The paper was published in the Proceedings of the 8th International Symposium on Deformation Characteristics of Geomaterials (IS-PORTO 2023) and was edited by António Viana da Fonseca and Cristiana Ferreira. The symposium was held from the 3rd to the 6th of September 2023 in Porto, Portugal.

In situ ageing of a lime/cement-treated expansive clayey soil

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ABSTRACT

This paper focuses on the performances of a treated expansive clayey soil sampled on an embankment constructed in 2010. Two types of treatment used during construction are considered: 4% lime as well as a mix of 2% lime and 3% cement. Oedometer tests were carried out on different parts of the embankment, to assess the compressibility of the soil. The results were compared to the compression curve of the untreated soil, also sampled in the same embankment. Several complementary aspects were also investigated (moisture content, dry density,…) to assess the ageing process of the embankment. The obtained results showed that the behaviour of the material from the outer part of the backfill is similar to the mechanical performances of the untreated soil, demonstrating a strong alteration of the effect of both treatments. This alteration is noticeable until a horizontal distance of about two meters from the surface. Beyond this distance, the performance of the soil is comparable to the mechanical behaviour of treated soil. These observations, similar for each treatment dosage, tend to question the durability of the treatment at the edge of the earth structure.

Keywords: Soil treatment; Durability; Expansive clays; Compressibility.

1. Introduction

Soil treatment with lime and/or cement is a widely used technique in geotechnical engineering to improve low-quality materials for the construction of structures such as pavements, embankments, etc. The treatment improves the mechanical characteristics such as strength and elastic modulus of the material by creating cementitious bonds between the soil particles (e.g., (Brandl, 1981; Kafodya and Okonta, 2018; Poncelet and François, 2022). Soil treatment is also widely used because of its lowering effect on the swelling and shrinkage of plastic soils, such as clays (e.g., Nalbantoglu and Tuncer, 2011; Herrier et al., 2015; Wang et al., 2020).

Aside from the short-term benefits of using a treatment, a key issue is the long-term behaviour of the treated soil. Numerous laboratory studies highlighted the detrimental effects of exposure to climatic conditions on the long-term characteristics of treated materials. Freezing-thawing cycles (Dempsey and Thompson, 1967; Consoli et al., 2017; Lu et al., 2020), as well as leaching (McCallister and Petry, 1991; Khattab et al., 2007; Le Runigo et al., 2011; Deneele et al., 2016) and carbonation process (Ho et al., 2018; Xu et al., 2020; Deneele et al., 2021) tended to alter the effect of treatment. Some authors also showed that the alternation of dry and wet periods induced a sharp reduction in the mechanical performances of treated soils (Guney et al., 2007; Khoury and Zaman, 2007; Consoli et al., 2017). Liu et al. (2019) studied the impact of water immersion and subsequent wetting and drying periods on sand treated with calcite precipitation. These cycles induced a decrease of up to 80% in the compressive strength for stabilised specimens after 5 cycles. Other studies (Stoltz et al., 2012; Mehenni et al., 2020; Wassermann et al., 2022) adapted the simulation procedures for water cycling by controlling the suction in the specimens, highlighting that the amplitude of the cycles controls the intensity of the degradation effects of the treatment. Thus, several concerns exist regarding the long-term characteristics of treated soils exposed to climatic conditions.

However, the in-situ conditions experienced by soil-treated structures are a combination of hydric, thermal and/or chemical stresses depending on the type of structure and its location. Despite the need to predict the service time of treated earth structures, less is known about the in-situ performance of such stabilised materials several years after their erection (Cuisinier and Deneele, 2010; Rosone et al., 2018; Das et al., 2021; Chabrat et al., 2022). These studies are generally facing various issues: in the case of the Friant-Kern Canal built in the 1970s in California (Herrier et al., 2012), Akula et al., 2020 evaluated the long-term durability of silt treated with 4% lime. The physico-chemical analysis of the material recovered 40 years after the construction of the structure concluded that the treatment dosage was appropriate to last over this period. But the brittle behaviour of the treated material associated with a manual rotary drill sampling made it difficult to preserve the structure of the soil and thus, assessing correctly its mechanical behaviour. Cuisinier et al. (2012) also studied the temporal evolution of the properties of a treated material in the case of an embankment, 7 years after its construction. A series of triaxial tests revealed a strong disparity of results among the different specimens. This heterogeneity could be assigned to the nature of the soils used, and the weathering of certain areas of the structure, but also tends to question the proper execution during construction. Thus, little is yet known about the evolution of treated earth structures.

