HAL open science

Hydromechanical and pore-structure evolution in lime-treated kneading compacted soil

Geetanjali Das, Andry Razakamanantsoa, Gontran Herrier, Dimitri Deneele

To cite this version:

Geetanjali Das, Andry Razakamanantsoa, Gontran Herrier, Dimitri Deneele. Hydromechanical and pore-structure evolution in lime-treated kneading compacted soil. Geo-Congress 2022, Mar 2022, CHARLOTTE, NORTH CAROLINA, United States. 10 p., 10.1061/9780784484012.026 . hal-03629338

HAL Id: hal-03629338

https://hal.science/hal-03629338v1

Submitted on 4 Apr 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Hydromechanical and pore-structure evolution in lime-treated kneading compacted soil.

Geetanjali Das,[1] Andry R. Razakamanantsoa,[2]
Gontran Herrier[3] and Dimitri Deneele[4]

[1]Ph.D student, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France (corresponding author). ORCID: https://orcid.org/0000-0003-0573-9077.
E-mail : geetanjali.das@univ-eiffel.fr
[2]Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France.
E-mail : andry.razakamanantsoa@univ-eiffel.fr
[3]Senior Research Engineer, Lhoist Recherche et Développement, rue de l'Industrie 31, 1400 Nivelles, Belgique. Email : gontran.herrier@lhoist.com
[4]Researcher, Université Gustave Eiffel, Laboratoire GERS-GIE, F-44344 Bouguenais, France. Researcher, Université de Nantes, CNRS, Institut des Matériaux Jean Rouxel, IMN, F-44000 Nantes, France. E-mail: dimitri.deneele@univ-eiffel.fr

ABSTRACT

Hydromechanical performances and pore-structure evolution in in-situ lime-treated soil is influenced by the implemented methodology of execution. In-situ lime-treated soil experiences kneading action during soil compaction; however, little is investigated regarding the contribution of the kneading mechanism towards hydromechanical and pore-structure evolution. This study evaluates the evolution of Unconfined Compressive Strength (UCS), hydraulic conductivity, and pores of different categories in laboratory kneaded soil. The evaluation involves results from lime-treated soil subjected to different curing times and temperatures. The results obtained from laboratory kneaded and cured soils are interpreted with the one obtained from in-situ sampled soil of the same configuration after 7 years of atmospheric curing. The obtained interpretation provides an acceptable insight towards the expected long-term hydromechanical and pore-structure evolution of lime-treated soil. Thus, the study highlights the importance of reproducing an implementation mechanism in the laboratory which closely represents the field compaction.

INTRODUCTION

Management of natural resources such as soil is essential in any land development project. In this context, improvement of the engineering properties of natural soil by chemical stabilization using lime was shown to be an efficient and effective process (Bell 1996; Little 1995). In addition to chemical stabilization, mechanical improvement, which involves the implementation of control mixing and compaction conditions by incorporating appropriate water content, binder amount, compaction energy, and compaction mechanism, was also important (Das et al. 2020, 2021; Le Runigo et al. 2009, 2011; Makki-Szymkiewicz et al. 2015).

The present literature provides several laboratories (Bell 1996; Das et al. 2021) and few field studies evidencing the improvement brought in the soil through lime treatment. One such field study was recently reported by Das et al. (2020). Das et al. (2020) reported the long-term effect of lime treatment on the compressive strength, physicochemical and microstructural modification on specimens sampled from an experimental embankment, which has been exposed

to the external atmosphere for 7 years. A significant evolution of average UCS of 3.29 ± (0.45) MPa was reported in core-sampled soil. Besides, a uniform distribution of pH and water content was reported throughout the embankment. The study concluded that due to controlled mixing and compaction condition implemented during the construction of the embankment, as reported by Makki-Szymkiewicz et al. (2015), such homogeneity in the physicochemical measurement was attained. A similar conclusion was reported by Makki-Szymkiewicz et al. (2015) regarding the contribution of controlled mixing and compaction condition towards attaining a lower permeability in lime-treated soil. Thus, the above studies highlight the importance of undergoing a proper implementation process during the construction of a lime-treated structure.

