Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Enhancing the uniformity and extent of bio-cementation soil improvement: physical experiments and reactive transport modelling

Amélioration de l'uniformité et de l'étendue de l'amélioration des sols par bio-cimentation: expériences physiques et modélisation du transport réactif

Michael G. Gomez & Minyong Lee
Dept. of Civil and Environmental Engineering, University of Washington, USA, mggomez@uw.edu

Alexandra C.M. San Pablo & Jason T. DeJong
Dept. of Civil and Environmental Engineering, University of California, Davis, USA

Charles M.R. Graddy, & Douglas C. Nelson
Dept. of Microbiology and Molecular Genetics, University of California, Davis, USA

ABSTRACT: Bio-cementation continues to show promise as an environmentally-conscious soil improvement technology. As the process transitions from the laboratory to field setting, approaches that can improve the spatial uniformity of cementation and maximize treatment extent will be critical towards reducing implementation costs and environmental impacts. In this study, a series of soil column experiments were performed at multiple scales to investigate the potential of novel treatment strategies to control microbial reaction rates and enable improved control of bio-cementation spatial distributions. During all experiments, indigenous ureolytic microorganisms were enriched and resulting reaction rates and cementation distributions were characterized. A one-dimensional advective-dispersive reactive transport model was used to extrapolate the results of the physical experiments to further understand the effect of reaction and injection rates on bio-cementation distributions. Collectively these results suggest that indigenous ureolytic microorganisms can be enriched to perform bio-cementation at controlled reaction rates thereby enabling improved control of bio-cementation distributions and successful improvement of soils over meter-scale treatment distances.

RÉSUMÉ: La bio-cimentation continue d'être prometteuse en tant que technologie d'amélioration des sols respectueuse de l'environnement. Au fur et à mesure que le processus passe du laboratoire au terrain, de nouvelles approches qui peuvent améliorer l'uniformité spatiale de la cimentation et maximiser l'étendue du traitement seront essentielles pour réduire les coûts de mise en œuvre et les impacts environnementaux. Dans cette étude, une série d'expériences de colonne de sol ont été effectuées à plusieurs échelles pour étudier le potentiel de nouvelles stratégies de traitement pour modifier les taux de réaction microbienne et permettre un meilleur contrôle des distributions spatiales de bio-cimentation. Au cours de toutes les expériences, les micro-organismes uréolytiques indigènes ont été enrichis et les vitesses de réaction et les distributions de cimentation résultantes ont été caractérisées. Un modèle de transport réactif advectif-dispersif unidimensionnel a été utilisé pour extrapoler les résultats des expériences physiques afin de mieux comprendre l'effet des taux de réaction et d'injection sur les distributions de bio-cimentation. Collectivement ces résultats suggèrent que les microorganismes uréolytiques indigènes peuvent être enrichis pour effectuer la bio-cimentation à des taux de réaction contrôlés, permettant ainsi un meilleur contrôle des distributions de bio-cimentation et une amélioration réussie des sols sur des distances de traitement à l'échelle du mètre.

KEYWORDS: Soil improvement, Bio-cementation, Bio-mediated, MICP, Liquefaction mitigation.

1 INTRODUCTION

Bio-mediated soil improvement processes offer the potential to markedly improve soil engineering behaviors with reductions in environmental impacts (Seagren & Aydilek 2010; DeJong & Kavazanjian 2019). Bio-cementation, or Microbially-induced Calcite Precipitation (MICP), is perhaps the most widely studied bio-mediated ground improvement method and improves soils through the precipitation of calcium carbonate ($CaCO_3$) minerals on and between soil particles, thereby increasing soil stiffness, strength, and liquefaction triggering resistance, among other aspects (DeJong et al. 2006, Montoya et al. 2013, Xiao et al. 2018, Lee et al. 2020). The technology may be particularly effective for the stabilization of liquefiable soils beneath existing structures, an application for which few technologies currently exist. While the process holds significant promise for practical ground improvement applications, challenges have persisted with respect to controlling the spatial distribution and uniformity of bio-cementation at the meter-scale (DeJong et al. 2013). As the technology transitions to the field setting, approaches that can improve the spatial uniformity of bio-cementation and maximize treatment extent will be critical towards reducing implementation costs and impacts (San Pablo et al. 2020).

