Impact of weathering on a cement-treated sand

Alice Wassermann[1#], *Adel* Abdallah[1], and *Olivier* Cuisinier[1]

[1] *Université de Lorraine, LEMTA, UMR 7563 - Université de Lorraine - CNRS - LEMTA – Nancy - France*
[#]*Corresponding author: alice.wassermann@univ-lorraine.fr*

ABSTRACT

This study's main goal was to examine how the wetting/drying solicitations affect the mechanical behavior of a cement-treated sand. A quantitative method based on the stress-dilatancy approach was used to assess the effects of two types of wetting and drying cycles of different intensities. The results showed that bonding is primarily altered by the wetting/drying cycles, leading to lower mechanical performances. It has been demonstrated that the weathering effect not only depends on the cement dosage, but also on the cycles' intensity. The early cycles appeared to have the greatest impact on changes in mechanical performance on the samples treated with 4% cement. However, the accumulation of numerous cycles caused a more progressive degradation on the samples treated with 1% cement. The quantitative assessment of the treatment effect and the weathering progress with cycles was made possible through the evaluation of the bonding ratio. The importance of the imposed wetting/drying cycle protocol for a proper evaluation of the long-term performance of treated soils is highlighted. Further research is needed to define an appropriate weathering protocol that makes sense in light of the real solicitation faced by engineered structures.

Keywords: soil stabilization; triaxial tests; wetting and drying cycles; bonding ratio.

1. Introduction

Several authors (e.g., (Brandl 1981) and (Bell 1996) have shown that soil treatment with lime and/or cement generally improves soil characteristics such as workability, uniaxial compression and shear strength. A key question is how the performance of treated soils changes over the lifespan of the structure due to external solicitations. Some in-situ studies of lime-stabilized pavement structures have qualitatively shown that exposure to climatic conditions could have a negative impact on the long-term behavior of stabilized soils (e.g., (Kelley 1988). This has also been highlighted by laboratory studies that have shown that successive wetting/drying cycles (Khattab, Al-Mukhtar, and Fleureau 2007); (Chittoori et al. 2008) or repeated freezing/thawing periods (e.g., (Consoli et al. 2017), can lead to a significant decrease of the hydromechanical characteristics of treated soils. The durability of the performance of treated soils is therefore essential to consider in the design process of such structures, and it is of primary interest to understand the impact of climatic conditions on the long-term behavior of stabilized soils. The objective of this study is to assess the impact of thermo-hydric solicitations on the mechanical behavior of a treated soil.

Several methods of imposing wetting/drying cycles are listed in the literature, depending on the duration of the drying and wetting phases, their intensity (e.g. by increasing the temperature during drying), and the wetting method (capillary action, immersion, etc.). However, many studies are based on the D559 standard (ASTM 2015) which recommends for each cycle, 5h of immersion in water at room temperature and then 42h in an oven at 71°C. Some authors have shown the impact of cycle intensity on the extent of specimen weathering. For example, (Cuisinier and Masrouri 2020) found that the extent of the decrease in uniaxial compression strength was a function of the technique for imposing cycles, the dosage and the type of treatment. They also showed a negative impact of the cycles on the hydraulic conductivity of the samples. Beyond the experimental protocol for imposing the cycles, a fundamental aspect is the quantification of the mechanical effects of these cycles. Most studies available in the literature have based their analysis on tracking sample mass loss or uniaxial compression strength as a function of the number of the cycles applied ((Packard and Chapman 1963); (Mehenni 2015); (Cuisinier and Masrouri 2020). However, these macroscopic indicators do not provide insight into the degradation process associated with cycling. A more refined understanding of the behavior of treated soils and in particular the degradation mechanisms is needed. An essential point is the quantification of inter-particle bonds associated with treatments. Two approaches can be found in the literature. The first one is based on an explicit quantification of the cementitious products according to the treatment conditions. This quantification can be achieved by chemical or microstructural analysis methods. In a few studies, the relationship between mechanical characteristics and the amount of cementitious products was investigated (e.g., (Chiu, Zhu, and Zhang 2009); (Dadda et al. 2019). The second approach quantifies the bonding effect indirectly through the analysis of the mechanical behavior. In this case, the behavior of the untreated soil is generally taken as a reference (e.g., (Leroueil and Vaughan 1990). For example, triaxial test results were interpreted using the stress-dilatancy theory of (Rowe 1962) and (Cuccovillo and Coop 1999) by (Wang et al. 2021) to compare the mechanical behavior between biocement-treated sand

and CEM I-treated sand. In particular, this approach analyzed the development of dilatancy and mobilization of cementitious bonds by introducing a bonding ratio, η_{bond}.