Of the several parameters maintained during implementation, the compaction mechanism is an important parameter. However, how well the laboratory implemented compaction mechanism represents the in-situ implementation mechanism is less investigated. Thus, it is essential to bring a comparative interpretation between the evolution of properties between filed and laboratory compacted lime-treated soils. On the field, fine-grained soil, particularly clayey soil, is preferred to be compacted by a vibratory Padfoot roller. Padfoot roller, during compaction, produces a combined rolling and kneading action. The impact of the rolling mechanism on natural soil during compaction was shown by Sedeki et al. (2018). However, the effect of the kneading mechanism is not well investigated. The importance of implementing kneading action at laboratory scale was urged by Clegg (1964) and Kouassi et al. (2000), who showed a similar generation of soil structure, residual interparticle stresses, and other soil properties between in-situ compacted and laboratory kneaded fine-grained natural soil.

Recently, Das et al. (2021) demonstrated the importance of undergoing kneading compaction of lime-treated soil by showing the contribution of kneading action towards long-term strength evolution. Thus, it becomes important to undergo further studies on the lime-treated kneaded soil and to investigate the relevancy between laboratory and field obtained results. In this context, this study focuses on evaluating the evolution of Unconfined Compressive Strength (UCS), hydraulic conductivity, and pore-structure of laboratory kneaded lime-treated soil. The obtained laboratory results are then interpreted with lime-treated specimens sampled from 7 years atmospherically cured experimental embankment built with the same soil configuration to understand the long-term evolution.

MATERIALS

This study involves the use of in-situ sampled soil from a 7 year environmentally cured experimental embankment, which was built with 2.5% quicklime treated Marche-Les-Dames (MLD, Belgium) silty soil. Details regarding the sampling procedure and layout of sampling depths were reported in Das et al. (2020). Compacted specimens in the form of blocks and loose materials were obtained at a depth of 0.30m and 0.75m from the slope of the experimental embankment, *i.e.*, specimens were sampled from the core of the embankment.

The same silty soil and lime content were used for the preparation of specimens in the laboratory. The quicklime used consists of 90.9% of available CaO and a reactivity (t_{60}) of 3.3 min, as reported by Nguyen (2015). The Lime Modification Optimum (LMO) of the silt was 1% by weight of lime, which was determined by Eades and Grim test as per ASTM D 6276-99a (ASTM 2006).

SAMPLE PREPARATIONS

The compaction characteristics of the soil were similar to the one reported by Das et al. (2020), which were obtained as per ASTM D698-91 (ASTM 2012) before the construction of the embankment. The maximum dry density and optimum moisture content (OMC) of untreated soil were 18.4 kN/m^3 and 14.3%, respectively, and for 2.5% lime-treated soil were 17.1 kN/m^3 and 18.5%, respectively.

The experimental embankment was constructed with 2.5% quicklime at a wet of optimum moisture content (WMC), which was 1.1 times OMC (Makki-Szymkiewicz et al. 2015). Hence, the laboratory specimens were also prepared at the same lime content and water content. The prepared soil paste was then placed in sealed plastic bags for 24 hours at ambient laboratory temperature to allow the soil to undergo moisture content homogenization. Then, the soil paste was mixed with 2.5% lime and was set aside for 1 hour before the soil mixture was subjected to compaction. This process of sample preparation employed herein was according to the procedure mentioned in French GTS Technical Guide for soil treatment (GTS - LCPC-Setra Technical Guide 2000). This reference of sample preparation is also followed during the in-situ construction of lime-treated structures.

Three cubic specimens of dimension having a length to diameter ratio (l/d) of 1 were trimmed from the block excavated at the core of the embankment. 2 of these were from the block sampled at depth 0.30m, and the remaining ones from the block sampled at a depth of 0.75m from the slope. The former specimen is represented as $S_{0.30}$ and the latter as $S_{0.75}$, respectively, in the rest of the study. Correspondingly, cylindrical specimens of length and diameter, each of 0.05m, were prepared by kneading compaction, *i.e.*, the same l/d ratio was maintained with the field sampled soil. The kneading compaction was performed by a laboratory-developed kneading tool, which was reported in the study of Das et al. (2021). During the application of kneading compaction, specimens were kneaded by rotation of the 3-kneading feet at an angle of 45° between 2 successive loadings. A dynamic load corresponding to the compaction energy as per the ASTM D698-91 (ASTM 2012) was applied. The process of kneading compaction is similar to the one mentioned by Das et al. (2021). Nine specimens were prepared, of which 3 were untreated, and 6 were lime-treated soils. The specimens were then wrapped in plastic film. The untreated and 3 lime-treated specimens were cured for 28 days at laboratory ambient temperature of 20°C and the remaining lime-treated specimens were subjected to accelerated curing at 40°C for 90 days. A similar level relative humidity is maintained in both curing conditions.

