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Evaluation of the geomechanical properties of lime-treated silt samples extracted from an experimental levee 6 years after construction

Évaluation des propriétés géomécaniques d'échantillons de limons traités à la chaux extraits d'une digue expérimentale 6 ans après construction

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ABSTRACT: In recent decades, multiple research projects have shown the positive impact of lime treatment on the construction or improvement of hydraulic structures. Both the hydraulic and the mechanical properties of lime-treated soils can be improved allowing for new design techniques and potential resource saving. In July 2015, as part of the DigueELITE project, a full-size experimental levee was built in a meander of the Vidourle River (Gard, France). The structure comprises a first section with a platform and a settling basin at the toe of the slope constructed with silty soil treated with 2% lime, and a second section built with the same soil untreated. As a primary objective, the resistance to external erosion of the lime-treated soil was quantified by performing overflow tests in 2016 and 2017. Then, the monitoring of the durability of the structure treated with lime was carried out. For this latter purpose, a test campaign took place in June 2021; samples were extracted from the core of the structure on the platform in lime-treated soil and characterized. This paper provides a brief description of the experimental levee, the experiments previously carried out, and the procedure implemented to study the geomechanical behavior of the samples extracted. Finally, the results of permeability, UCS, shearing strength, and oedometric compressibility tests, performed 6 years after the construction, are presented, and compared with those acquired just after the construction of the levee on samples prepared in the laboratory and cured for 7 to 28 days.

RÉSUMÉ: Récemment, de multiples projets de recherche ont montré l'impact positif du traitement à la chaux pour la construction ou l'amélioration des ouvrages hydrauliques. L'amélioration des propriétés hydrauliques et mécaniques des sols traités à la chaux, permet d'envisager des nouvelles techniques de conceptions plus économes en ressources. En juillet 2015, dans le cadre du projet DigueELITE une digue expérimentale de taille réelle a été construite dans un méandre du fleuve Vidourle (Gard, France). Le démonstrateur est constitué d'une première section construite avec un limon traité à 2% de chaux et d'une seconde section construite avec le même limon non traité. L'ouvrage comprend aussi une plateforme et un bassin de décantation construits en limon traité. L'objectif premier du projet était de quantifier la résistance à l'érosion externe du sol traité à la chaux à l'aide d'essais de surverse réalisés en 2016 et 2017. Un second sujet d'intérêt concerne le suivi de la durabilité des ouvrages traités à la chaux. A ce titre, une campagne d'essais a eu lieu en juin 2021 et des prélèvements en cœur d'ouvrage ont été réalisés. Ce papier fournit une brève description de la digue et des expérimentations précédemment réalisés puis présente les moyens mis en œuvre pour étudier le comportement géomécanique des échantillons prélevés. Finalement les résultats obtenus en termes de perméabilité, de résistance à la compression simple et au cisaillement, et de compressibilité œdométrique sur le matériau extrait à 6 ans de cure sont présentés et comparés à ceux acquis lors d'une étude antérieure datant de la construction de l'ouvrage et réalisée sur des échantillons préparés en laboratoire et consolidés de 7 à 28 jours.

Keywords: Silty soil; lime; durability; compressive strength; shear strength; permeability.

1 INTRODUCTION

The chemical treatment of soils with lime is a technique widely used on earthworks to improve poor-quality soils containing a clay fraction. The benefits of treating fine silty-clay soils with lime are twofold. Firstly, the addition of lime allows for better control and improves the physical characteristics of the soil and its compaction behaviour during processing, making it much easier to reuse. Secondly, over and above the short-term improvement effect, the addition of lime in sufficient quantity enables the development of improved geotechnical properties compared with untreated soil, particularly in terms of compressive and shear strength (Bell, 1996; Little, 1995). Recent research programs have also demonstrated the positive effects of treating soils for hydraulic structures, thanks to the increased resistance to erosion provided by the treatment, and the adaptation of treatment processes to meet low permeability requirements (Herrier et al., 2012; Nerincx et al., 2018; Herrier et al., 2018). The behaviour of treated soils is widely studied at the laboratory level, but only a few real structures have been monitored years after their construction (Haas et al., 2019, Das et al., 2021; Chabral et al., 2023).

This paper reports the monitoring of the properties of an experimental levee built on a meander of the river Vidourle in France. After a brief presentation of the experimental structure and the initial project, the method for taking and preparing the samples for the laboratory investigation is described. Finally, the results of permeability, UCS, shear strength, and oedometric compressibility tests, performed 6 years after the construction are presented and compared with those acquired on samples prepared and cured in a laboratory for 7 and 28 days.