Therefore, to assess the evolution of the performance of stabilised soils over time, an original approach based on investigations carried out on an earth structure has been adopted. The article presents results obtained from samples taken from a clayey soil embankment built in 2010 and treated with lime and/or cement. Its construction has been carefully monitored, and several aspects were monitored over time until today (moisture content, temperature, etc.). In this paper, the characteristics of the material used and the structural characteristics of the earth structure are detailed. Then, the sampling campaign is specified. In the last part of this article, results from oedometer tests will be discussed. The overall durability of the embankment will be evaluated in terms of its mechanical behaviour eleven years after completion.

2. The experimental embankment

The experimental structure selected for this article was built in 2010 as a part of a French research project (ANR TerDOUEST 2008-2012) in Héricourt (France). The embankment is 112 m long and 5 m high. The slope of the earth structure is 50%, and its width is 25 m at the base and 5 m at the top. The structure was intensively monitored at the time of its construction (Froumentin and Boussafir, 2013). Many studies related to the embankment were produced afterwards regarding soil-atmosphere interactions (Bicalho et al., 2015; An et al., 2016; Boussafir et al., 2016; An et al., 2017; Boussafir et al., 2018; Bicalho et al., 2018), the influence of the treatment mixing and aggregate size (Razakamanantsoa et al., 2012; Dong, 2013; Wang et al., 2017) and the hydromechanical behaviour of the soil (Stoltz et al., 2012, 2014; Tran et al., 2014; Herrier et al., 2015; Wang et al., 2020).

2.1. Soil characterization

The embankment was constructed with a clayey soil extracted nearby the construction site. The soil is an inorganic clay of high plasticity (CH group symbol) according to the Unified Soil Classification System, its characteristics are given in Table 1. Smectite and muscovite have been identified as the main minerals (Stoltz et al., 2012). The swelling potential of the soil at the optimum moisture content (OMC) was measured at 14.1%, while the swelling pressure of the material treated with 1% lime is 0.1% (Stoltz et al., 2014).

Table 2 shows the compaction characteristics of the clay at the optimum moisture content for different treatment dosages. These characteristics were determined following a pre-construction laboratory test campaign (Froumentin and Boussafir, 2013).

Table 1. Main geotechnical properties of the studied clayey soil

Passing sieve 80 µm (%)	90
Clay size content (<2 µm) (%)	70
Specific gravity Gs (-)	2.675
Liquid limit (%)	71
Plastic limit (%)	29
Plasticity index (%)	42

Table 2. Compaction characteristics under normal Proctor energy of the treated clayey soil used for the embankment

Treatment	0%	4 % CaO	2 % CaO + 3 % CEM II
w_{OMC} (%)	26.5	38	32.5
$\rho_{d,Max}$ ($Mg.m^{-3}$)	1.45	1.24	1.34
e_i (-)	0.84	1.15	1.00

2.2. Background material on the embankment

2.2.1. Structure of the embankment

The embankment was constructed with the clayey soil presented before and is divided into 3 sections (Figure 1). For each section, the lower part (from 0.40 to 2.50 m of height) and the upper part (from 2.50 to 3.70 m of height) were built with different treatment mixes (Table 3). The base (from 0 to 0.40 m of height) and the top (from 3.70 to 5.15 m of height) of the embankment were erected with different treatments and are not considered in this article. The design method is presented in Froumentin's (2012) report. At the end of the construction, a waterproof layer made of asphalt emulsion was applied on the top of the structure. A layer of topsoil of approximately 0.10 m was also added to the edge of the earth structure. Finally, the embankment was constructed with an excess width of 1 m to the horizontal slope of the finished structure. This excess width has been removed at the end of the construction. This method limits potential compaction issues at the edge of the embankment.

Table 3. Treatment dosage for each section of the embankment

Section	1	2	3
Upper part	4% CaO	4 % CaO	2 % CaO + 3 % CEM II
Lower part	Untreated	4 % CaO	2 % CaO + 3 % CEM II

2.2.2. Treatment method

Each layer was treated on-site by spreading lime/cement depending on the section. The binding agent and the soil were first mixed with pulvimixer at optimum moisture content. The soil was then compacted using a sheepsfoot roller. The density target during construction was 95% of the maximum dry density (given for each treatment in

), which is a common target for such earth structures in France.