LABORATORY EXPERIMENTS

Two cubic fields sampled soil, *i.e.*, $S_{0.30}$ and $S_{0.75}$, and 6 laboratory cured specimens were subjected to UCS test using a mechanical press with a load sensor at a constant displacement rate of 1mm/min. The 6 laboratory specimens consist of 2 of each 28 days laboratory cured and 90 days accelerated cured soils.

The remaining one cubic field sampled soil ($S_{0.30}$), and 3 laboratories cured specimens, *i.e.*, one untreated 28 days cured, and two lime-treated 28 days and 90 days accelerated cured subjected to hydraulic conductivity test. The hydraulic conductivity test was performed using a low ionic strength solution, *i.e.*, 10^{-3} NaCl. This is because the in-situ hydraulic structure is in general subjected to water from natural sources, which may consist of few to numerous dissolved minerals. Besides, use of 10^{-3} NaCl was commonly made in previous studies (Razakamanantsoa et al. 2016; Sato et al. 2017). The hydraulic conductivity test was conducted using a flexible wall permeameter, in which water was allowed to pass through the base of the specimens, and the effluents are collected from the top. This was done to ensure a uniform flow of water through the specimens

and to reduce any entrapped air if present within the compacted soil. A confining pressure of 88±2 kPa and a hydraulic head of 170±5 cm were applied to the specimens during the hydraulic conductivity test. The applied hydraulic head was intended to keep almost similar to the in-situ embankment's height which is about 180 cm, as reported in the study of Das et al. (2020). The measurement of hydraulic conductivity was conducted until the last five values of Electric Conductivity measured from the effluents collected became stable.

Loose specimens obtained from the core of the in-situ sampled block ($S_{0.30}$) and those obtained from laboratory kneaded soil at the end of curing were subjected to pore-structure analysis. Specimens were freeze-dried and then were subjected to Mercury Intrusion Porosimetry (MIP), and Brunauer-Emmett-Teller (BET) (Brunauer et al. 1938) tests to analyze the pore-structure evolution. The procedure of MIP and BET tests can be referred to in studies of Romero and Simms (2008) and Westermarck (2000), respectively. The discussion made regarding pore-structure involves the classification provided in IUPAC (Rouquerol et al. 1994), which categories pores as macropores (>500 Å), mesopores (20-500 Å), and micropores (<20 Å).

RESULTS

Evolution of Unconfined Compressive Strength in lime-treated soil

Figure 1 presents the comparative evolution of UCS in the kneaded silty soil with and without lime treatment after being exposed to different curing conditions (*i.e.*, temperature and duration of curing). The UCS of the untreated laboratory kneaded soil after 28 days of curing at laboratory temperature was 0.21 MPa. The same soil being treated with 2.5% lime and cured under similar conditions presented a UCS of 0.70 MPa.

To attain the maximum strength in an acceptable laboratory duration and to compare the same with the 7 years atmospherically cured soil, 2.5% lime-treated laboratory kneaded soil was subjected to 90 days of accelerated curing at 40˚C. The resulting UCS was 3.80 MPa. The average UCS obtained from the environmentally cured core-sampled specimens, *i.e.*, from $S_{0.30}$ and $S_{0.75}$ was 4.40 MPa.

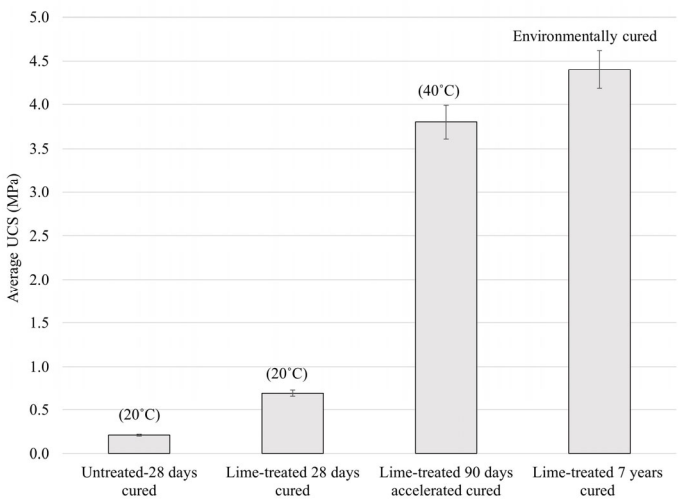

Figure 1. Comparative evolution of UCS in untreated to lime-treated kneaded soil subjected to different curing conditions.