The literature review showed that the understanding of the degradation mechanisms of treated soils exposed to weathering cycles remains an open question. The objective of this paper is to study the impact of the type and number of cycles on the mechanical behavior of a cement-treated sand, the bonding ratio η_{bond} will be taken as an indicator of the degradation. First, the materials and methods as well as the experimental program will be presented. Then, the results will be divided into two parts: (i) the effects of the hydric cycles on the stress-strain behavior and (ii) the effects on the bonding ratio. Finally, the outcomes of the study will be discussed.

2. Materials and methods

2.1. Tested materials

The selected soil is a sand sampled in the eastern part of France. It has been classified as an S1-type soil according to the French classification system (AFNOR 2018) and an SW soil according to the Unified Soil Classification System (Table 1).

Table 1. Geotechnical properties of the sand

Properties	Values
Maximum /minimum void ratio	0.69 / 0.52
Maximum diameter, D_{max} (mm)	4
Uniformity coefficient, Cu	5.88
Curvature coefficient, Cc	1.24

The cement used in this study is Portland cement (CEM I 52,5 N) containing at least 95% clinker. The specific gravity considered for this type of cement is 3.15. Compressive strength tests on this cement showed that 97% of the maximum strength is reached after 7 days, as per the NF EN 196-1 standard (AFNOR 2016). A cement setting test was also performed, and the measured setting time was 2 h 50 min (AFNOR 2017).

2.2. Experimental processes description

2.2.1. Triaxial tests

A triaxial device was used to perform consolidated and drained (CD) tests. To control the saturation of the specimens, a back pressure is applied to achieve a Skempton B-value greater than 0.95. The selected shearing speed is 0.1/mm.min^{-1}. The volumetric variations are estimated by the water variations in the sample and measured with a pressure-volume controller. The use of internal sensors was not compatible with the brittle and friable character of the sand specimens with a low cement dosage.

2.2.2. Wetting/Drying cycles

Two different types of wetting/drying cycles were employed to investigate the impact of cycling intensity on mechanical behavior.

The type I cycle derives from the one proposed by (ASTM 2015). The humidification process involves immersing the samples in water at room temperature for 8 hours. Then, the samples are placed for 16 hours in an oven at 65°C for the drying phase.

The type II cycle is based on previous work (Stoltz, Cuisinier, and Masrouri 2014); (Mehenni 2015). The humidification process is similar to the type I cycle but the phase lasts 48 hours. This method uses a climate chamber (SECASI technologies SH-600 ©) to impose the drying phase on the sample under a relative humidity of 50% and a temperature of 20°C for 5 days. This humidity was chosen because it corresponds to the average relative humidity that can be reached in summer in the northern part of France.

Thus, the type I cycle is a rather intense cycle whereas the type II cycle corresponds to moderate intensity conditions that may be more representative of the real conditions experienced by the structures.

2.3. Quantification of the bonding ratio

The approach developed by (Cuccovillo and Coop 1999), based on the work by (Rowe 1962) and the Cam-Clay model, makes it possible to express the total work dissipated during the shearing of a soil into a pure friction component and another one related to the progressive degradation of the cementitious bonds between the soil grains. In this context, we can write:

$$\Delta W = \Delta W_{fric} + \Delta W_{bond} \quad (1)$$

With ΔW_{bond} the energy loss due to cement bond failure, ΔW_{fric} the energy loss due to friction, ΔW the total work of a processed soil sample subjected to shear. Under axisymmetric conditions, the total work can be written:

$$\Delta W = q\delta\varepsilon_s^p + p'\,\delta\varepsilon_v^p \quad (2)$$

In the theoretical framework of the Cam-Clay model, ΔW_{fric} can be written:

$$\Delta W_{fric} = Mp'\,\delta\varepsilon_s^p \quad (3)$$

Equation (1) can be rewritten:

$$q\delta\varepsilon_s^p + p'\delta\varepsilon_v^p = Mp'\,\delta\varepsilon_s^p + \Delta W_{bond} \quad (4)$$

Or:

$$\text{So } \frac{q}{p'} = M - \frac{\delta\varepsilon_v^p}{\delta\varepsilon_s^p} + \frac{\Delta W_{bond}}{p'\delta\varepsilon_s^p} \quad (5)$$

These equations show that the stress ratio $\eta = \frac{q}{p'}$ at the critical state depends on 3 components: the slope of the critical state line M, the expansion ratio $d = -\frac{\delta\varepsilon_v^p}{\delta\varepsilon_s^p}$, and the energy dissipation due to the destruction of cementitious bonds, the bonding ratio.