2 PRESENTATION OF THE EXPERIMENTAL LEVEE

The construction of the experimental levee for the DigueELITE research program was completed in July 2015. Located on the edge of the Vidourle River, the structure is part of the work to improve the network of local levees. With a length of 50 m, a crest height of 3.5 m and a slope of 1.5H/1V, the demonstrator comprises a section of lime-treated soil and a section of untreated soil, and it is shown in Figure 1. The soil used is a locally extracted silt (Plasticity Index = 5), treated in a mobile plant with 2% quicklime. The slopes are not covered with topsoil, so the soil is directly exposed to the environment. The levee concerned by the experiments faces south and is therefore subject to wide temperature variations. The levee is not in direct contact with the Vidourle, which is several meters below; the water table is 2 to 3 meters below the structure.

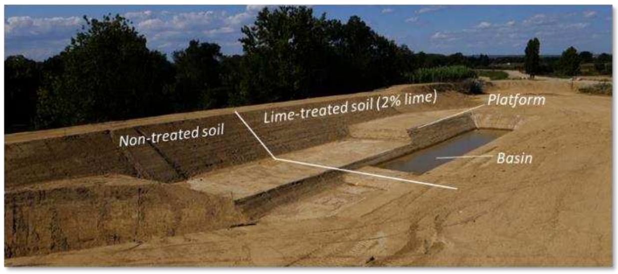


Figure 1. Aerial view of the Vidourle experimental levee. The platform and basin were also made with lime-treated soil and used for overflow test purposes.

This demonstrator was built to conduct overflow tests to quantify and compare the erosion resistance of treated and untreated soil on a real scale. Details of the tests and the overflowing simulator are presented in Bonelli et al. (2018). The project also made it possible to confirm the procedures for using treated soils in the construction of hydraulic structures, which differ from conventional treatment procedures. Thanks to its well-known construction history, the structure can now be used to conduct tests aimed at assessing the durability of the lime treatment solution.

3 SAMPLE COLLECTION AND PREPARATION

In 2021, the external erosion resistance of the treated and untreated soil was assessed using the JET test (Nicaise et al., 2024). This was also an opportunity to take samples from the body of the lime-treated levee on the platform part to assess its geomechanical performance. As for the experimental backfill in Rouen (Saussaye et al., 2020), blocks were extracted with a mechanical shovel using a small bucket to dig two narrow trenches 30 cm wide, 1 m apart from each other. The blocks were then lifted out from the backfill by planting the teeth of a wide bucket in the interlayers identified, with the mechanical shovel overhanging the platform. The extracted pieces were then carefully handled and cut on site using a floor saw to reduce their size and facilitate the handling (Figure 2). The final blocks obtained were approximately 40x40x30 cm in size and showed no visible cracks caused by the handling. After identification, the blocks were sealed in watertight plastic sheets. The material sampled corresponded to layer 6 and layer 7 of the lime-treated silt platform as shown in Figure 3.

The samples for the œdometric tests were obtained by machining the blocks using a milling machine to obtain a diameter of 5 cm and a height of 1.5 cm

(Figure 2). While to carry out direct shear and permeability tests, the samples were obtained by dry coring over a diameter of 10 cm with a height of about 10 cm. For simple compression tests, the same process was implemented, but the ratio length/diameter of the samples varied between 1 and 1.6. The high resistance of the treated soils made them fragile, and the sporadic presence of pebbles did not allow to obtain longer samples with a good yield.

Figure 2. Left: View on the two trenches and the mechanical shovel. Middle: An extracted block re-sized using a floor saw for conditioning. Right: A re-sized block used to shape a sample by milling.

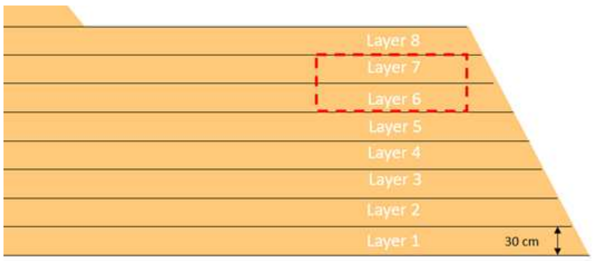


Figure 3. Schematic cross-visualization of the location of layer 6 and layer 7 of the material extracted from the platform in the lime-treated soil.

