Impact of wetting/drying cycles on the hydromechanical behaviour of a treated soil

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Abstract. The positive effects of lime or cement treatment could be altered by weathering in the very long term. In this context, the main purpose of this study is to examine the impact of wetting/drying cycles on the strength and the hydraulic conductivity of a compacted soil treated with lime and cement. Compacted specimens were cured for 90 days before being exposed up to twelve wetting and drying cycles. A special concern of the study was the experimental method to impose the wetting and drying cycles. Two protocols were employed: one relied on relative humidity control to dry the samples, while the other was based on oven drying. The impact of the cycles was quantified by comparing the performance of the samples exposed to the cycles to the performance of the unsolicited samples. The results showed that the cycles induced a major alteration of the strength of the samples, with both methods. This degradation is associated to a significant increase of the hydraulic conductivity of the samples with the number of cycles.

1 Introduction

The main effects of lime / cement treatments are relatively well characterised. Several authors [1]–[3] showed that lime treatment improves the soil workability as well as the soil strength and elastic modulus. They also impact the hydraulic conductivity of soils depending the compaction conditions [2], limit the swelling potential of expansive soils [3], or improve soil resistance to erosion [4].

Beyond the performance obtained with a given treatment, an important concern is the evaluation of the alteration of the performances of the treated soil over the service life of the structure to be built. Some in situ investigations of lime stabilised roads showed qualitatively that exposure to climatic conditions can have a negative impact on the behaviour of stabilised soils in the long term [5]–[7]. This was also evidenced through laboratory studies that showed that successive wetting/drying periods [8], [9] may lead to a significant decrease of the treated soil hydromechanical characteristics. Thus, several concerns exist regarding the long term characteristics of the stabilised soil when exposed to climatic conditions.

In most of the existing studies, the wetting and drying cycles experimental protocol is derived from the ASTM D559 standard [10] where the soil samples are alternatively immersed in water, and then placed in an oven for complete drying [11], [12]. The alteration degree can be evaluated by measuring the loss in mass of the samples after each cycle, or by the determination of mechanical characteristics (strength, resilient modulus, etc.) as a function of the number of cycles. The beneficial effects of lime/cement stabilisation are partly lost once the mixture has been subjected to several wetting/drying cycles. However, this protocol rises several questions since it can appear relatively severe compared to the field conditions a treated soil can be exposed to. Indeed, during such cycles, the water content of the sample fluctuates between full saturation and totally dry state. Immersion in water may result in the progressive leaching of the treatment product out of the tested sample with a detrimental impact of long-term performance [13]. Moreover, the high temperature the soil is exposed to in an oven could impede the results. First, the setting reactions are influenced by the temperature [14] and, secondly, it is also known that significant alteration of soil microstructure is associated to oven drying, especially compared to other methods of drying [15]. Tang et al. [16] showed that the bonding induced by lime-treatment are progressively altered by successive wetting and drying cycles. Therefore, a significant additional degradation of soil performance may result from a drying phase applied at elevated temperature. Moreover, some authors suggested a positive relationship between the amplitude of the wetting and drying cycles and the degree of alteration of the performance [5], [17]. Therefore, employing an aggressive method may lead to over-conservative conclusions on the long term performance of a given stabilised soil exposed to wetting and drying cycles.

In this context, the objective of this study was to evaluate impact of the wetting and drying protocol on the hydromechanical behaviour of a lime or cement stabilised silty soil. Successive wetting and drying cycles were imposed to treat samples with two different protocols. The first one was derived from the ASTM D559 standard. The second one was based on the control of the suction imposed to the samples at room temperature, to thus
obtain more realistic conditions for the wetting and drying cycles. Such more realistic experimental protocol would permit to evaluate the alteration of the performance over time with the accumulation of wetting and drying cycles. The unconfined compressive strength (UCS) and saturated hydraulic conductivity were monitored as a function of the number of cycles.