2.2.3. Soil parameters at the time of construction

The moisture content of the material has been controlled for each 0.30 m layer of stabilized soil in the embankment. The dry density of each layer of soil was also measured using a gamma-densimeter. The results of these controls are shown in Table 4 and compared to the targeted values of water content and dry density. The observed moisture content values showed that the soil was compacted on the dry side in the first two sections (33.0% for section 1 and 35.0% for section 2, both treated with 4% lime), and at optimum moisture content for section 3 For all sections, a slight over-compaction was obtained with a compaction factor higher than 100%.

Table 4. Moisture content and dry density controls of the different sections of the embankment during construction

Section	1	2	3
Treatment	4% CaO	4 % CaO	2 % CaO + 3 % CEM II
w (%)	33.0	35.0	32.8
$w\text{-}w_{OMC}$ (%)	-5.0	-3.0	+0.3
ρ_d ($Mg.m^{-3}$)	1.36	1.33	1.39
$\rho_d/\rho_{d,Max}$ (%)	109.6	106.0	104.3

3. Experimental program

Samples were retrieved from the three sections of the embankment, to assess the hydromechanical performance of the treatment. Results presented in this article are expressed as a function of horizontal distance alongside the sampling line (Figure 1) to highlight the potential impact of soil-atmosphere interactions. First, the operation method for sampling is discussed. Then the storage and sample preparation are presented. At last, the experimental strategy of the soil is depicted.

3.1. Soil sampling

The sampling campaign was carried out in November 2020. Figure 1 summarizes the different samples collected during the operation. Horizontal coring was carried out in the upper part of the three sections, approximately 1.80 m above the natural ground level. Vertical coring was also performed in the three sections at the top of the embankment, allowing the sampling from the lower part of the embankment. Rotational coring with water as the drilling fluid was chosen to guarantee the quality of the samples. A mean recovery rate of 97% was achieved for the horizontal cores.

3.2. Specimen preparation

All samples were stored at 20±5 °C in Plexiglas tubes with internal diameters of 100 mm and lengths of 1.50 m. To minimize the impact of sample preparation, soil cores were first cut with a dicing saw equipped with a diamond wire. the height of the specimens after dicing was 15±3 mm. The diameter of each specimen was then adjusted using a cutting ring of 70 mm.

3.3. Laboratory tests

Preliminary tests were first performed to better understand the actual state of the earth structure. Gravimetric moisture content was directly determined from the specimens coming from the cores. The dry density, as well as the void index, were also assessed to evaluate the compaction state of the soil 11 years after the construction. These compaction parameters are compared to the moisture content and dry density measured during construction (Table 4).

Then, oedometer tests were carried out to assess the effects of the treatment on the mechanical behaviour of the soil. This approach consists of comparing the compression curves of specimens coming from a different horizontal distance (Stoltz et al., 2014), as shown in Figure 1. An oedometer test coming from the untreated part of the embankment (lower portion of the first section as shown in Table 3) was performed. This test was used as a reference to quantify the effects of the