The bonding ratio ηbond is calculated via equation (6):

$$\eta_{bond} = \frac{\Delta W_{bond}}{p'\delta\varepsilon_s^p} = \frac{q}{p'} - M + \frac{\delta\varepsilon_v^p}{\delta\varepsilon_s^p} \quad (6)$$

With p' the average effective stress and $\delta\varepsilon_s^p$ the increment of plastic shear strains. Thus, equation (7) can be written:

$$\eta = M + d + \eta_{bond} \quad (7)$$

Further details about this approach to quantify the cementitious bonds are available in (Wassermann, Abdallah, and Cuisinier 2022).

2.4. Experimental program

Specimens treated with 1, 2 and 4% cement were subjected to wetting and drying cycles. Triaxial tests were performed under a confining pressure of 100 kPa. Six tests were duplicated to check the repeatability of specimen preparation and testing procedure.

3. Results and discussion

3.1. Impact of the cycles on the stress-strain behavior

The effect of the two types of cycles was first studied on the stress-strain and volume strain curves for a cement content of 1%. A control specimen, which was not exposed to the hydric cycles, was used as a reference to assess the extent of the degradation. The maximum deviatoric stress, q_{max}, of the control specimen is about 590 kPa.

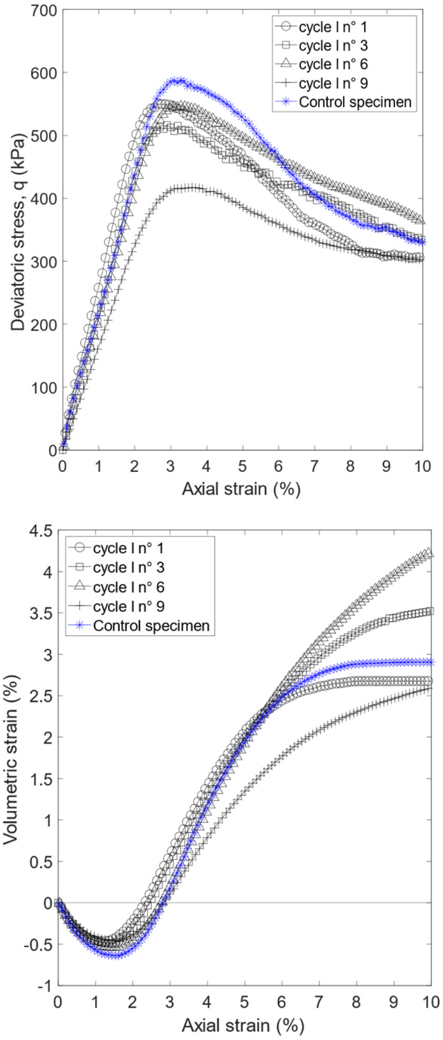

Figure 1. Stress-strain and volumetric strain curves for sand treated with 1% of cement under 100 kPa of confining pressure after type-I cycles.

This peak strength decreased with type I cycles, the maximum deviatoric stress decreases by about 30% (Figure 1.) during these cycles versus only 12% after type II cycles (Figure 2). The E_{50} modulus decreases after 6 type I cycle while it remained stable after 9 type II cycles. Type I cycles do not seem to modify the volumetric behavior for specimens treated with 1% cement till the 9th cycle for which the dilatancy angle decreases (Figure 1). The maximum of dilatancy seemed to be delayed in the case of type II cycles (Figure 2).

For specimens treated with 4% cement, the control specimen has a q_{max} of about 1550 kPa. The maximum deviatoric stress, q_{max} is reduced by about 27% with type I cycles (Figure 3). For type II cycles (Figure 4), there are variations in strength (-18%). Cycles I have no significant effect on the E_{50} modulus and cycles II do not allow to detect any clear trend on strength evolution. The volumetric behavior is modified for specimens treated with 4% cement after type I cycles (Figure 3) mainly by decreasing dilatancy angle. Dilatancy seems not to be modified after the type II cycles (Figure 4).