In this study, two sets of soil column experiments were performed to investigate the potential of novel treatment strategies to enable improved control of bio-cementation distributions and treatment extent. In all experiments, indigenous ureolytic microorganisms were enriched to complete the process (i.e. bio-stimulation) (Fujita et al. 2000, 2008; Burbank et al. 2011; Gomez et al. 2016, 2018; Graddy et al. 2018), thereby forgoing the need for injection of exogenous laboratory-cultured microorganisms (i.e. bio-augmentation). Employed treatment techniques were intended to vary microbial ureolytic activities to highlight how altering the magnitudes of $CaCO_3$ precipitation reactions occurring during injections can influence resulting bio-cementation distributions. First, soil column experiments were performed at the centimeter-scale to demonstrate how changes in microbial reaction rates could be achieved using new treatment strategies. Following these experiments, a one-dimensional advective-dispersive reactive transport model was used to extrapolate the implications of the centimeter-scale experiments in an attempt to better understand the interplay between reaction and injection rates and their collective impacts on bio-cementation uniformity. Following these simulations, results from recent meter-scale soil column experiments wherein microorganisms were enriched to achieve relatively high and low

ureolytic rates (San Pablo et al. 2020) are discussed.

2 MATERIALS & METHODS

2.1 *Centimeter-scale Soil Column Experiments*

Four soil columns were prepared in acrylic cylinders (15.2 cm length, 7.6 cm ID) and contained Concrete Sand used in past bio-cementation experiments (Gomez et al. 2014 and others). Concrete Sand has a USCS classification of SP (ASTM, 2017), a D50 of 1.1 mm, and a fines content of 1.1% by mass. Sand was placed within columns using moist tamping to obtain relative densities near 55% and pore volumes (PV) near 250 mL. All columns had aqueous sampling ports at mid-height and were subjected to a vertical effective stress of 100 kPa. Columns received daily treatment injections in four different phases: stimulation, carbonate flushing, cementation, and ammonium by-product rinsing. During treatments, solution volumes of 375 mL (≈1.5 PV) were applied from the bottom to the top of columns at a flow rate of 10 mL/min (≈2.4 PV/hr). During the first 6 days, columns received stimulation solution injections once daily that were pH-adjusted to 9.0 and included 50 mM urea, 42.5 mM sodium acetate, 100 mM ammonium chloride, and varying yeast extract (YE) concentrations intended to alter obtained microbial ureolytic activities (Gomez et al. 2018, San Pablo et al. 2020). Three soil columns received daily stimulation solutions containing either 0.01 g/L, 0.07 g/L, or 0.2 g/L YE while a fourth column received stimulation solutions containing either 0.07 g/L or 0 g/L YE, which was alternated every treatment. It was hypothesized that soil columns receiving solutions with higher YE would have higher ureolytic cell densities and thus higher ureolytic activities. Following stimulation treatments, columns received a carbonate flush injection that was identical to the stimulation solution but was not pH-adjusted to remove high aqueous carbonate concentrations (Gomez et al. 2019). Immediately after the flush injection, all columns received ten daily cementation treatments that were identical to the composition of the stimulation solutions but contained 250 mM calcium chloride and 350 mM urea to induce bio-cementation. YE additions during cementation were identical to those used during stimulation. For select treatments, solution samples were collected in time to monitor changes in ureolytic activities. Solution urea measurements were completed using a colorimetric urea assay similar to Knorst et al. (1997). Following cementation, ammonium rinse solutions (initial pH = 9.0, 500 mM calcium chloride) following Lee et al. (2019) were applied to all columns to remove aqueous ammonium. Following rinsing, soil columns were drained, extruded, oven-dried, and soil subsamples were obtained at four discrete sections at varying distances from the injection port (0 to 38 mm, 38 to 76 mm, 76 to 114 mm, 114 to 152 mm). Sections were homogenized to yield subsamples for CaCO3 content measurements which were quantified in accordance with ASTM D4373 (ASTM, 2014).