Evolution of hydraulic conductivity in lime-treated soil

The evolution of hydraulic conductivity in the untreated and the lime-treated soil cured under different conditions was measured up to 100 days of percolation time and is compared in Figure 2.

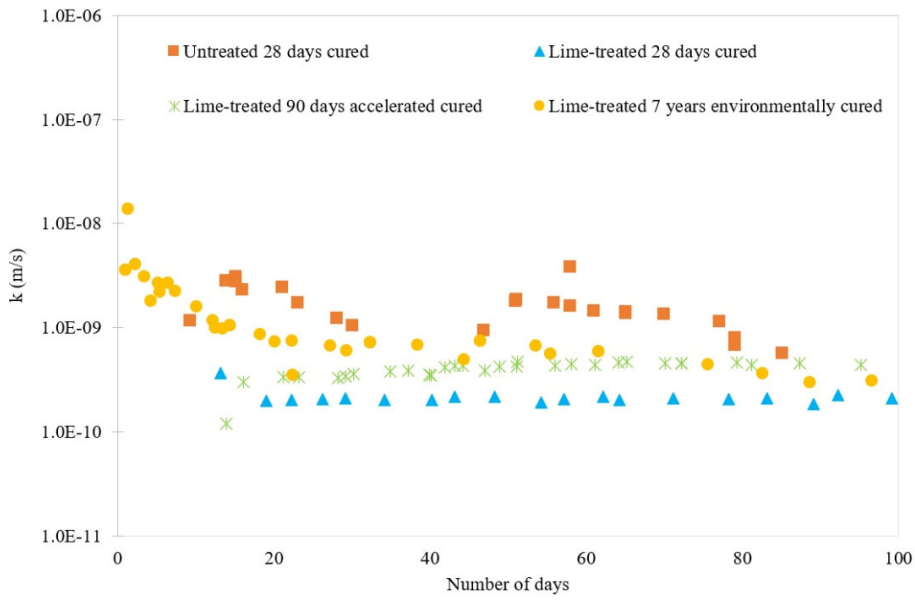

Figure 2. Comparative evolution of hydraulic conductivity in untreated to lime-treated kneaded soil subjected to different curing conditions.

The measurement of hydraulic conductivity was expressed in terms of the magnitude of permeability coefficient, *k*. From Figure 2, it was observed that almost all the lime-treated specimens, despite being subjected to different curing conditions, attained stability of *k* after about 20 days of percolation time, which is in the same range, *i.e.*, lower than 10^{-9} m/s and higher than 10^{-10} m/s. However, the hydraulic conductivity of the untreated soil was slightly higher than the lime-treated soils.

Evolution of pore structure in lime-treated soil

The hydraulic conductivity of lime-treated soil was demonstrated to be affected by the inter-aggregates pore of diameter greater than 10000 Å (Le Runigo et al. 2009). In this context, the cumulative macropore volume of pores greater than 10000 Å, which was analyzed by the MIP test, was compared between the untreated and lime-treated soil in Figure 3.

The untreated silty soil was observed to exhibit the maximum cumulative pore volume of diameter greater than 10000 Å. This feature was comparatively lower in the lime-treated soil, and the minimum was observed for the environmentally cured $S_{0.30}$ soil.

Since lime treatment of soil was shown to enhance the development of pores lower than 3000 Å (Das et al. 2020, 2021) thus, the evolution of such pores was expressed by the isotherm plots obtained from the BET test in Figure 4. This is because BET analysis was shown to provide

an elaborative explanation of smaller pores formed due to lime treatment in the study reported by Das et al. (2020).