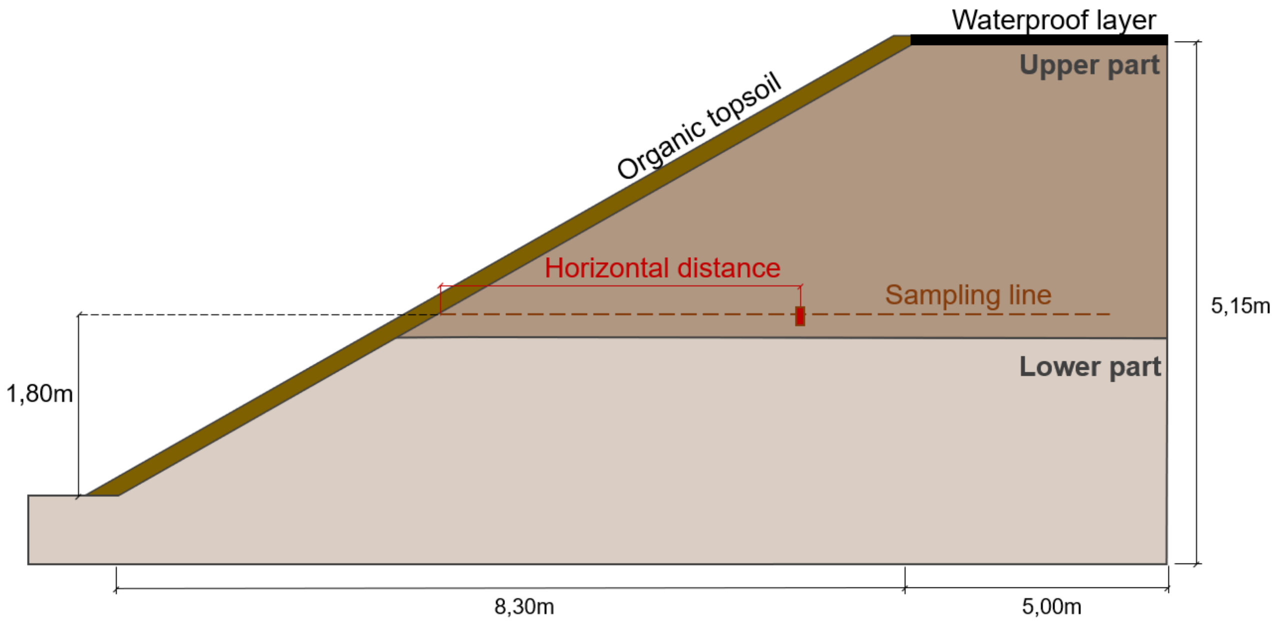

Figure 2. Core drilled zone in the upper and lower part of the embankment.

treatment. Several tests on the horizontal cores (from 0 to 4.50 m of horizontal distance) and one on the vertical core were also carried out for each part of the embankment (at the same height as the horizontal tests). All specimens were saturated and subjected to step loading up to 7.0 MPa. Thus, the compressive curve of the untreated soil will be compared to the compressive curves from the other tests.

4. Distribution of water content and dry density

Identification tests were first carried out along the horizontal axis at 1.80 m height (Figure 1) to assess the current state of the embankment. For each section of the backfill, the moisture content and the dry density of the soil are plotted in Figure 2.

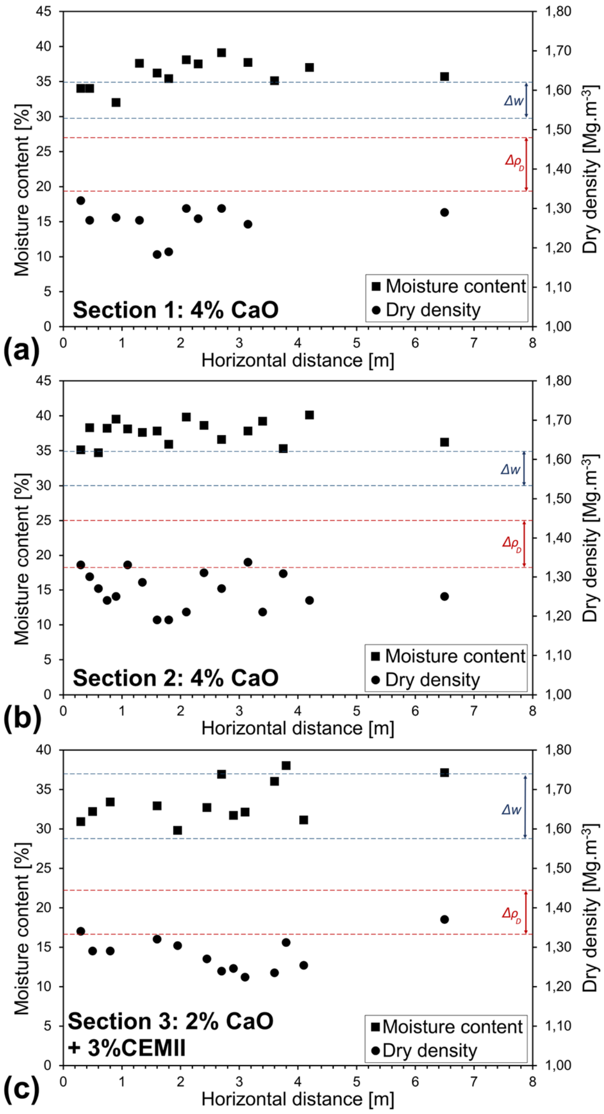

Figure 2. Moisture content and dry density evolution along the horizontal cores for section 1 treated with 4% lime (a), section 2 treated with 4% lime (b), and section 3 treated with 2% lime and 3% cement (c).