2.2 *Meter-scale Soil Column Experiments*

Two soil column experiments were performed to examine the effect of changes in stimulated ureolytic activities on the distribution and extent of bio-cementation at meter-scale. A summary of relevant materials and methods is provided here with a complete description provided in San Pablo et al. (2020). Meter-scale soil columns were 3.67 m in length, square in cross-section (0.2 m by 0.2 m), and contained 0.15 m3 of sand. Columns received all injections in a single direction to simulate a stream tube within a well-to-well half-space. Both columns contained the same Concrete Sand used in the centimeter-scale experiments and were prepared using moist tamping to achieve relative densities from 55% to 65% and pore volumes near 50 L. Prior to treatments, columns were saturated with an artificial groundwater solution following Ferris et al. (1997) and passive tracer testing was completed to evaluate differences in transport conditions between columns. During tracer testing, 76 L (≈1.5 PV) of a 15 mM sodium bromide solution was injected, followed by 76 L (≈1.5 PV) of de-ionized water to examine the arrival and removal of bromide ions at the outlet well. A flow rate of 400 mL/min (≈0.5 PV/hr) was used for all tracer injections and solution samples were collected at column outlets at various times. Solution conductivity measurements were used to estimate bromide concentrations and measurements were normalized by the conductivity of the injected solution (C0). Following tracer testing, columns received treatments in the same four phases used for the centimeter-scale experiments. All stimulation, carbonate flushing, and cementation treatment injection volumes were 76 L (≈1.5 PV) and were applied at a constant flow rate of 400 mL/min (≈0.5 PV/hr). During the first six days, both columns received stimulation solution injections once daily, however, the applied YE concentrations were varied. The "low ureolytic rate" soil column received stimulation solutions that were pH-adjusted to 9.0 and contained 50 mM urea, 100 mM ammonium chloride, 42.5 mM sodium acetate, and 0.04 g/L YE. The "high ureolytic rate" soil column received similar stimulation solutions that had a higher YE concentration of 0.2 g/L. Following stimulation, carbonate flush solutions identical to cementation solutions but without urea or calcium were applied to both columns. After flushing, cementation injections were then applied to both columns. The "low ureolytic rate" column received cementation solutions containing 250 mM calcium chloride, 250 mM urea, 12.5 mM ammonium chloride, 42.5 mM sodium acetate, and 0.02 g/L YE once every 48 hours for 18 days (9 injections). The "high ureolytic rate" column received similar cementation solutions with a higher YE concentration of 0.2 g/L once every 24 hours for 9 days (9 injections). Following all cementation injections, a single 525 L (≈10.5 PV) volume of ammonium rinse solution (initial pH ≈ 10.0, 200 mM calcium chloride) was applied to each column at a flow rate of 750 mL/min (≈0.9 PV/hr). Following all injections, soil samples were collected from the center of the columns at various distances from the injection location. Soil samples were oven-dried and CaCO3 contents were determined following ASTM D4373 (ASTM, 2014).

2.3 *Reactive Transport Modeling*

A one-dimensional advective-dispersive soil column transport model was used to explore relationships between changes in urea hydrolysis rates and transport conditions on resulting bio-cementation distributions. Soil column models were developed using PHREEQC (Parkhurst and Appelo, 2013), an open-source geochemical software package. Models were 3.67 m long and consisted of 163 cells intended to match the meter-scale experiments described previously. Model advective-dispersive parameters were calibrated to match the passive tracer behaviors observed in the physical experiments. In all simulations, columns had spatially uniform ureolytic rates, however, changes in the magnitudes of ureolytic rates were explored. Three different ureolytic rates were considered that corresponded to urea degradation observed in the 0.01 g/L YE daily, 0.07 g/L YE alternating, and 0.2 g/L YE daily centimeter-scale experiments during cementation injection 8. To approximate these rates, a Michaelis-Menten kinetic model for ureolysis (Eq. 1) was calibrated to urea degradation trends observed in column experiments. In this model, bulk Vmax was the bulk solution maximal velocity and Km was the half-saturation coefficient of whole cell urease. In all models a Km of 305 mM urea was assumed following values reported by Graddy et al. (2018) for S. pasteurii (ATCC 11859). Bulk Vmax values were varied to calibrate models to observed urea degradation. In all models, CaCO3 precipitation was treated as an equilibrium reaction following Burdalski and Gomez (2020). Nine simulations were

performed to explore the interrelations between injection flow rates and ureolytic reaction rates as well as their resulting effects on bio-cementation magnitudes and distributions. In all simulations, columns received a single 76 L (≈1.5 PV) cementation solution injection identical to that used during the meter-scale experiments, which was applied at flow rates of either 50 mL/min (0.06 PV/hr), 500 mL/min (0.6 PV/hr), or 1500 mL/min (1.8 PV/hr). For all simulations, CaCO3 content distributions were determined following a retention period that was varied to allow for reaction completion (≈11 to 175 hours).

$$\frac{d[Urea]}{dt} = \left(\frac{Bulk\ V_{max}[Urea]}{K_m + [Urea]}\right) \quad (1)$$

3 RESULTS & DISCUSSION

3.1 *Centimeter-scale Soil Column Experiment*

In centimeter-scale soil column experiments, aqueous urea concentrations were monitored after select injections to examine changes in ureolytic activities. All measurements were normalized by injected urea concentrations (C_0). Figure 1 presents measurements of normalized urea concentrations (C/C_0) in time obtained during stimulation injection 6 and cementation injection 8. As shown during stimulation injection 6, increases in ureolytic rates were observed with increases in supplied YE. Although the injected urea concentration was fully hydrolyzed after the retention period in the 0.2 g/L YE daily, 0.07 g/L YE daily, and the 0.07 g/L YE alternating columns, only ≈20% of the injected urea was hydrolyzed in the 0.01 g/L YE daily column.