2 Tested soil and samples preparation

The soil selected to perform this study was sampled in Northern France (Table 1). This soil can be classified as ML following the Unified Soil Classification System Quicklime (1 and 3%) and cement (3 and 6%) were selected as the treatment products. The product dosages were calculated on a dry soil weight basis. The quicklime selected as the treatment products. The product dosages determined for each type and percentage of treatment were mixed together in a mechanical mixer during a few minutes. The compaction curves were determined for each type and percentage of treatment (Table 2).

The optimum water content and the maximum dry density for each soil for each treatment dosage were determined. In a first stage, the moisture content was set to the target value for compaction. A storage period of 24h prior use was required to reach homogenisation of the moisture content of the soil. Then, the wet soil and the treatment product were mixed together in a mechanical mixer during a few minutes. The compaction curves were determined for each type and percentage of treatment (Table 2).

The investigations were focused on one specific compaction state for each treatment and each percentage corresponding, on the wet side of the optimum moisture content (OMC). This state was defined by $w = w_{OMC} + 3\%$ and $\rho_d = 0.96 \rho_{max}$, depending on the nature and percentage of each treatment, where $w$ is the compaction moisture content (%), $w_{OMC}$ is the optimum moisture content (%), $\rho_d$ is the dry density (Mg/m$^3$) and $\rho_{max}$ is the maximum dry density (Mg/m$^3$) (Table 2).

The soil samples employed for strength and permeability determination, untreated and treated, were statically compacted by static axial compression in a cylindrical mold to the target dry density (Table 2). The initial height of the samples was 70 mm with a diameter of 35 mm. After treatment and compaction, the soil specimens were sealed in airtight bags and cured at 20°C during a period of 90 days prior to use.

3 Wetting and drying cycles protocols

Two experimental protocols were employed to impose the wetting and drying cycles. The first one is derived from the ASTM 559 standard. Samples, after the selected curing period, were successively immersed in water for two days, and then oven dried at 60°C for another two days. This method is denoted AG in the paper.

The second method employed a climatic chamber (SECASI technologies SH-600 ©) to impose the drying phase to the sample under a relative humidity of 54 % and a temperature of 20°C. This humidity was selected as it corresponds to the mean relative humidity that can be reached in summer in the Northern part of France. The wetting phase was applied by capillary rise: the samples were placed over a porous stone in contact with demineralised water in a closed chamber, the temperature being maintained at 20°C and the relative humidity of the chamber close to saturation. To ensure homogeneity of the samples, they were periodically turned back during the wetting phase. One wetting and drying cycle lasted approximately 25 days. This method is denoted HR in the remaining of the paper. The temperature was kept at 20°C to avoid any impact of temperature modification on the long term behaviour of the samples with that protocol.

In both cases, the mass of the samples was checked at the end of each phase and their dimensions measured. Only samples without a dry mass loss lower than 5% compared to the initial state were employed for strength and permeability analysis.

4 Determination of mechanical and hydraulic characteristics

The hydromechanical characteristics were determined after the exposure of the samples with the two above mentioned protocols. Unconfined compressive strength UCS was determined with a displacement rate of 1.04 mm.min$^{-1}$. For each combination of parameters, three samples were tested in this case. The results provided in the following figures are the mean of the three values.

Saturated hydraulic conductivity was determined in flexible wall permeameters connected to three pressure
volume controllers installed in a temperature-controlled room. This technique was used to limit preferential flow paths along the sample, especially after the wetting and drying cycles. The protocol developed to ensure full saturation of the samples is described in [4]. The inflow and outflow were also carefully monitored. The final degree of saturation, after the test, was determined and was always higher than 98.5%. One complete hydraulic conductivity determination test lasted about a month.

5 Experimental results

5.1 Impact on strength

The strength of the untreated soil was determined as a reference. It is equal to about 145 kPa. The treatment by lime increased the strength up to 340 and 480 kPa with 1 or 3% of lime respectively after 90 days of curing at constant water content. With 3 or 6% of cement, the strength after 90 days of curing was equal to 820 and 1575 kPa respectively. Those values correspond to the strength measured at 0 cycles in Fig. 1.

