Quarterly Progress and Performance Indicators Report:
Project Number and Title: 2.9: Carbonating Subgrade Materials for In-Situ Soil Stabilization
Research Area: New Materials for Longevity and constructability
PI: Aaron Gallant, Ph.D., P.E., University of Maine
Co-PI(s): Warda Ashraf, Ph.D., University of Texas at Arlington
Reporting Period: 7/1/2022-9/30/2022
Submission Date: 9/30/2022

****IMPORTANT: Please fill out each section fully and reply with N/A for questions/sections with nothing to report. For ease of reporting to the USDOT, please do not remove, or change the order of, any sections/text. You may remove/add each rows in tables as needed. Thank you! *****
The report is due on the last day of the reporting period in .doc format to tidc@maine.edu.

Overview:

- Previously we have reported the successful completion of a large-scale freeze-thaw (F-T) experiment, first of its kind, to evaluate durability carbonated soils to frost action (Figure 1). During this reporting period, we processed and analyzed test data to understand the changes in shear wave velocity, and vertical movements (heave/settlement), and soil strength/stiffness via the California bearing ratio (CBR) within the carbonated subgrade soil.
- We also investigated the long-term strength of carbonated soils that were subjected to saturation and freeze-thaw cycles (summer field condition) via field California Bearing Ratio (CBR) testing. A total of 10 CBR tests were performed at different depths. A glimpse of CBR results to demonstrate the long-term (after 3-months) post F-T strength is presented in Figure 2. It is observed that the cemented soils (between 0-150 mm) were able to regain the strength after being subjected to two F-T cycles. This result is encouraging in terms of durability of the materials.

Meeting the Overarching Goals of the Project:
How did the previous items help you achieve the project goals and objects? Please give one bullet point for each bullet point listed above.

- The above activities helped to evaluate the freeze-thaw performance (durability) of frost susceptible subgrade soils (silt with sand, ML) that was stabilized via carbonation.
- The direct quantification of strength of carbonated soils at different testing protocols via CBR testing provided material quality/rating (refer to Figure 1) which would be helpful to make recommendations on the applicability of this novel soil cementation method (i.e. carbonation) in the cold regions of the U.S., for example in Maine, for pavement subgrade soil stabilization.

Accomplishments:
List any accomplishments achieved under the project goals in bullet point form…

- One peer-reviewed conference paper has been published in ASCE Geotechnical Special Publication No. 315 which was presented at Geo-Congress 2020 in Minneapolis, MN.
- The innovative ground improvement (i.e. soil carbonation) method to support transportation infrastructure is presented in 2022 Chicago Geotechnical Lecture Series and 4th annual TIDC conference.

Task, Milestone, and Budget Progress:

Complete the following tables to document the work toward each task and budget (add rows/remove rows as needed, make sure you complete the Overall Project progress row and include all tasks even if they have ended or have not been started)…

Table 1: Task Progress			
Task Number: Title	**Start Date**	**End Date**	**% Complete**
Task 1.1: Literature review, scope of the research, and further study	September 2018	Ongoing	100% to date
Task 2.1: Elemental testing on lime mixed soils	December 2018	December 2020	100%
Task 2.2: Laboratory trial of aqueous-phased carbonation	February 2021	April 2021	100%
Task 2.3: Bench scale trial (gaseous carbonation at elevated pressure)	April 2021	May 2021	100%
Task 3.1: Planning, design, and site establishment for carbonation testing in a large soil box	May 2021	September 2021	100%
Task 3.2: Performing the pseudo-field carbonation and freeze-thaw (durability) testing	October 2021	August 2022	100%
Task 3.3: Soil box experiment-data processing and interpretation	December 2021	December 2022	90%
Task 3.4: Technical manuscript and report preparation	September 2022	May 2023	20%
Phase 1 Overall	September 2018	Ongoing	100% to date
Phase 2 Overall	December 2018	April 2021	100%
Phase 3 Overall	May 2021	May 2023	85%

Table 2: Milestone Progress			
Milestone #: Description	**Corresponding Deliverable**	**Start Date**	**End Date**
Milestone 1:			
Milestone 2:			
Milestone 3:			
Milestone 4:			
Milestone 5:			
Milestone 6:			
Milestone 7:			
Milestone 8:			
etc.			

Table 3: Budget Progress		
Project Budget	**Spend – Project to Date**	**% Project to Date (include the date)**
Enter Phase 1 Full Budget	Enter Phase 1 Full Spend Amount (Federal + Cost Share)	Enter Phase 1 % Spent
Enter Phase 2 Full Budget	Enter Phase 2 Full Spend Amount (Federal + Cost Share)	Enter Phase 2 % Spent
Enter Phase 3 Full Budget	Enter Phase 3 Full Spend Amount (Federal + Cost Share)	Enter Phase 3 % Spent

Is your Research Project Applied or Advanced?