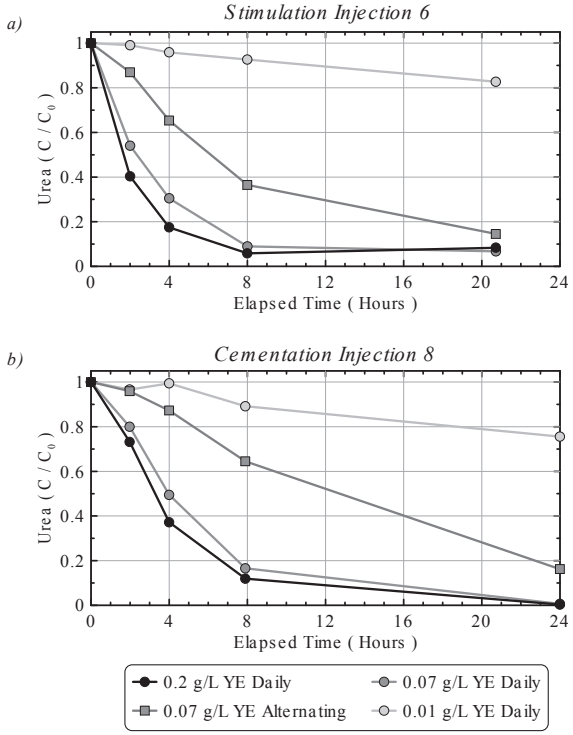

Figure 1. Normalized urea concentrations (C/C_0) in time during (a) stimulation injection 6 and (b) cementation injection 8.

After cementation injections were initiated, similar rate differences were observed between columns early on during the cementation phase (data not shown). During cementation injection 8, all columns hydrolyzed between 10% and 95% of the injected urea concentration after 8 hours. Although the 0.2 and 0.07 g/L YE daily columns achieved reaction completion after the retention period, the 0.07 g/L YE alternating and 0.01 g/L YE daily columns hydrolyzed less urea due to slower ureolytic rates.

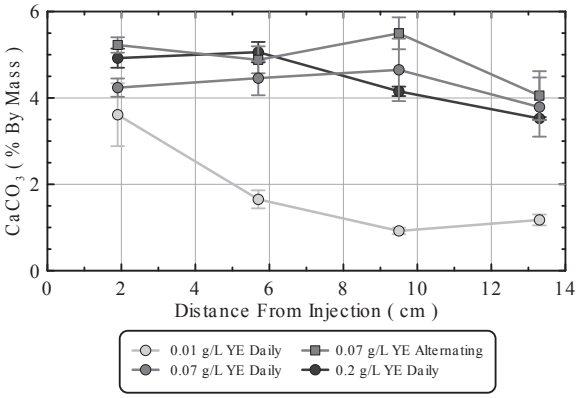

Figure 2. $CaCO_3$ content distributions for centimeter-scale soil columns. Error bars reflect ± one standard deviation from measurement averages.

Figure 2 presents soil $CaCO_3$ content measurements for all centimeter-scale columns with distance from the injection location. As shown, the 0.2 g/L YE daily, 0.07 g/L YE daily, and the 0.07 g/L YE alternating columns all had similar $CaCO_3$ contents between 4 and 5.5% by mass along their length. Although urea hydrolysis rates between columns differed, these similar $CaCO_3$ contents reflect similar total urea degradation during the 24-hour cementation treatment retention periods. The 0.01 g/L YE column hydrolyzed significantly less urea during cementation and thus achieved much lower $CaCO_3$ contents.

3.2 *Reactive Transport Modelling*

Advective-dispersive soil column numerical models were calibrated to match the experimental passive tracer data while assuming a total porosity of 0.30, an effective porosity of 0.234, longitudinal dispersivity (α_L) of 0.3 m, and hydraulic conductivity of 2.2 x 10^{-4} m/s. Figure 3 presents a comparison between normalized bromide concentrations (C/C_0) measured at the column outlet during the physical experiments as well as values simulated using PHREEQC. Normalized concentrations were similar between the model and experiments, suggesting that transport conditions were well approximated.