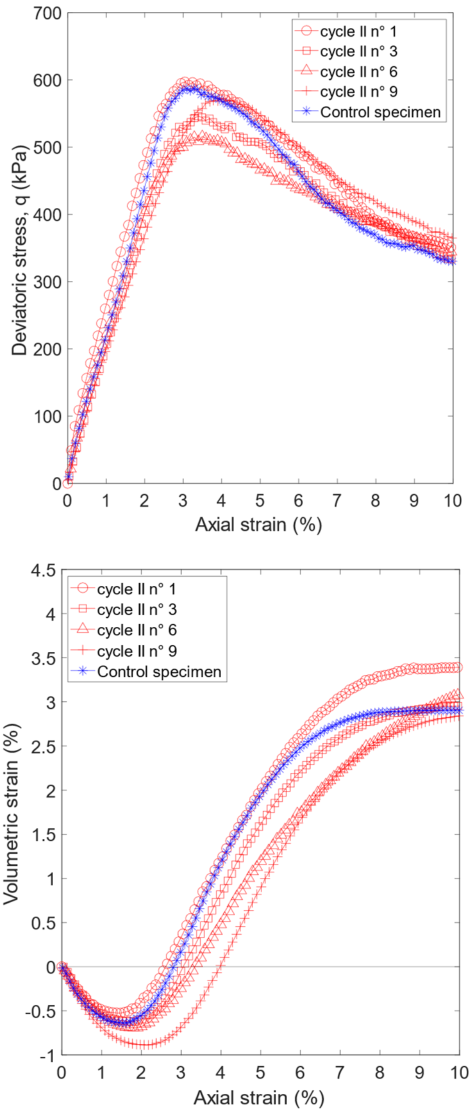

Figure 2. Stress-strain and volumetric strain curves for sand treated with 1% of cement under 100 kPa of confining pressure after type-II cycles.

3.2. Impact of the cycles on the bonding ratio

The bonding ratio (equation 5) allows to estimate the mobilization of the cementitious bonds during shearing. The maximum value of the bonding ratio indicates the maximum mobilization of the bonds upon shearing. Total destructuration is achieved when the bonding ratio returned to 0. The control specimen treated with 1% cement shows a maximum η_{bond}, of about 0.6 while the control specimen treated with 4% cement reaches a maximum η_{bond} of about 1.8. Figure 5.a. shows that type I cycles lower the maximum η_{bond} for a specimen with 1% cement. In contrast, type II cycles (Figure 5.b) do not really seem to decrease the maximum η_{bond} and no clear trend can be identified. For specimens treated with 4% cement, the same observations can be made. Type I cycles reduce the maximum η_{bond} by about 30% (Figure 6.a.) while no clear trend is noticeable for type II (Figure 6.b) cycles (-15% but not related to the accumulation of the number of cycles).

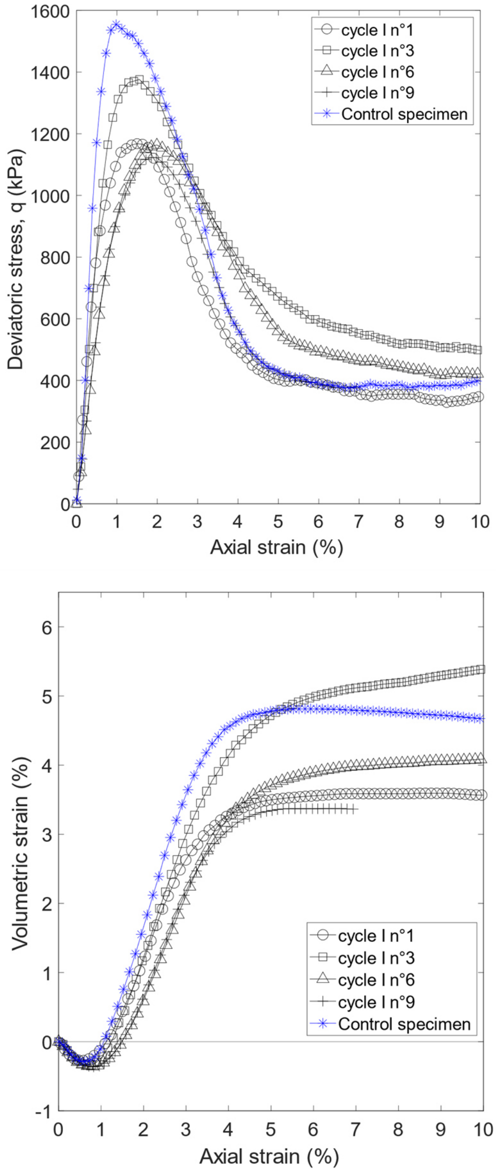

Figure 3. Stress-strain and volumetric strain curves for sand treated with 4% of cement under 100 kPa of confining pressure after type-I cycles.

3.3. Discussion

This study highlighted the effect of cement content, hydric cycle type, and number on mechanical behavior. Hydric cycles induced a decrease of the maximum bonding ratio and of the maximum deviator stress. This effect can be evidenced by plotting the stress-dilatancy curves and comparing the control specimens with those submitted to 9 cycles of each type. The maximum η_{bond} changes for type I cycles and in the case of 1% cement dosage from 1.2 to 0.75, and the yield point is reached for a lower stress ratio. The observations are similar for the 4% cement dosage to a lesser extent. The range of the maximum dilatancy ratio is 1.7 to 1.97. It can be seen that the type II cycles have no significant impact on the maximum dilatancy, the maximum deviator stress, or the yield point for specimens treated with cement to 1% (Figure 7.a) and 4% (Figure 7.b).