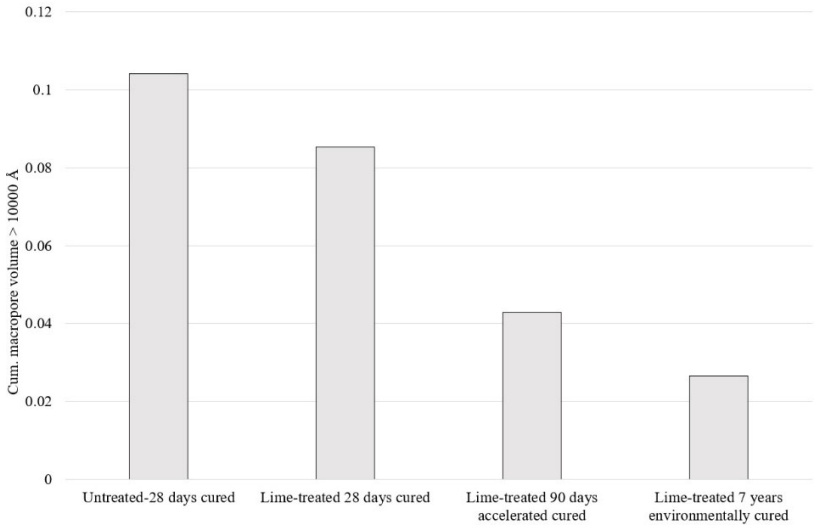

Figure 3. Comparative evolution of cumulative macropore volume by MIP test between untreated and lime-treated soil subjected to different curing conditions.

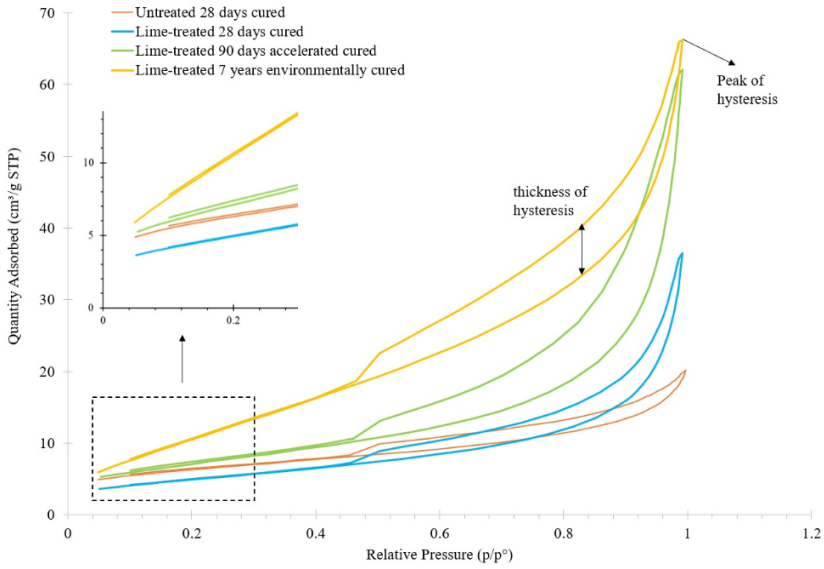

Figure 4. Comparative evolution of the characteristics of the isotherm obtained from BET test between untreated and lime-treated soil subjected to different curing conditions.

From the obtained isotherm plots, three distinct features can be observed, *i.e.*, the evolution of (i) micropores, (ii) hysteresis thickness, and (iii) the peak of the isotherm. The first feature, *i.e.*, the total availability of micropores, is usually demonstrated to corresponds to the range of relative pressure of 0.05-0.3 (Huang et al. 2014). In the present soil, this feature was slightly lower in the

28 days cured lime-treated soil compared to the untreated soil. Then with increased curing time to 90 days and under accelerated conditions, this feature increased compared to both the untreated and 28 days cured soil. However, the preceding feature was significant in the 7 years cured $S_{0.30}$ soil.

The hysteresis region in the isotherm was delineated to be associated with the delay in capillary condensation and evaporation that occurs in the mesopores (20-500 Å) by McGregor et al. (2014) and Collet et al. (2008). In the present case, the hysteresis thickness was minimum for the untreated soil and then increased with an increase in curing time and temperature of the laboratory cured lime-treated soil. However, this thickness is slightly lower for the environmentally $S_{0.30}$ cured soil compared to the accelerated cured soil.