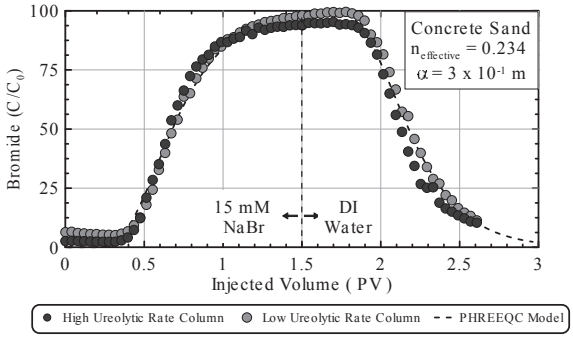

Figure 3. Normalized bromide concentrations (C/C_0) measured at meter-scale column outlets with values simulated using the PHREEQC model.

In order to explore the effect of changes in ureolytic rates on bio-cementation distributions using the PHREEQC model, the cell-normalized Michaelis-Menten ureolytic kinetic expression (Eq. 1) was calibrated to urea degradation measurements from the centimeter-scale experiments by varying bulk V_{max} values. Figure 4 presents normalized urea concentrations (C/C_0) in time for the 0.01 g/L YE daily, 0.07 g/L YE alternating, and 0.2 g/L YE daily columns during cementation injection 8 along with simulated trends from the calibrated models. Bulk V_{max} values of

6.4, 28.8, and 108.8 mM urea/hr were used to match urea degradation behaviors.

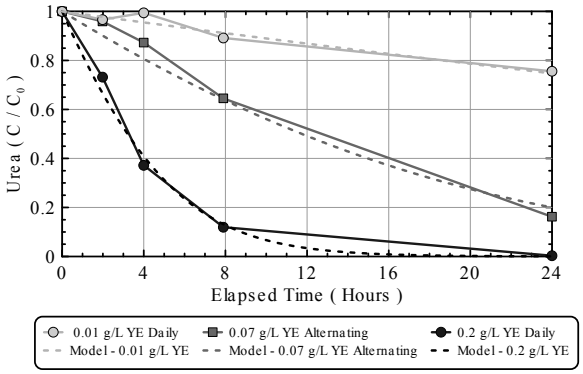

Figure 4. Comparison between normalized urea concentrations (C/C_0) in time from centimeter-scale columns during cementation injection 8 and simulated trends from calibrated PHREEQC models.

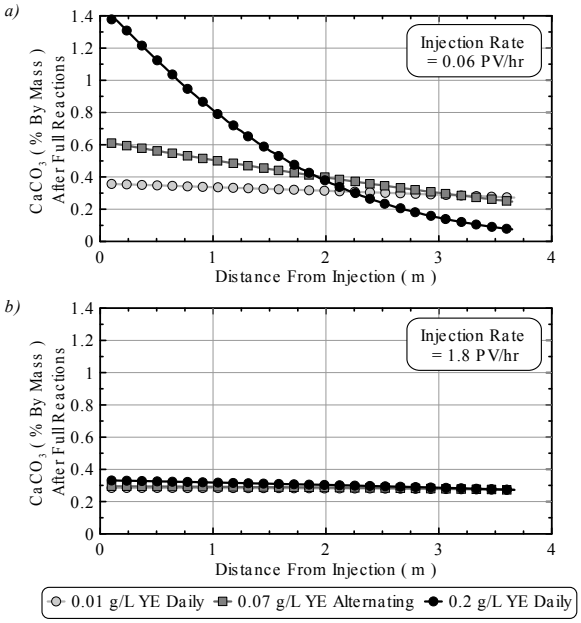

Figure 5. Simulated soil column $CaCO_3$ distributions for injection flow rates of (a) 0.06 PV/hr and (b) 1.8 PV/hr with varying ureolytic rates (as described by YE concentrations).