For section 1, the moisture content was comprised between 34% and 39% with a mean value of 36.1%. The lowest values of water content were found at low horizontal distances. The average dry density was found equal to 1.26 $Mg.m^{-3}$. In section 2, the average dry density was also 1.26 $Mg.m^{-3}$ while the average moisture content was 37.5%. Moisture contents and dry densities along the sampling line were also measured for the third section treated with 2% of lime and 3% of cement. The mean value of the moisture content was 33.4%, while the average dry density was found at 1.29 $Mg.m^{-3}$. The density and moisture content found in section 3 were slightly different from the other sections, as the optimum moisture content depends on the treatment dosage.

5. Hydromechanical behaviour of the specimens taken from the embankment

Up to 17 oedometer tests were performed in each section. Examples of the compressibility curves obtained from each section are plotted in Figure 3. The yield stresses determined in each oedometer test are shown in Figure 4. The results of these tests were compared to the curve obtained from the specimen taken from the untreated part of the backfill (lower part of section 1).
The yield stress determined at the edge of the backfill in section 1 was equal to about 20 kPa. The compression curve of this specimen is very close to the one obtained with the untreated sample (Figure 3); the yield stress determined from both curves is of the same order of magnitude. The swelling index C_S of the two specimens were also very close. The results showed that the yield stress of the sample taken at the center of the backfill exhibited a yield stress of about 1000 kPa, significantly larger than the one determined on the sample taken at the edge. Figure 4a shows that there is a progressive increase of the yield stress from the surface up to about 2.70 m, the yield stress remaining stable between 2.70 m and the inner part of the backfill.

The analysis of the oedometer tests carried out in section 2, also treated with 4% lime, are plotted in Figure 3b and Figure 4b. At 0.30 m from the surface, the yield stress was slightly lower than the yield stress of the untreated specimen compacted at the optimum moisture content. This might be related to the initial void ratio of the treated sample that was lower than the one of the untreated sample. The yield stress progressively increased up to about 1200 kPa at 2.40 m from the surface. Between 2.40 and 6.50 m from the surface, the yield stress remained almost constant and higher than 1000 kPa.

A similar trend was observed in section 3. On the edge, the yield stress of the specimen was equivalent to the one of the untreated soil and equal to 20 kPa (Figure 3c). The yield stress gradually increased until a distance of 2.00 m from the surface. After that, it remained significantly higher than the yield stress of the untreated soil, even if the scattering of the data is greater compared to the results obtained in the first two sections.