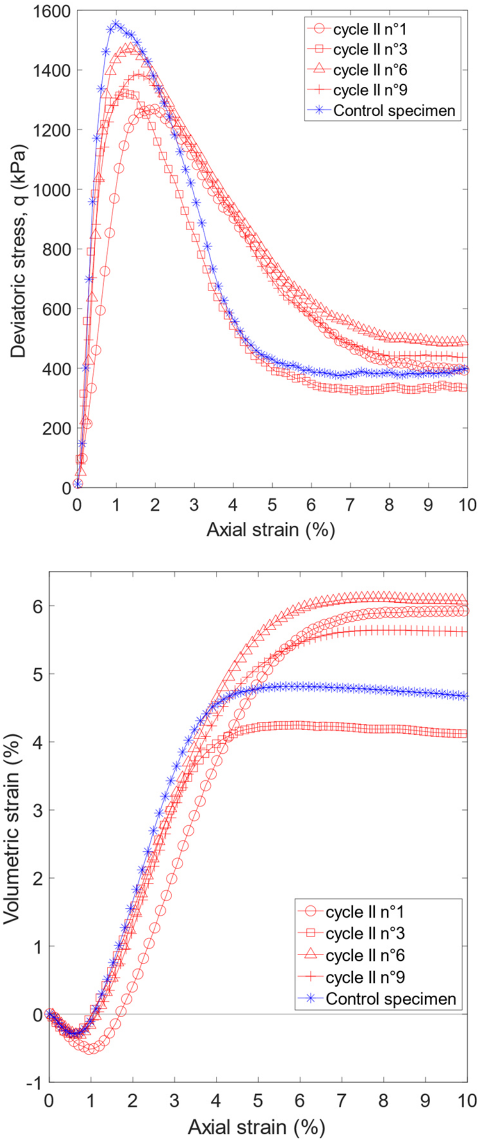

Figure 4. Stress-strain and volumetric strain curves for sand treated with 4% of cement under 100 kPa of confining pressure after type-I cycles.

The control specimen had a bonding ratio of 0.6, 1.4 and 1.8 for 1%, 2% and 4% of cement respectively. The bonding ratio decreased with the number of type I cycles while being unaffected on the long term by type II cycles (Figure 8). Type II cycles result in a very minor alteration. The degradation of bonding started after the 9th cycle for specimens treated with 1% cement, but only after one cycle for specimens treated with 4% cement as previously observed for the maximum strength.

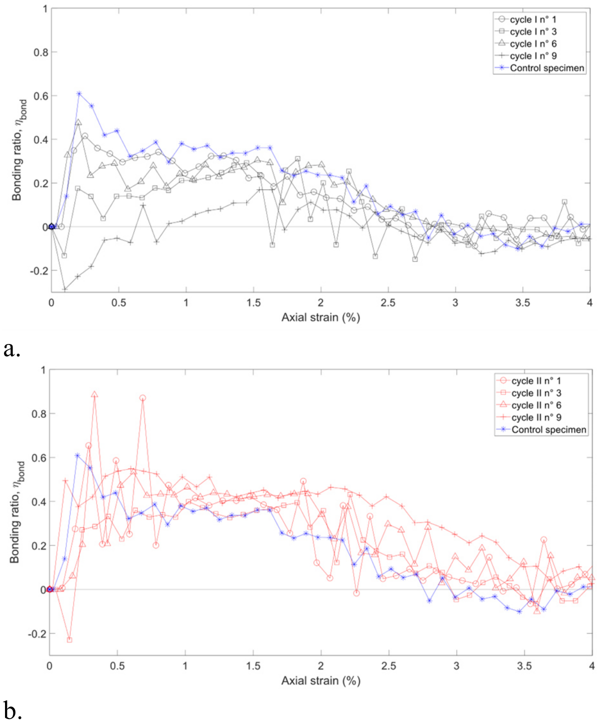

Figure 5. a and b: Influence of the type and the numbers of wetting-drying cycles on the bonding ratio for sand treated with 1% of cement under 100 kPa of confining pressure.