In order to further investigate relationships between ureolytic rates, solution transport conditions, and resulting bio-cementation distributions, nine simulations were performed using the developed numerical model. All simulations involved a single 76 L (≈1.5 PV) injection of a cementation solution identical to the meter-scale experiment, which was applied at varying injection rates and allowed to achieve full reaction completion by varying the retention periods. Figure 5 presents soil column $CaCO_3$ distributions after reaction completion for the lowest and highest injection rates as well as the three different ureolytic rates shown in Figure 4. At the lowest injection rate considered (0.06 PV/hr), significantly larger $CaCO_3$ contents were observed near the injection location (distance ≈0 m) when compared to $CaCO_3$ contents near the end of the column (distance ≈3.67 m). This localization of bio-cementation near the injection source was more pronounced with increases in ureolytic activity, which limited transport of reactants to further distances within columns. When injection rates were increased, however, more limited reactions occurred during injections resulting in more uniform $CaCO_3$ contents along column lengths, albeit with smaller $CaCO_3$ magnitudes. Interestingly at the highest injection rate, differences in ureolytic rates had minimal effects on resulting $CaCO_3$ distributions as almost all precipitation reactions occurred during retention periods.

Figure 6 presents relationships between average $CaCO_3$ contents in columns after reaction completion as well as the ratio between $CaCO_3$ contents at column outlets and inlets versus injection rates for simulations. When either injection rates were reduced or ureolytic rates were increased, large increases in column average $CaCO_3$ contents were observed due to greater precipitation reactions occurring during injections (Figure 6a). As injection rates increased, however, average $CaCO_3$ contents were similar for all columns despite differences in ureolytic rates, reflecting the minimal reactions that occurred during injections. Significant non-uniformity in $CaCO_3$ distributions were observed for the highest ureolytic rate columns (0.2 g/L YE daily) with outlet $CaCO_3$ contents ranging between 5% and 85% of inlet $CaCO_3$ contents (Figure 6b). In contrast, outlet $CaCO_3$ contents were between 75% and 95% of inlet values for the lowest ureolytic rate columns (0.01 g/L YE daily). While changes in injection rates dramatically altered $CaCO_3$ uniformity in columns with high ureolytic rates, the effect of injection rate on $CaCO_3$ uniformity was minimal for columns with low ureolytic rates, which achieved greater uniformity for all scenarios.

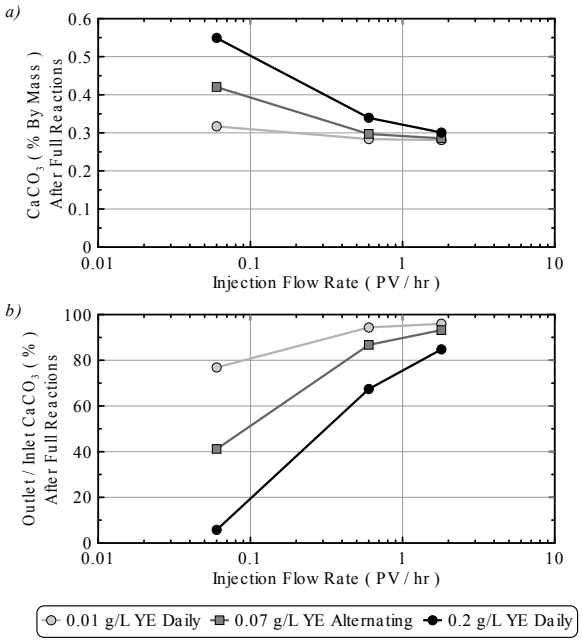

Figure 6. Relationships between (a) average column $CaCO_3$ contents after full reactions and (b) outlet to inlet $CaCO_3$ ratios for varying injection rates and ureolytic reaction rates.

3.3 *Meter-scale Soil Column Experiment*

Although simulations demonstrated the collective effects of both changes in injection and ureolytic rates on bio-cementation distributions, all simulations assumed that columns achieved uniform ureolytic activities along their entire lengths. While earlier results demonstrated that treatment techniques could be used to achieve lower ureolytic rates at the centimeter-scale, it remained unknown if such techniques could be successfully applied to more practical meter-scale lengths to realize hypothesized improvements in uniformity and extent. Figure 7 presents soil $CaCO_3$ content distributions for both the low and high ureolytic rate meter-scale columns. As shown, $CaCO_3$ contents in the high ureolytic rate column were larger over the first 2.5 m with $CaCO_3$ contents ranging between 3.5% and 7% by mass. Over this same distance, $CaCO_3$ contents in the low ureolytic rate column varied between 3% and 6% by mass. At

large injection distances near 3.4 m, however, the low ureolytic rate column achieved significantly larger $CaCO_3$ contents than the high ureolytic rate column. This difference resulted from lower ureolytic activities, which promoted both a more uniform distribution of reactants after injection as well as a greater extent of reactants and related improvement.