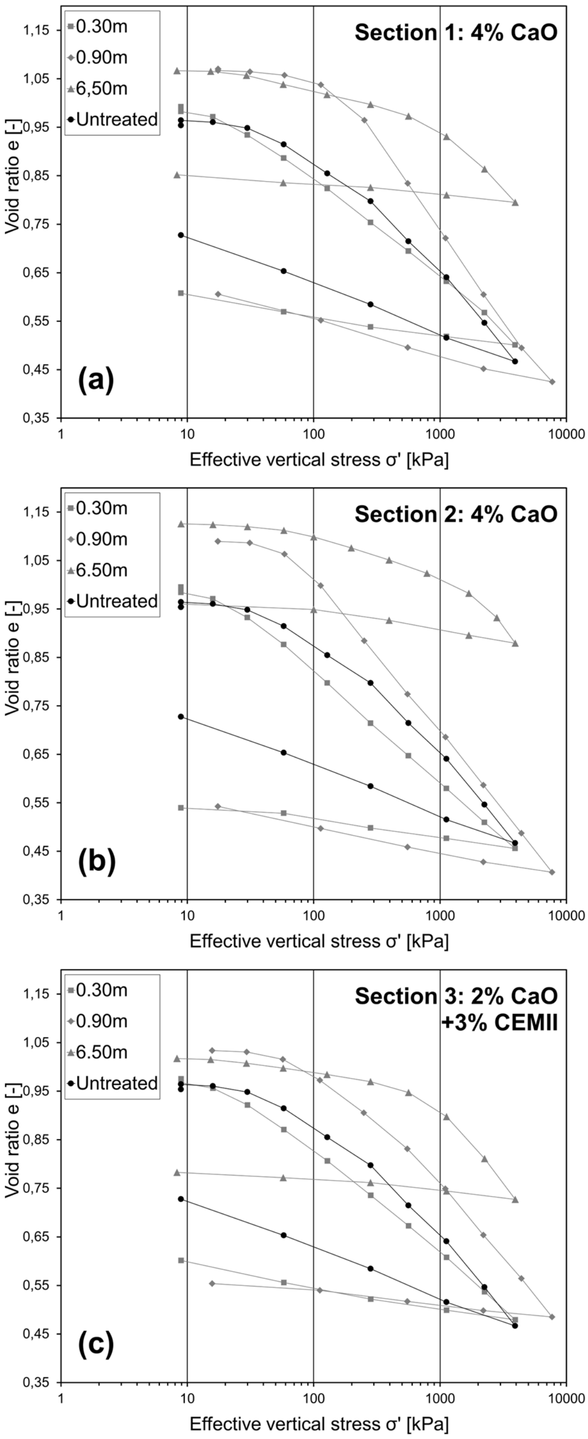

Figure 3. Compression curves of specimens taken from various horizontal distances for section 1 treated with 4% lime (a), section 2 treated with 4% lime (b), and section 3 treated with 2% lime and 3% cement (c).

6. Discussion

The performances of the stabilized soil 11 years after its erection, can be assessed through the tests performed on the samples retrieved from the embankment.

Moisture content presented in Figure 2 can be compared to the one measured at construction time (Table 4). Moisture content values from all sections slightly increased since construction time: from 33.0% to 36.1% for section 1, from 35.0% to 37.5% for section 2 and from 32.8% to 33.4% for section 3. The edge of the backfill was however slightly drier than the inner part of the backfill (Figure 2). These results tend to indicate that the moisture content of the backfill has not significantly changed since the time of construction.Besides, moisture content values suggest that the soil was not impacted by the water used for drilling. These results are in line with the data collected by the in-situ sensors and presented by Bicalho et al. (2015). Continuous monitoring over a year indicated that the volumetric water content measured at 0.50 m of horizontal distance could vary from 0 to 1.5%. On the other hand, moisture sensors installed in the core of the embankment (at 4.50 m of horizontal distance) did not detect relevant variations of volumetric water content. Thus, the compaction parameters of the soil remained nearly unchanged over the years, except for the edge of the embankment where the soil is most exposed to atmosphere interactions. This confirms that the impact of climatic conditions on moisture content is limited to the first tens of centimeters of the embankment.

In all sections, the three series of oedometer tests showed a progressive increase of the yield stress from the surface until about 2.50 m towards the inner part of the backfill. Beyond 2.50 m, the performance of the soil remained stable with values of yield stress higher than 1000 kPa. On the edge, the behaviour of the specimens is very close to the behaviour of the untreated soil. This indicates that the treatment is no longer impacting significantly the yield stress of the soil. Results obtained in section 1 and section 2, both treated with 4% lime, led to the same degradation of the edge of the embankment. This tends to confirm the repeatability of the tests performed. The yield stress of the soil treated with quicklime after 360 days of curing (at constant moisture content) was determined by Stoltz et al. (2014). It was equal to 3500 kPa with 5 % of quicklime and equal to 1200 kPa with 2 % of quicklime. These results demonstrate that both the yield stress of specimens from the inner part and the yield stress from treated specimens prepared and cured in laboratory have the same order of magnitude. It can be thus concluded that the treated soil was altered on the first two meters of the backfill, while the inner part performance is comparable to what has been observed after curing at constant moisture content in the laboratory.

The degradation that is observed on the outer part of the backfill can be partly explained by moisture content variations that are known to alter the behaviour of stabilised soils (Guney et al., 2007; Consoli et al., 2017; Liu et al., 2019). Indeed, the monitoring of the backfill showed that the moisture content variation was limited to the first tens of centimeters from the edge of the backfill (Bicalho et al., 2015). Freezing/thawing cycles over the years could have explained the degradation of the performances (Dempsey and Thompson, 1967; Consoli et al., 2017; Lu et al., 2020). However, *in situ* thermal sensors installed at 0.25 m from the surface did not evidence any temperature below 0°C (Bicalho et al., 2015). Other hydro-chemical processes like carbonation, temperature or water leaching could also have led to the degradations observed here, but complementary analyses are required to confirm their potential contribution.