4 GEOMECHANICAL PROPERTIES AFTER 6 YEARS

4.1 Oedometric compressibility

The œdometric tests were performed by placing the milling-shaped samples between two porous stones in œdometric cells. After a period of saturation in water, loading and unloading tests were carried out in saturated conditions, and the vertical displacement of the samples was measured after stabilization. Ten loading/unloading bearings were applied in the following sequence: 25, 50, 100, 200, 400, 800, 1600 kPa, then 400, 100, and 25 kPa. Three samples from layer 6 were tested in loading up to 800 kPa, and six samples from layer 7 were tested three with loads up to 800 and three with loads up to 1600 kPa. The objective was to verify potential heterogeneities between layers, but also within the same layer.

The results of the compressibility tests are presented in Figure 4 and compared with the results obtained on samples prepared in the laboratory in 2015.

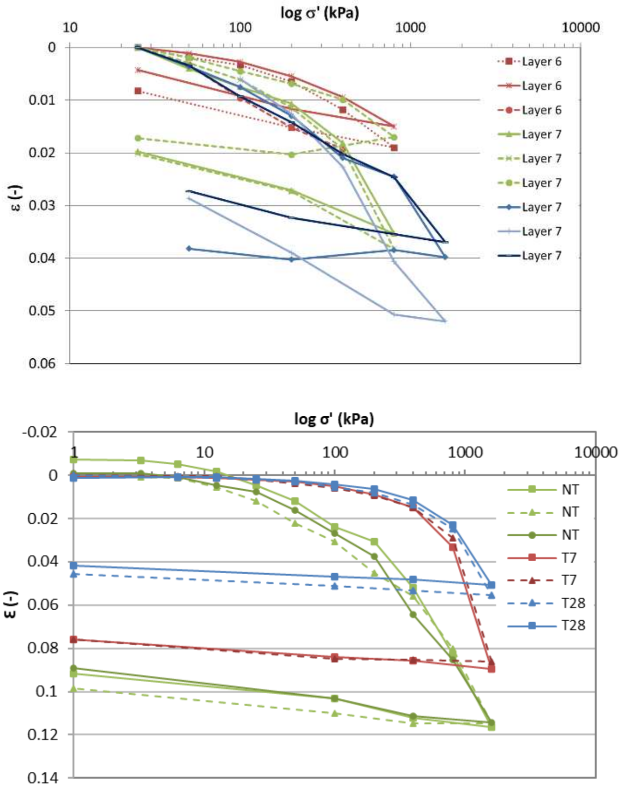


Figure 4. Top: Compression curves of the specimen extracted after 6 years. Bottom: Compression curves of the specimen non-treated (NT) and treated in the laboratory after 7 (T7) and 28 (T28) days of curing.

Table 1 summarizes the various parameters calculated from the compression curves.

Table 1. Parameters measured during the compressibility tests on the samples extracted from the Vidourle levee after 6 years of aging (onsite samples) and compared to values obtained on laboratory samples tested at younger ages.

Study	Soil - Cure	Compressibility index	Swelling index	Pre-consolidation stress σ' (kPa)
This study *(onsite samples)*	Layer 7 (2% treated soil) - 6 years	0.0205	0.0041	> 600
	Layer 6 (2% treated soil) - 6 years	0.0092	0.0040	200 - 600
2015 study *(laboratory samples)*	Untreated soil	0.0415	0.0030	109
	2% treated soil – 7 days	0.0527	0.0016	565
	2% treated soil – 28 days	0.0292	0.0012	503

According to the results, the treated soil, sampled after 6 years of weathering, maintains, or even improves, its compressibility characteristics. Layer 7 shows a compressibility behaviour similar to that of the laboratory-treated soil after 7 and 28 days of curing, significantly improved in comparison with the behaviour of the untreated soil.

A significant difference between layer 6 and layer 7 is observed as layer 6 is less compressible. Furthermore, layer 6's material shows an improved behavior compared to that of the soil tested in the lab at a shorter curing time. Its pre-consolidation stress probably exceeds 600 kPa but remains non-calculable as it is doubtful that the plastic range is reached at 800 kPa. In general, the results obtained within the same layer are close and reproducible.