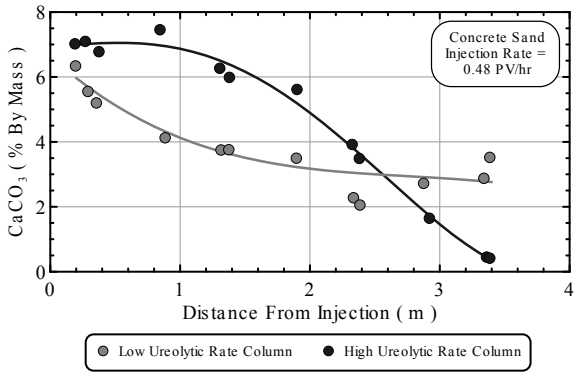

Figure 7. Soil $CaCO_3$ content distributions for low and high ureolytic rate meter-scale soil columns.

4 CONCLUSIONS

From the results of this study, the following conclusions can be made: (1) Treatment techniques can be modified to enrich native ureolytic microorganisms to achieve a wide variety of ureolytic rates. Variations in supplied yeast extract were shown to effectively regulate observed ureolytic activity in both centimeter- and meter-scale experiments. (2) PHREEQC simulations further illustrated that variations in ureolytic activity can be used to alter bio-cementation distributions including uniformity and extent for a variety of different transport conditions. For similar injection rates, higher ureolytic rates resulted in greater consumption of the supplied reactants during injections and therefore reduced treatment uniformity and extent. In contrast, lower ureolytic rates resulted in greater spatial uniformity and extent of improvement due to minimal reactions during transport. Uniformity in columns with low ureolytic rates also showed minimal sensitivity to changes in transport conditions. (3) Meter-scale experiments by San Pablo et al. (2020) confirmed that treatment techniques could be up-scaled to practical meter-scale distances to achieve differences in ureolytic rates that controlled cementation uniformity and extent as expected. In these experiments, greater cementation uniformity was observed in the low ureolytic rate column, with more significant localization of cementation near the injection source in the high ureolytic rate column. (4) While desired cementation distributions may be governed by the particular geotechnical applications of interest, the results of this study demonstrate that stimulated ureolytic rates can be regulated with the potential to improve control of bio-cementation distributions for varying transport conditions and different intended engineering applications.

5 ACKNOWLEDGEMENTS

The presented study involves work supported the Engineering Research Center Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-1449501 and the University of Washington. Any opinions, findings and conclusions or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect the views of the National Science Foundation. Research assistance from Colin Kolbus, Lucas Lindberg, Carson Valente, Mahanoor Khan, Atefeh Zamani, Nina Martin, Catalina Acuff, Daret Kehlet, Bill Sluis, Victor Jones, Lin Huang, Tamar Baumer, Matthew Burrall, Maya El Kortbawi, and Emmanuel Vasquez are acknowledged and greatly appreciated.

6 REFERENCES

ASTM. (2014). "Standard test method for rapid determination of carbonate content of soils." ASTM D4373-14, West Conshohocken, PA.

ASTM. (2017). "Standard Practice for Classification of Soils for Engineering Purpose.", *ASTM D2487-17e1*, West Conshohocken, PA.

Burbank, M., Weaver, T., Green, T., Williams, B., and Crawford, R. (2011). "Precipitation of calcite by indigenous microorganisms to strengthen liquefiable soils." *Geomicrobiology Journal*, 28(4), 301–312.

Burdalski, R., Gomez, M.G. (2020). "Investigating the Effects of Biogeochemical Conditions During Microbially Induced Calcite Precipitation (MICP) Soil Improvement", In *Geo-Congress 2020: Biogeotechnics*, Minneapolis, MN.

DeJong, J. T., & Kavazanjian, E. (2019). Bio-mediated and Bio-inspired Geotechnics. In *Geotechnical Fundamentals for Addressing New World Challenges* (pp. 193-207). Springer, Cham.

DeJong, J. T., Fritzges, M. B., & Nüsslein, K. (2006). "Microbially induced cementation to control sand response to undrained shear." *Journal of Geotechnical and Geoenvironmental Engineering*, 132(11), 1381- 1392.

DeJong, J.T., Soga, K.S., Kavazanjian, E., Burns, S., van Paassen, L., …, Weaver, T. (2013). "Biogeochemical processes and geotechnical applications: progress, opportunities and challenges." *Geotechnique*, 63(4), 287-301.