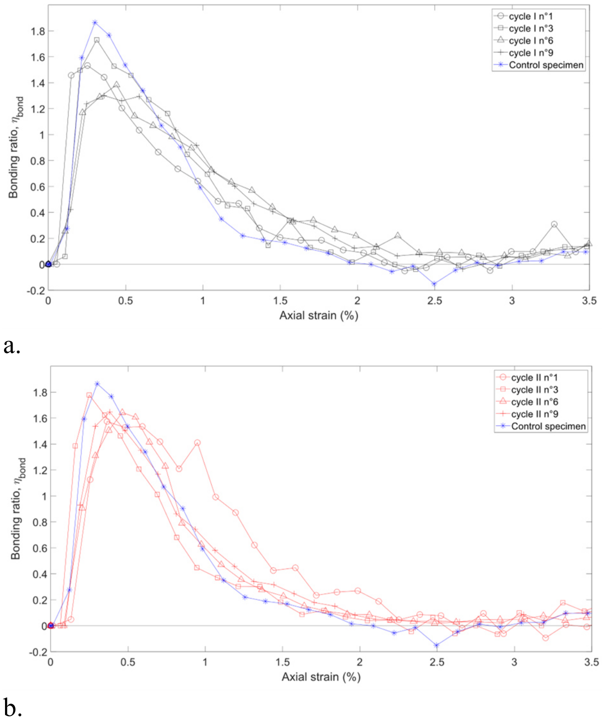

Figure 6. a and b: Influence of the type and the numbers of wetting-drying cycles on the bonding ratio for sand treated with 4% of cement under 100 kPa of confining pressure.

The mechanical behavior of the samples treated with 2% of cement was close to the one observed with 4% of cement. The third first cycles seem to condition the alteration. With increasing cycle number, the contrast between the bonding ratio after cycles of varying intensities grows. The analysis of the bonding ratio also showed that because of the significant noise found in the data, it was more challenging to interpret the results for 1% than for 2 and 4%.

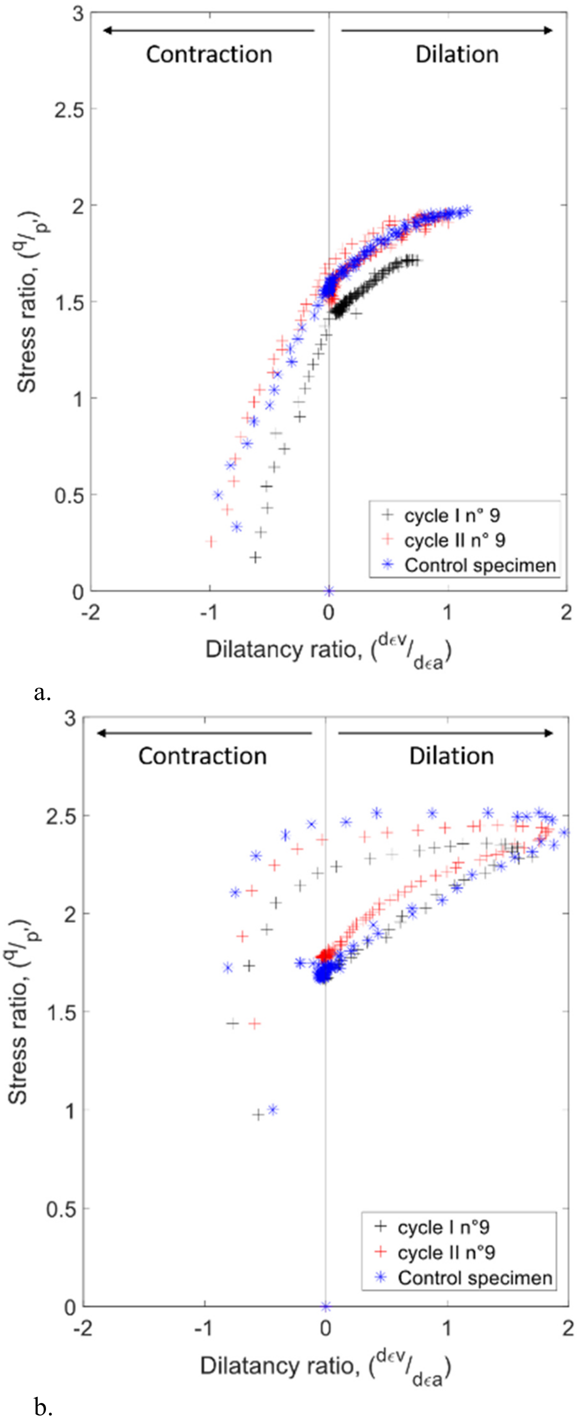

Figure 7. Stress ratio (q/p') as a function of the dilatancy ratio (d) a. 1% of cement b. 4% of cement.