The peak of the isotherm represents the total nitrogen adsorption capacity of the present soil in the range of pore diameter of about 20-2000 Å, as obtained through Barrett-Joiner-Halenda pore (BJH) analysis (Barrett et al. 1951). This range involves the total generation of pores lower than 3000 Å due to lime treatment. Thus, an enhanced peak indicates a greater presence of pores of diameter 20-2000 Å. In the present case, the maximum peak was observed for the 7 years $S_{0.30}$ environmentally cured soil, followed by the laboratory accelerated cured and 28 days cured soil. The minimum was observed for the untreated specimen.

DISCUSSIONS

UCS evolution in lime-treated soil was shown to be contributed by the generation of pores lower than 2000 Å (Das et al. 2021). This evolution of pores is influenced by curing time and temperature (Little 1995; Lemaire et al. 2013). Again, pores lower than 2000 Å involves the complete range of micropores, mesopores, and a part of macropores as per IUPAC classification. However, little is known regarding the evolution of each pore category in lime-treated soil exposed to different curing conditions and its contribution to UCS. In the present case, the isotherm in Figure 4 provides a distinguishing feature of the above pore categories. As expected, 28 days cured lime-treated soil showed an increase in UCS compared to the untreated kneaded soil (Figure 1). This is attributed to the increased hysteresis peak and hysteresis thickness which indicated the evolution of pores in the pore range 20-2000 Å (Figure 4). However, the slightly lower presence of micropores in the short-term 28 days cured lime-treated soil compared to the untreated was a consequence of flocculation of clay particles (Little 1995). On curing the same lime-treated soil at an elevated temperature of 40˚C and for a longer time, the pozzolanic reactions were accelerated, giving to the quick development of smaller pores, particularly in the pore range 20-2000 Å (Figure 4). This phenomenon resulted in increased UCS by about five times than the 28 days cured soil (Figure. 1). However, the evolution of micropores in the accelerated cured soil though higher than 28 days cured soil, was less significant. This indicates that accelerated curing brings modifications, particularly in pores greater than 20 Å. At the same time, the same configured soil, after 7 years of curing, showed the maximum micropores and hysteresis peak (Figure 4). However, the hysteresis thickness in the 7 years cured soil was slightly lower than the accelerated cured soil. The preceding observations explain the increased intensities of micropores with increased curing time due to increased cementitious bonding, which have led to the maximum UCS (Figure 1). The above discussion helps in visualizing the evolution of pores of different categories in soil exposed to different curing conditions and its contribution to UCS. Thus, based on the above interpretation made, the evolution of UCS and pore-structure observed in the in-situ sampled soil can be said to be an expected long-term evolution of the laboratory kneaded soil.

Short-term cured lime-treated soil was shown to have resulted in an increase in permeability due to the formation of pores greater than 10000 Å as a result of aggregation compared to the untreated soil (Khattab and Suhail 2002; Rajasekaran and Rao, 2002). However, Locat et al. (1996) demonstrated that after long-term curing, lime-treated soil shows a decrease in hydraulic conductivity due to increased formation of smaller pores as a result of pozzolanic reactions. Recently, Makki-Szymkiewicz et al. (2015) explained that a controlled mixing and execution process during construction of a lime-treatment embankment could give a level of hydraulic conductivity close to the untreated soil even after 6 months from construction. This embankment was the same embankment from which in-situ sampled soil was reported herein. Figure 2 showed a level of permeability between 10^{-9} to 10^{-10} m/s in the in-situ sampled soil, which was almost similar to the level reported by Makki-Szymkiewicz et al. (2015). This indicates that though a significant evolution of pores lower than 2000 Å occurred during the 7 years of curing (Figure 4), the level of permeability remained almost the same as the one obtained after 6 months from construction. The same configured soil, when prepared by laboratory kneading action, gave the same level of permeability despite being subjected to different curing conditions (Figure 2). The preceding observations made in the in-situ sampled and laboratory specimens again confirm the fact that the attainment of lower permeability in lime-treated soil is dependent on the implementation mechanism. However, the hydraulic conductivity of the untreated soil was slightly higher compared to the lime-treated soil (Figure 2). This is attributed to the maximum availability of cumulative pores volume of diameter greater than 10000 Å in the untreated (Figure 3). However, the difference in cumulative pores volume of diameter greater than 10000 Å between lime-treated soil seems to have an insignificant effect on the evolution of hydraulic conductivity.