4.2 Unconfined compressive strength (UCS)

The unconfined compressive strength (UCS) of the samples from both the layers was measured on cylindrical drilled samples. The length/diameter ratio of the samples being systematically lower than 2, a corrective factor on the measured resistance was applied, under the recommendations of the ASTM C42 standard. The tests were carried out at the natural water content, without resaturation; the samples were placed between two horizontal plates and the vertical movement of the upper plate was controlled at a speed of 0.3 mm/min. The vertical deformations were deduced from the measurements of the top plate displacement through two external displacement sensors (LVDT). Table 2 summarizes the corrected UCS values obtained for both layers and compares them to the values obtained on the laboratory samples of the same treated and untreated soil.

Table 2. UCS measured on the samples extracted from the Vidourle levee after 6 years of aging (onsite samples), compared to values obtained on laboratory samples at younger ages.

Study	Curing	UCS (MPa)
This study *(onsite samples)*	Layer 7 – 6 years	0.82
	Layer 6 – 6 years	1.77
2015 study *(laboratory samples)*	Untreated soil	0.21
	7 days	0.32
	28 days	0.39
	60 days	0.44
	90 days	0.53
	180 days	0.73
	365 days	1.20

These results show a similar trend to that already observed; the results are reproducible and relatively homogeneous. Layer 7 displays lower UCS values than layer 6 and comparable with the values obtained for a soil compacted and tested in laboratory after 180 days of cure. Layer 6 exhibits higher strength and stiffness with an improved resistance compared to the one measured on laboratory samples after 1 year, probably reflecting the good development and conservation of pozzolanic reaction products.

4.3 Permeability

Permeability tests were performed on the samples intended for direct shear tests. Samples of 10 cm of diameter and +/- 10 cm of height were wrapped in a latex membrane with two porous stones placed on both free sides. The whole specimen was installed in a confining cell fixing the membrane against the sample. The lower porous stone was connected to a pressure/volume controller to impose pressure and measure the volume of water injected. The upper porous stone was connected to a drainage circuit allowing water to drain to the open air. A pressure of 1 bar (= 100 kPa) was imposed on the base while the pressure at the top of the sample corresponded to the atmospheric pressure.

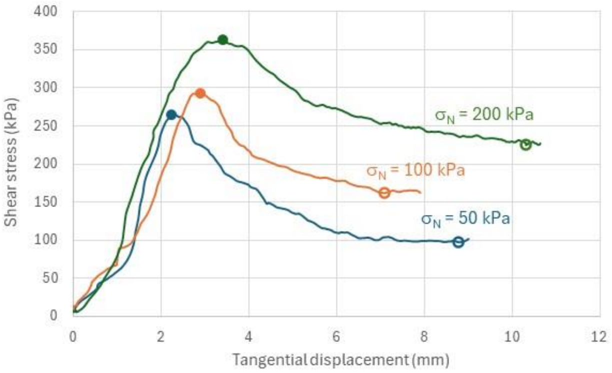
Table 3 summarizes the permeability coefficients obtained. Overall, the results are reproducible, and the permeability measured is very low for both layers.

Table 3. Permeability measured on the samples extracted from the Vidourle levee after 6 years of aging.

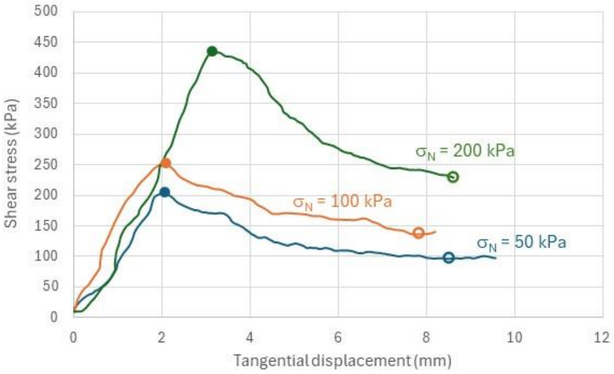
Soil - Cure	Permeability k (m/s)
Layer 7 (2% treated soil) - 6 years	$1.9.10^{-10}$
	$1.8.10^{-8}$
	4.10^{-9}
Layer 6 (2% treated soil) - 6 years	$1.61.10^{-8}$
	$3.38.10^{-8}$
	$1.06.10^{-8}$
	$2.41.10^{-9}$
	$8.52.10^{-9}$
	$2.99.\ 10^{-9}$

4.4 Shear strength

The same saturated samples that led to the permeability measurements were used to perform direct shear tests under the following normal stresses: 50 kPa, 100 kPa and 200 kPa. The rate of shearing was fixed low enough, at 6 mm/hour, to maintain drained conditions during shearing. According to ASTM D3080, with a coefficient of consolidation of 2E-5 m^2/s (deduced from the permeability and the stiffness), a thickness of specimen of 10 cm and a failure occurring at 3 mm of displacement, the maximum speed should be 9 mm/hour. The evolutions of shear stress versus tangential displacement are reported in Figure 5. The peak state is defined as the maximum ratio of shear (τ) versus the normal (σ_N) stress, while the residual state corresponds to the minimum of this ratio (τ/σ_N) after passing the peak.