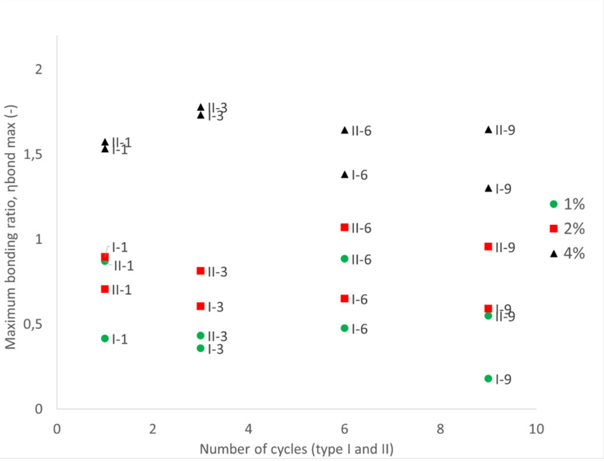

Figure 8. Bonding ratio as a function of the type of cycles and the number of cycles for 1%, 2% and 4% cement content.

It can be seen from the results on the three cement contents that after the first three cycles the value of the maximum deviatoric stress may be higher than the value of the control specimen. This finding relates to type II cycles. This is consistent with the results by (Consoli et al. 2018) who reported that cement-treated sand's UCS tends to increase during the initial cycles. The mass loss and moisture content throughout all the cycles was monitored. The observed trend is similar to the one reported by (Consoli et al. 2018) obtained on a nonplastic silt stabilized with Portland cement. For all dosages and both cycle types, the moisture content was higher during the initial cycles. After the two different types of cycles, the mass loss for the samples treated with 4% was identical. After the type-I cycles, there is an additional 1% mass loss for the samples that were treated with 1%. During the first three cycles, the moisture content was always higher before stabilizing during the late cycles. For both types of cycles, the variation for 4% cement is between 5% (dry phase) and 11% (wet state). For 1%, type I cycles' variations range from 6% to 15%, and type II cycles' variations range from 6% to 12%. The parameters that differ between the two types of cycles are their duration, but primarily the drying phase's heat. A few studies (e.g., (Salih and Maulood 1988); (Bachmann et al. 2021) have assessed the effect of temperature on several parameters such as wettability of the samples or modulus at failure. It has been shown that high temperatures (during wetting or drying phases) affect the samples and reduce the strength. Exposing the samples to water and heat is most likely to reactivate the cement hydration reactions and so the physico-chemical processes, leading to the creation of new bonds and an increase in the soil strength (Stoltz, Cuisinier, and Masrouri 2014); (Lemaire et al. 2013).

4. Conclusions

This study evaluated the impact of the intensity and number of hydric cycles on the durability of the performance of cement-treated samples after the imposition of several wetting/drying cycles of two different intensities. This evaluation is based on a stress-dilatancy approach and in particular on the bonding ratio which measures the gain in mechanical performance brought by the treatment.

The main effect of the drying-wetting cycles is to alter the cementitious bonds, and subsequently the mechanical behavior. This alteration depends on the cement dosage but also on the intensity and the number of cycles. Indeed, type I cycles (high intensity), lead to a greater degradation than type II cycles (moderate intensity) whatever the cement dosage. For specimens treated with 4% cement, the early cycles seem to bring the most significant alteration of mechanical performances whereas with 1% cement, the accumulation cycles effect leads to a more progressive degradation. The bonding ratio allowed to quantify the impact of the treatment and its evolution with the cycles. However, it should be noticed that the interpretation of this ratio is difficult with the lowest cement dosage due to some scattering data linked to the method used for volume variation measurement.

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References

AFNOR. 2016. “NF EN 196-1 : Méthodes d’essais Des Ciments - Partie 1 : Détermination Des Résistances.” AFNOR Editions.

AFNOR. 2017. “NF EN 196-3 : Méthodes d’essai Des Ciments - Partie 3 : Détermination Du Temps de Prise et de La Stabilité.” AFNOR Editions.

AFNOR. 2018. “NF EN 16907-2: Terrassement — Partie 2 : Classification Des Matériaux.” AFNOR Editions.

ASTM. 2015. “D559/D559M − 15 : Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures.” ASTM International.

Bachmann, J., S. Söffker, N. Sepehrnia, M.-O. Goebel, and S. K. Woche. 2021. “The Effect of Temperature and Wetting–Drying Cycles on Soil Wettability: Dynamic Molecular Restructuring Processes at the Solid–Water–Air Interface.” *European Journal of Soil Science* 72 (5): 2180–98. https://doi.org/10.1111/ejss.13102

Bell, F.G. 1996. “Lime Stabilization of Clay Minerals and Soils.” *Engineering Geology* 42 (4): 223–37. https://doi.org/10.1016/0013-7952(96)00028-2

Brandl, H. 1981. “Alteration of Soil Parameters by Stabilization with Lime.” In , 587–94.

Chittoori, B. S., A. J. Puppala, S. Saride, S. Nazarian, and L. R. Hoyos. 2008. “Durability Studies of Lime Stabilized Clayey Soils.” In *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering*, 5.