The samples were submitted to the wetting and drying cycles after 90 days of curing at constant water content. The results were plotted as a function of the number of cycles (Fig. 1). For both treatments, the cycles induced a significant reduction of the strength of the treated samples. The strength reduction depends on the technique employed to impose the cycles but it is also a function of the amount of treatment product. The AG method in the case of the 1% lime treatment led to the destruction of the sample after a couple of cycles, while the lime-treated samples with 1% of lime were able to sustain 12 wetting and drying cycles with the HR method. The UCS reached a stable value after 6 cycles with the HR method. In the case of the cement treated samples, it can be seen that the cycles reduced the strength of the samples. However, with the HR cycles, the strength reached a stable value after 6 wetting and drying cycles. With the AG-method, the samples exhibited a continuous decrease as a function of the number of imposed cycles.

The strength of the samples was normalised respectively to the strength of the samples after 90 days of curing, i.e. strength reached by the samples before the beginning of the wetting and drying cycles (Fig. 2). This approach allowed to compare quantitatively the strength reduction associated to each wetting and drying protocol. The AG protocol induced a significantly higher strength reduction compared to the HR method, for all the cases considered in this study. The HR induced a significant strength reduction, but the degradation stopped after three to six cycles. In the case of the AG method, a continuous decrease of the strength was observed.

The detrimental effect of the wetting and drying cycles was also quantified (Fig. 2). The strength after the wetting and drying cycles can be compared to the strength of the samples that have been cured at constant water content. The wetting and drying cycles started after 90 days of curing at constant water content. As an example, the strength of the samples treated with 6% of cement increased by about 30% between 90 and 260 days when the samples were cured without being exposed to cycles.

When exposed to wetting and drying cycles, the samples strength was reduced by about 50% with the HR cycles, and by about 70% with the AG cycles.

The impact of the wetting and drying cycles was quantified relatively to the performances of the treated soil cured at constant water content, without being exposed to wetting and drying cycles and kept up to 300 days at constant temperature, wrapped in plastic to avoid any loss or gain of water exchange with the atmosphere. This comparison must take into account the time required to impose the different cycles since 4 days are required for the method AG while 25 days are necessary for HR method. Therefore, the results were plotted as a function of the number of wetting and drying cycles.

![Fig. 1](https://example.com/fig1.png)  
**Fig. 1.** Evolution of strength as a function of the number of wetting and drying cycles.
5.2 Impact on hydraulic conductivity

The hydraulic conductivity of the untreated soil increased from $6.0 \times 10^{-9}$ m/s up to $5.0 \times 10^{-8}$ m/s after the imposition of 6 HR cycles. The hydraulic conductivity remained stable between 6 and 12 cycles. It was not possible to determine the hydraulic conductivity with the AG method, the sample being too much damaged even after one cycle of wetting and drying.

The hydraulic conductivity of the samples treated with 1% of quicklime was equal to $9.0 \times 10^{-9}$ m/s, after 90 days of curing (Fig. 3). After 300 days of curing, no significant modification of the hydraulic conductivity was observed. The imposition of the cycles with the RH method led to a progressive increase of the permeability up to $6.0 \times 10^{-8}$ m/s after 6 cycles, the permeability remained stable between 6 and 12 cycles. After the first cycle with the AG-method, the results showed an increase of the permeability after the first wetting and drying cycle. Additional cycles led to a dramatic degradation of the sample, proper measurement of the permeability was thus no longer possible because the samples were damaged.

A significant increase of the hydraulic conductivity up to $2.0 \times 10^{-7}$ m/s was observed after 6 cycles of wetting and drying performed with HR method. No loss of mass or modification of dimensions was evidenced during the cycles. The samples did not exhibit any external sign of damage. With the AG wetting and drying protocol, an increase of hydraulic conductivity was observed even after the first cycle up to $4.80 \times 10^{-8}$ m/s, and remained almost constant up to 6 cycles. It was not possible to determine the hydraulic conductivity beyond 6 wetting and drying cycles.