(a)



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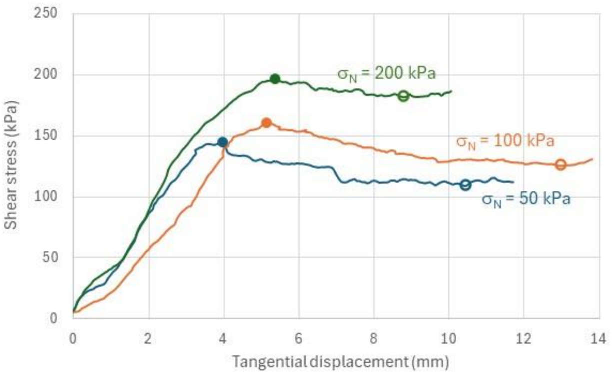

(c)

Figure 5. Direct shear tests performed on the specimens extracted after 6 years, at normal stress of 50 kPa, 100 kPa and 200 kPa. (a) 1st series on layer 6, (b) 2nd series on layer 6, (c) series on layer 7. Peak and residual states are reported by full and empty circles, respectively.

The peak and residual cohesion (c) as well as the associated friction angles (ϕ) measured are presented in Table 4. The peak values are compared with those obtained on laboratory samples cured for 7, 14 and 28 days, tested in consolidated undrained triaxial compression.

As for the other geomechanical properties measured, the layer 7 shows lower values than layer 6, with a significant drop in the friction angle. However, in both cases there is a positive change in cohesion which has greatly increased compared to that developed by samples produced and tested in laboratory at younger ages with values multiplied by a factor of 4 to 6. When compared to the natural soil, the treated soil exhibits values 10 to 20 times higher demonstrating a far greater resistance.

5 CONCLUSIONS

The objective of the present study was to carry out a series of geomechanical tests on samples of soil extracted from the Vidourle levee to assess the characteristics and the durability of the lime-treated soil after 6 years of weathering. Based on the results presented above, the following considerations can be drawn:

- the permeability measured on the soil treated with lime is consistently low;
- the soil treated with 2% of lime and then subject to weathering for 6 years has shown to maintain enhanced geomechanical properties if compared to the same natural soil tested in the laboratory (untreated);
- the geomechanical properties of the soil treated with lime tend to increase with the sample depth in the body of the levee;
- the geomechanical properties are significantly improved for the deeper layer (layer 6) demonstrating the positive impact of the pozzolanic reaction in the long term.

The upper layer considered in the study is located at a depth between 30 and 60 cm from the surface. Its position closer to the surface and the fact that the Vidourle levee is subjected to strong variations in temperature and humidity throughout the years, can possibly explain its worse behaviour. Deterioration due to weathering, or a different kinetics of development compared to the deeper material, more protected, could have caused this phenomenon. To verify this hypothesis, an additional monitoring campaign including sampling and testing is planned for 2024 to better investigate this topic.

Table 4. Parameters measured during the shearing tests performed on the samples extracted from the Vidourle levee after 6 years of aging (onsite samples) (from consolidated drained direct shear test) and compared to values obtained on laboratory samples tested at younger ages (from consolidated undrained triaxial tests).

Study	**Soil - Cure**	**Peak resistance**		**Residual resistance**	
		c (kPa)	Φ (°)	c (kPa)	Φ (°)
This study *(onsite samples)*	Layer 7 (2% treated soil) – 6 years	126	18	78	24
	Layer (2% treated soil) – 6 years	157 – 230	32 – 43	54 – 65	36 – 37
2015 study *(laboratory samples)*	Untreated soil	11	33	(residual state not measured from CU triaxial tests)	
	2% treated soil – 7 days	25	48		
	2% treated soil – 14 days	28	46		
	2% treated soil – 28 days	40	42		

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