Chiu, C.F., W. Zhu, and C.L. Zhang. 2009. “Yielding and Shear Behaviour of Cement-Treated Dredged Materials.” *Engineering Geology* 103 (1–2): 1–12. https://doi.org/10.1016/j.enggeo.2008.07.007

Consoli, N. C., S. F. V. Marques, M. F. Floss, and L. Festugato. 2017. “Broad-Spectrum Empirical Correlation Determining Tensile and Compressive Strength of Cement-Bonded Clean Granular Soils.” *Journal of Materials in Civil Engineering* 29 (6): 1–7. https://doi.org/10.1061/(ASCE)MT.1943-533.0001858

Consoli, N. C., R. A. Quiñónez Samaniego, L. E. González, E. J. Bittar, and O. Cuisinier. 2018. "Impact of Severe Climate Conditions on Loss of Mass, Strength, and Stiffness of Compacted Fine-Grained Soils–Portland Cement Blends." *Journal of Materials in Civil Engineering* 30 (8): 04018174. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002392

Cuccovillo, T., and M. R. Coop. 1999. "On the Mechanics of Structured Sands." *Géotechnique* 49 (6): 741–60. https://doi.org/10.1680/geot.1999.49.6.741

Cuisinier, O., and F. Masrouri. 2020. "Impact of Wetting/Drying Cycles on the Hydromechanical Behaviour of a Treated Soil." Edited by R. Cardoso, C. Jommi, and E. Romero. *E3S Web of Conferences* 195: 1–6. https://doi.org/10.1051/e3sconf/202019506008

Dadda, A., C. Geindreau, F. Emeriault, S. Rolland du Roscoat, A. Esnault Filet, and A. Garandet. 2019. "Characterization of Contact Properties in Biocemented Sand Using 3D X-Ray Micro-Tomography." *Acta Geotechnica* 14 (3): 597–613. https://doi.org/10.1007/s11440-018-0744-4

Kelley, C.M. 1988. "A Long Range Durability Study of Lime Stabilized Bases at Military Posts in the Southwest." *National Lime Association,* Bulletin 328 (2nd edition).

Khattab, S. A., M. Al-Mukhtar, and J.-M. Fleureau. 2007. "Long-Term Stability Characteristics of a Lime-Treated Plastic Soil." *Journal of Materials in Civil Engineering* 19 (4): 358–66. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:4(358)

Lemaire, K., D. Deneele, S. Bonnet, and M. Legret. 2013. "Effects of Lime and Cement Treatment on the Physicochemical, Microstructural and Mechanical Characteristics of a Plastic Silt." *Engineering Geology* 166 (November): 255–61. https://doi.org/10.1016/j.enggeo.2013.09.012

Leroueil, S., and P. R. Vaughan. 1990. "The General and Congruent Effects of Structure in Natural Soils and Weak Rocks." *Géotechnique* 40 (3): 467–88. https://doi.org/10.1680/geot.1990.40.3.467

Mehenni, A. 2015. "Comportement hydromécanique et érosion des sols fins traités." Thèse de doctorat, Nancy, France: Université de Lorraine.

Packard, R G, and G A Chapman. 1963. "Developments in Durability Testing of Soil-Cement Mixtures." *Highway Research Record* 36: 97–123.

Rowe, P.W. 1962. "The Stress-Dilatancy Relation for Static Equilibrium of an Assembly of Particles in Contact." *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 269 (1339): 500–527. https://doi.org/10.1098/rspa.1962.0193

Salih, R.O., and A.O. Maulood. 1988. "Influence of Temperature and Cycles of Wetting and Drying on Modulus of Rupture." *Soil and Tillage Research* 11 (1): 73–80. https://doi.org/10.1016/0167-1987(88)90032-3

Stoltz, G., O. Cuisinier, and F. Masrouri. 2014. "Weathering of a Lime-Treated Clayey Soil by Drying and Wetting Cycles." *Engineering Geology* 181 (October): 281–89. https://doi.org/10.1016/j.enggeo.2014.08.013

Wang, L., J. Chu, S. Wu, and H. Wang. 2021. "Stress–Dilatancy Behavior of Cemented Sand: Comparison between Bonding Provided by Cement and Biocement." *Acta Geotechnica* 16 (5): 1441–56. https://doi.org/10.1007/s11440-021-01146-4

Wassermann, A., A. Abdallah, and O. Cuisinier. 2022. "Impact of Wetting and Drying Cycles on the Mechanical Behaviour of a Cement-Treated Soil." *Transportation Geotechnics* 36 (September). https://doi.org/10.1016/j.trgeo.2022.100804