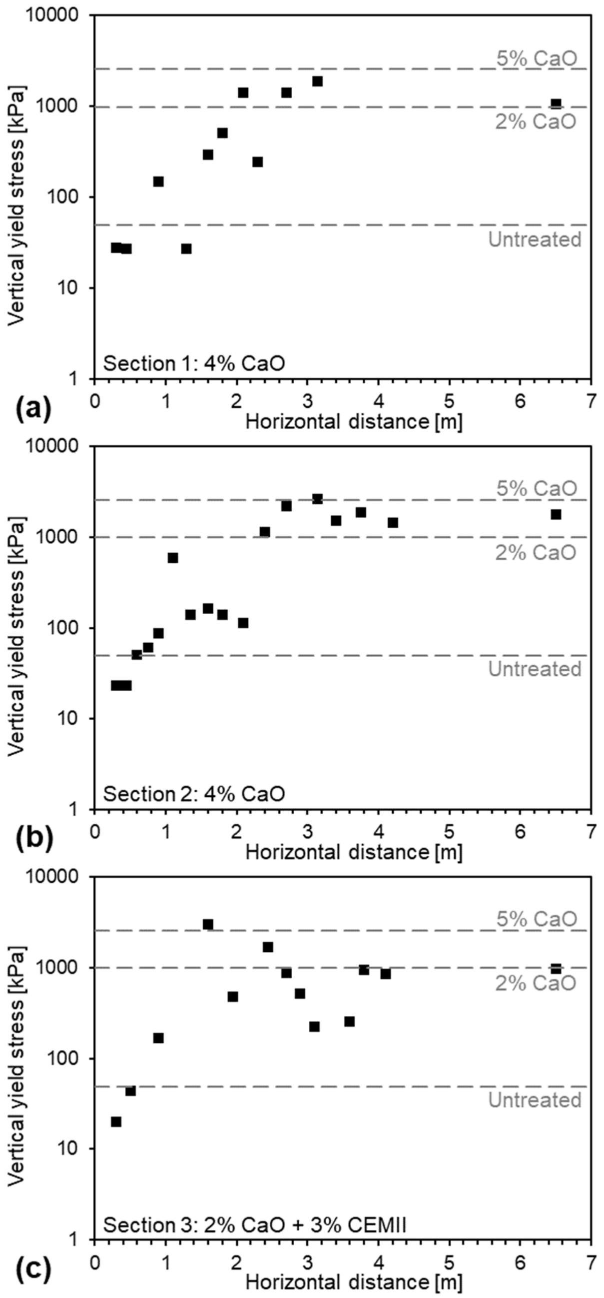

Figure 4. Yield stress of specimens taken from various horizontal distances of the three different sections and compared to the yield stress of the untreated clayey soil, and to the yield stress of specimens treated in laboratory at 2% and 5% lime.

7. Conclusions and perspectives

The objective of this study was to assess the *in situ* ageing and the treatment performances of an expansive clayey soil treated with lime and lime/cement. An existing embankment constructed in 2010 was sampled between the edge and the core of the backfill in 2021. The durability of the soil treated with 4% lime, and 2% lime/3% cement was evaluated with oedometer tests. The following conclusions were drawn from this study:

- The performance of the soil sampled beyond 2.00 m of horizontal distance was equivalent to the performance of the same soil cured in the laboratory at constant moisture content.
- The outer part of the backfill, between 0 and 2.00 m, appeared to be significantly altered compared to the inner part of the backfill. A progressive degradation of the performance from 2m towards the surface was detected. The behaviour of the specimen taken from the edge of the backfill was comparable to the behaviour of the untreated soil, indicating that the effect of treatment is no longer significant.
- The degradation can only be partly explained by moisture content variations that appeared to be limited to the first tens of centimeters of the backfill.
- The weathered area (from 0 to 2.00 m of horizontal distance) was identified on both sections treated with 4% lime. This weathered area was also found on section 3 of the embankment treated with 2% lime and 3% cement. These results suggest that both treatments led to a similar alteration process, and were not able to prevent the deterioration of the treatment effects.

These observations question the durability of the treatment at the edge of the embankment. The alteration process of the soil will be clarified in the future by micro-structural (mercury intrusion porosimetry) and physico-chemical (thermo-gravimetric analysis) analysis of the specimens sampled in the embankment. This multi-scale approach will provide a concrete methodology for predicting the durability of treated soil structures.

Acknowledgments

The project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 778120.

The authors are very thankful to Dr. Michel Khatib from Ginger CEBTP for his great scientific and technical support.

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