CONCLUSIONS

This study focuses on interpreting the comparative evolution of hydromechanical behaviors and pore-structure modifications between laboratory prepared and in-situ sampled lime-treated soil for emphasizing the relevancy of laboratory and field implemented kneading mechanisms. Comparison of laboratory kneaded untreated and lime-treated soil subjected to different curing times and temperatures and 7 years atmospherically cured specimens were made.

1) The evolution of UCS and pore-structure observed in the 7 years cured in-situ sampled soil can be said to be an expected long-term evolution of the laboratory kneaded soil. The laboratory kneaded soil showed a rise in mesopores and 70% UCS evolution after 28 days of curing compared to the untreated soil. After 90 days of laboratory accelerated curing at elevated temperature (40˚C), a slight increase in micropores and significant mesopores and 94% increase in UCS resulted. After 7 years of in-situ curing, the same configured soil showed the maximum micropores and 95% increase in UCS.

2) Attainment of lower permeability in lime-treated soil is dependent on the implementation mechanism and is less impacted by curing time and temperature. 28 days laboratory cured, and 90 days accelerated cured laboratory kneaded soil gave a magnitude of hydraulic conductivity almost similar to the one achieved in the 7 years cured in-situ sampled soil.

Thus, the above discussion confirms the relevancy between the laboratory and field-implemented kneading mechanism by interlinking the hydromechanical and microstructural

evolution. Hence, the development of kneading action at a laboratory scale is essential to have a close prediction of the hydromechanical evolution of a lime-treated in-situ structure. Besides, since the compaction mechanism plays an important role in the hydromechanical evolution of lime-treated soil, further investigation on the compaction mechanism, which involves kneading and rolling impact together, should be made. This is because the Padfoot roller, in addition to kneading action, produces roller action on the soil during in-situ compaction.

REFERENCES

ASTM (American Society for Testing and Materials). (2006) *Standard Test Method for Using pH to Estimate the Soil–Lime Proportion Requirement for Soil Stabilization*, Standard ASTM D 6276-99a.

ASTM (American Society for Testing and Materials). (2012) *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 Ft-Lbf/Ft3 (600 KN-m/M3))*, Standard ASTM D698-12e2.

Barrett, E.P., Joyner, L.G., and Halenda PP. (1951). "The determination of pore volume and area distributions in porous substances. I. Computations from nitrogen isotherms." *Journal of the American Chemical Society*, 73, 373–380. https://doi.org/10.1021/ja01145a126

Bell, F.G. (1996). "Lime stabilization of clay minerals and soils." *Engineering Geology*, 42, 223–37. https://doi.org/10.1016/0013-7952(96)00028-2

Brunauer, S., Emmett, P.H., and Teller, E. (1938). "Adsorption of gases in multimolecular layers." *Journal of the American Chemical Society*, 60, 309–319.

Clegg, B. (1964). "Kneading compaction." *Australian Road Research Board Bulletin*, 1.

Collet, F., Bart, M., Serres, L., and Miriel, J. (2008). "Porous structure and water vapour sorption of hemp-based materials." *Construction and Building Materials*, 22, 1271–1280. https://doi.org/10.1016/j.conbuildmat.2007.01.018

Das, G., Razakamanantsoa, A., Herrier, G., Saussaye, L., Lesueur, D., and Deneele, D. (2020). "Evaluation of the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric exposure: Mechanical, physicochemical, and microstructural studies." *Engineering Geology*, 281,105986. https://doi.org/10.1016/j.enggeo.2020.105986

Das, G., Razakamanantsoa, A., Herrier, G., and Deneele, D. (2021). "Compressive strength and microstructure evolution of lime-treated silty soil subjected to kneading action." *Transportation Geotechnics*, 100568. https://doi.org/10.1016/j.trgeo.2021.100568

GTS - LCPC-Setra Technical Guide. (2000). "Soil treatment with lime and/or hydraulic binders: Application to the Construction of fills and capping layers." LCPC Eds, Paris (France).

Huang, B., Bartholomew, C. H., and Woodfield, B. F. (2014). "Improved calculations of pore size distribution for relatively large, irregular slit-shaped mesopore structure." *Microporous and mesoporous materials*, 184, 112-121. https://doi.org/10.1016/j.micromeso.2013.10.008

Khattab, A., and Suhail, A. (2002). "Etude multi-échelles d'un sol argileux plastique traité à la chaux. " PhD diss., Orléans.