The hydraulic conductivity of the samples treated with 3% of cement was equal to $2.0 \times 10^{-9}$ m/s. The hydraulic conductivity increased progressively by more than one order of magnitude after the imposition of 12 cycles with the RH method, without any sign of external degradation of the samples. The wetting and drying cycles with the AG method induced similar increase of the hydraulic conductivity after 6 cycles, up to $2.1 \times 10^{-8}$ m/s. It was not possible to determine the hydraulic conductivity for a larger number of cycles because of the degradation of the sample. This degradation might explain the dispersion in the results that was observed after 3 and 6 cycles.

After 90 days of curing the hydraulic conductivity of the samples treated with 6% of cement was lower than $10^{-9}$ m/s. The imposition of the cycles with the HR method is associated to a progressive increase of the hydraulic conductivity of the treated soil up to $4.9 \times 10^{-8}$ m/s, after 12 cycles. Similar trend was observed consequently to the imposition of the cycles with the AG, the hydraulic conductivity was equal to $2.0 \times 10^{-8}$ m/s after 12 wetting and drying cycles. In both cases, the cycles induced an increase of the permeability without any significant external degradation of the samples or loss of mass over the cycles.

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**Fig. 2.** Normalised strength (% as a function of time since sample preparation for (a) lime-treated and (b) cement treated samples. The wetting/drying cycles started after 90 days of curing at constant water content.
samples by a progressive alteration of the soil microstructure [11], [16], [22], i.e. the cementation between the particles. This impact of the cycles on the microstructure of the soil, might also be connected to the fact that the samples were initially prepared at a moisture content on the wet side of the optimum moisture content, to minimise the initial saturated hydraulic conductivity of the samples. Indeed, some authors showed that, for untreated compacted soils, the higher the water content, the more important the micro-structural modifications induced by drying [23], [24].

The results also allow to evaluate the impact of the wetting and drying protocols. The results showed that the AG-cycles tend to induced a significantly higher degradation of the samples. However, the impact of the method of imposing cycles is closely related to the dosage of the treatment product. Indeed, with the lowest dosages in lime and cement, the AG-method led to the complete destruction of the samples, the performances being impossible to determine. However, samples treated under the same conditions but submitted to wetting and drying, with the HR method degraded but evidenced signs of stabilisation of the performances, for both strength and hydraulic conductivity. As an example, samples treated with 3% of cement started to be dramatically altered after 6 cycles, while the strength remained almost constant between 3 and 12 cycles. Optimisation of the treatment product dosage implies to limit the amount of treatment product to reach and maintain the design performance. Employing the AG-method may lead to an underestimation of the long term performance.

7 Conclusion

The long term performance of a stabilised compacted soil was studied by its exposition to repeated wetting and drying cycles employing different protocols. The results showed that the exposure to wetting and drying cycles with both experimental protocols AG and HR has a negative impact on the strength of a treated soil as well as on its hydraulic conductivity. Both methods employed for wetting and drying are able to provide an evaluation of the performance alteration as a function of the number of cycles. However, the method based on oven drying and full immersion appeared to be conservative, since it conducted to the destruction of the samples treated with a smaller amount of treatment product while using the HR wetting and drying method. The results also showed that the degradation of the treated samples strength is associated to an increase of up to two orders of magnitude of the hydraulic conductivity.

This study shows that assessing method to study the impact of wetting and drying cycles on mechanical and hydraulic behaviour of a stabilised soil is of primary importance since it can induce a dramatic alteration of the behaviour. The relevance of the experimental protocol employed to reproduce the cycles in the laboratory must be carefully evaluated since it could lead to over-conservative conclusions, or to the selection of a higher dosage of treatment products.

6 Discussion

The results evidenced a positive relationship between the strength degradation and the relative increase of hydraulic conductivity, after the wetting and drying cycles, for both AG and HR protocols. On one hand, it is known that the silty soil micro-structure is dramatically altered by cyclic moisture content modification [3], [15], [18], the soil hydraulic conductivity being directly impacted by these modifications of the micro-structure [19]–[21]. On the other hand, some authors explained the impact of wetting and drying cycles on the performance of lime-treated

Fig. 3. Evolution of hydraulic conductivity as a function of the number of time since the preparation of the samples (a) lime-treated samples and (b) cement treated samples (all cycles started after 90 days of curing).
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