Ferris, F.G., Stehmeier, L.G., Kantzas, A., & Mourits, F.M. (1997). "Bacteriogenic mineral plugging." *Journal of Canadian Petroleum Technology*, 36(09).

Fujita, Y., Ferris, F. G., Lawson, R. D., Colwell, F. S., and Smith, R. W. (2000). "Calcium carbonate precipitation by ureolytic subsurface bacteria." *Geomicrobiology Journal*, 17(4), 305–318.

Fujita, Y., Taylor, J., Gresham, T., Delwiche, M., Colwell, F.S., McLing, T., Petzke, L., & Smith, R. (2008). "Stimulation of microbial urea hydrolysis in groundwater to enhance calcite precipitation." *Environmental Science and Technology*. 42(8), 3025–3032.

Gomez, M. G., Anderson, C. M., Graddy, C. M. R., DeJong, J. T., Nelson, D. C., and Ginn, T. R. (2016). "Large-scale comparison of bioaugmentation and biostimulation approaches for biocementation of sands." *Journal of Geotechnical and Geoenvironmental Engineering*, 10.1061/(ASCE)GT.1943-5606.0001640, 04016124.

Gomez, M. G., Graddy, C. M., DeJong, J. T., & Nelson, D. C. (2019). Biogeochemical changes during bio-cementation mediated by stimulated and augmented ureolytic microorganisms. *Scientific Reports*, *9*(1), 1-15.

Gomez, M.G., Anderson, C. M., DeJong, J. T., Nelson, D. C., and Lau, X. (2014). "Stimulating in situ soil bacteria for bio-cementation of sands." *Geo-Congress 2014 Technical Paper*s, ASCE, Reston, VA, 1674–1682.

Gomez, M.G., Graddy, C.M.R., DeJong, J.T., Nelson, D.C., and Tsesarsky, M. (2018). Stimulation of Native Microorganisms for Biocementation in Samples Recovered from Field-Scale Treatment Depths. *Journal of Geotechnical and Geoenvironmental Engineering, 10.1061/(ASCE)GT.1943-5606.0001804*

Graddy, C. M., Gomez, M. G., Kline, L. M., Morrill, S. R., DeJong, J. T., & Nelson, D. C. (2018). Diversity of Sporosarcina-like bacterial strains obtained from meter-scale augmented and stimulated biocementation experiments. *Environmental Science & Technology*, *52*(7), 3997-4005.

Knorst, M. T., Neubert, R., & Wohlrab, W. (1997). Analytical methods for measuring urea in pharmaceutical formulations. *Journal of pharmaceutical and biomedical analysis*, 15(11), 1627-1632.

Lee, M., Gomez, M. G., El Kortbawi, M., & Ziotopoulou, K. (2020). Examining the Liquefaction Resistance of Lightly Cemented Sands Using Microbially Induced Calcite Precipitation (MICP). In *Geo-Congress 2020: Biogeotechnics,* 11 pp.

Lee, M., Gomez, M. G., San Pablo, A. C., Kolbus, C. M., Graddy, C. M., DeJong, J. T., & Nelson, D. C. (2019). Investigating Ammonium By-product Removal for Ureolytic Bio-cementation Using Meter-scale

experiments. *Scientific Reports*, *9*(1), 1-15.
Montoya, B.M., DeJong, J.T., & Boulanger, R.W. (2013). "Dynamic response of liquefiable sand improved by microbial-induced calcite precipitation." *Géotechnique*, 63(4), 302-312.
Parkhurst, D. L., & Appelo, C. A. J. (2013). Description of input and examples for PHREEQC version 3--A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. *U.S. Geological Survey Techniques and Methods*, book 6, chap. A43, 497 p
San Pablo, A.C.M, Lee, M., Graddy, C.M.R., Kolbus, C.M., Khan, M., Zamani, A., Martin, N., Acuff, C., DeJong, J.T., Gomez, M.G., and Nelson, D.C. (2020). "Meter-scale Bio-cementation Experiments to Advance Process Control and Reduce Impacts: Examining Spatial Control, Ammonium By-product Removal, and Chemical Reductions." *J. Geotech. Geoenviron. Eng., 146(11), 04020125.*
Seagren, E.A., & Aydilek, A.H. (2010). "Biomediated geomechanical processes." *Environmental microbiology,* 2nd Ed., 319-348.
Xiao, P., Liu, H., Xiao, Y., Stuedlein, A. W., & Evans, T. M. (2018). Liquefaction resistance of bio-cemented calcareous sand. *Soil Dynamics and Earthquake Engineering*, *107*, 9-19.