Kouassi, P., Breysse, D., Girard, H., and Poulain, D. (2000). "A new technique of kneading compaction in the laboratory." *Geotechnical Testing Journal*, 23, 72–82. https://doi.org/10.1520/GTJ11125J

Lemaire, K., Deneele, D., Bonnet, S., and Legret ,M. (2013). “Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt.” *Engineering Geology*, 166, 255–261. https://doi.org/10.1016/j.enggeo.2013.09.012

Le Runigo, B., Ferber, V., Cui, Y-J., Cuisinier, O., and Deneele, D. (2011). “Performance of lime-treated silty soil under long-term hydraulic conditions.” *Engineering Geology*. 118, 20–8. https://doi.org/10.1016/j.enggeo.2010.12.002

Le Runigo, B., Cuisinier, O., Cui, Y-J., Ferber, V., and Deneele, D. (2009). “Impact of initial state on the fabric and permeability of a lime-treated silt under long-term leaching.” *Canadian Geotechnical Journal*, 46, 1243–1257. https://doi.org/10.1139/T09-061

Little, D.N. (1995). “Stabilization of pavement subgrades and base courses with lime.”

Locat. J., Trembaly, H., and Leroueil, S. (1996). “Mechanical and hydraulic behaviour of a soft inorganic clay treated with lime.” *Canadian Geotechnical Journal*, 33, 654–69. https://doi.org/10.1139/t96-090-311

Makki-Szymkiewicz, L., Hibouche, A., Taibi, S., Herrier, G., Lesueur, D., and Fleureau, J-M. (2015). “Evolution of the properties of lime-treated silty soil in a small experimental embankment.” *Engineering Geology*, 191, 8–22. https://doi.org/10.1016/j.enggeo.2015.03.008.

McGregor, F., Heath, A., Fodde, E., and Shea, A. (2014). “Conditions affecting the moisture buffering measurement performed on compressed earth blocks.” *Building and Environment*, 75, 11–18. https://doi.org/10.1016/j.buildenv.2014.01.009

Nguyen, T.T.H. (2015). Stabilisation des sols traités à la chaux et leur comportement au gel.

Rajasekaran, G., and Rao, S.N. (2002). “Permeability characteristics of lime treated marine clay.” *Ocean Engineering*, 29,113–27. https://doi.org/10.1016/S0029-8018(01)00017-8

Razakamanantsoa, A.R., and Djeran-Maigre, I. (2016). “Long term chemo-hydro-mechanical behavior of compacted soil bentonite polymer complex submitted to synthetic leachate.” *Waste Management*, 53, 92–104. https://doi.org/10.1016/j.wasman.2016.04.023

Romero, E., and Simms, P.H. (2008). “Microstructure investigation in unsaturated soils: a review with special attention to contribution of mercury intrusion porosimetry and environmental scanning electron microscopy.” *Geotechnical and Geological Engineering*, 26, 705–727.

Rouquerol, J., Avnir, D., Fairbridge, C.W., Everett, D.H., Haynes, J.M., Pernicone, N., Ramsay, J.D.F., Sing, K.S.W., and Unger, K.K. (1994). “Recommendations for the characterization of porous solids (Technical Report).” *Pure and Applied Chemistry*, 66, 1739–1758.

Sato, K., Barast, G., Razakamanantsoa, A., Djeran-Maigre, Katsumi, T., and Levacher, D. (2017). “Comparison of prehydration an d polymer addings effects on Na activated Ca Bentonite by free swell index test.” *Applied Clay Science*, 142, 69-80. https://doi.org/10.1016/j.clay.2016.10.009

Sedeki, O., Razakamanantsoa, A., Fleureau, J.M., Gotteland, P., Le Borgne, T., and Hattab, M. (2018). “Degradability of unpaved roads submitted to traffic and environmental solicitations: laboratory scale.” *7th International Conference on Unsaturated Soils* (Hong Kong).

Westermarck, S. (2000). “Use of mercury porosimetry and nitrogen adsorption in characterisation of the pore structure of mannitol and microcrystalline cellulose powders, granules and tablets.”