Germany, Poland, Finland, Sweden, UK, Belgium, France and the Netherlands show the growing research field in this area. The partner conference which will be organized in Gdansk, 5-6 June 2014, is titled *South Baltic Conference on New Technologies and Recent Developments in Flood Protection* with a stronger focus on dikes and other flood protection measures under consideration of the findings of the DredgDikes project. Both conferences will thus be used as a forum to present and discuss DredgDikes topics as well as to bring the different innovative research and development groups together that deal with the management and reuse of dredged materials. This will hopefully give the opportunity for future collaborations on different research levels. Special thanks has to be given to the South Baltic Programme for the co-financing, the associated organisations of the project for their support and to BWK and HTG for their auspices of the conference.

Rostock, 10 April 2014

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