☒ **Applied** (*The systematic study to gain knowledge or understanding necessary for determining the means by which a recognized and specific need may be met.)*

☒ **Advanced** *(An intermediate research effort between basic research and applied research. This study bridges basic (study to understand fundamental aspects of phenomena without specific applications in mind) and applied research and includes transformative change rather than incremental advances. The investigation into the use of basic research results to an area of application without a specific problem to resolve.)*

Education and Workforce Development:

Answer the following questions (N/A if there is nothing to report):

1. Did you provide any workforce development or training opportunities to transportation professionals (already in the field)? If so, what was the training? When was it offered? How many people attended? (i.e. The research team provided an in the field training for the SAR technology for 3 maintenance crew members of the MassDOT on 3/31/2021. The members learned how to use the technology and interrupt the data.)
   N/A
2. Did you hold meetings with any transportation industry organizations or DOTs? If so, what was the meeting's purpose? When was it offered? How many people attended? (i.e. The research team held a meeting with MaineDOT to update them on the progress of the research findings and how the findings can be implemented on 3/31/2021. 15 DOT maintenance members were present at the meeting.)
   N/A
3. Did you host/participant in any K-12 education outreach activities? If so, what was the activity? What was the target age/grade level of the participants? How many students/teachers attended? When was the activity held? (i.e. 25 8th graders and 2 teachers visited the concrete lab and created small concrete trinkets like Legos on 3/31/2021. They learned about the different types of fibers that can be used in the concrete.)

   Soil carbonation was demonstrated for 40 high school students as part of the Upward Bound program during summer 2022. The students participated in a hands-on activity where they worked in teams and mixed, compacted, and carbonated soil.

   The carbonation approach was also introduced to 10 high school teachers during a separate visit in summer 2022 to illustrate how the soil stabilization approach could be demonstrated in the classroom.

Technology Transfer:

Complete all of the tables below and provide additional information where requested. Please provide ALL requested information as this is one of the most important sections for reporting to the USDOT. ***ONLY provide information relevant to this reporting period.***

Use the table below to complete information about conference sessions, workshops, webinars, seminars, or other events you led/attended where you shared findings as a result of the work you conducted on this project:

Table 4: Presentations at Conferences, Workshops, Seminars, and Other Events

Type	Title	Citation	Event & Intended Audience	Location	Date(s)
Conference	Successful scaling of an innovative subgrade stabilization method in the lab: what's next?	-	4th Annual Transportation Infrastructure Durability Conference Innovators, researchers, industry leaders, and transportation professionals	Wells Conference Center, UMaine, Orono, ME	August 11, 2022
N/A					

Use the table below to report any publications, technical reports, peer-reviewed articles, newspaper articles referencing your work, graduate papers, dissertations, etc. written as a result of the work you conducted on this project. Please list only completed items and exclude work in progress.

Table 5: Submitted/Accepted Publications, Technical Reports, Theses, Dissertations, Papers, and Reports

Type	Title	Citation	Date	Status
Peer-reviewed conference paper	Elemental testing of carbonated silty sand treated with lime	Hossen, S. B., Gallant, A. P., & Ashraf, W. (2020). Elemental Testing of Carbonated Silty Sand Treated with Lime. *Geo-Congress 2020*, ASCE GSP 315, Minneapolis MN, pp. 562-571.	February 21, 2020	Published
Peer-reviewed Journal	Influence of initial soil state parameters on strength improvement of granular soils under low CO_2 pressure conditions	Hossen, S. B., Gallant, A. P., & Ashraf, W. (2021). Influence of initial soil state on calcium carbonate binder precipitation and strength improvement of lime mixed granular soils via accelerated carbonation. *J. Geotech. Geoenviron. Eng.*, ASCE (In preparation).	-	Under in- house review for final submission

Answer the following questions (N/A if there is nothing to report):

1. Did you deploy any technology during the reporting period through pilot or demonstration studies as a result of this work? If so, what was the technology? When was it deployed?
   N/A
2. Was any technology adopted by industry or transportation agencies as a result of this work? If so, what was the technology? When was is adopted? Who adopted the technology?
   N/A
3. Did findings from this research project result in changing industry or transportation agency practices, decision making, or policies? If so, what was the change? When was the change implemented? Who adopted the change?
   N/A
4. Were any licenses granted to industry as a result of findings from this work? If so, when? To whom was the license granted?
   N/A

5. Were any patent applications submitted as a result of findings from this research? If so, please provide a copy of the patent application with your report.

   A due diligence review by UMaine's Department of Industrial Cooperation is currently underway for a patent application. At this time a non-disclosure agreement has also been signed by a potential industrial partner, Geopier, to explore potential avenues for scaling and implementing carbonation techniques to stabilize roadway subgrades.

6. Did industry organizations or DOTs provide cost-share (cash or in-kind) to your research during the reporting period? Who was the organization? Please provide an in-kind support invoice from the organization with your report (this is kept confidential and used for record keeping purposes only).
   N/A

Please add figures/images that can be included on the website and/or in marketing/social media materials to further clarify your research to the general public. This is very important to our Technology Transfer initiatives.

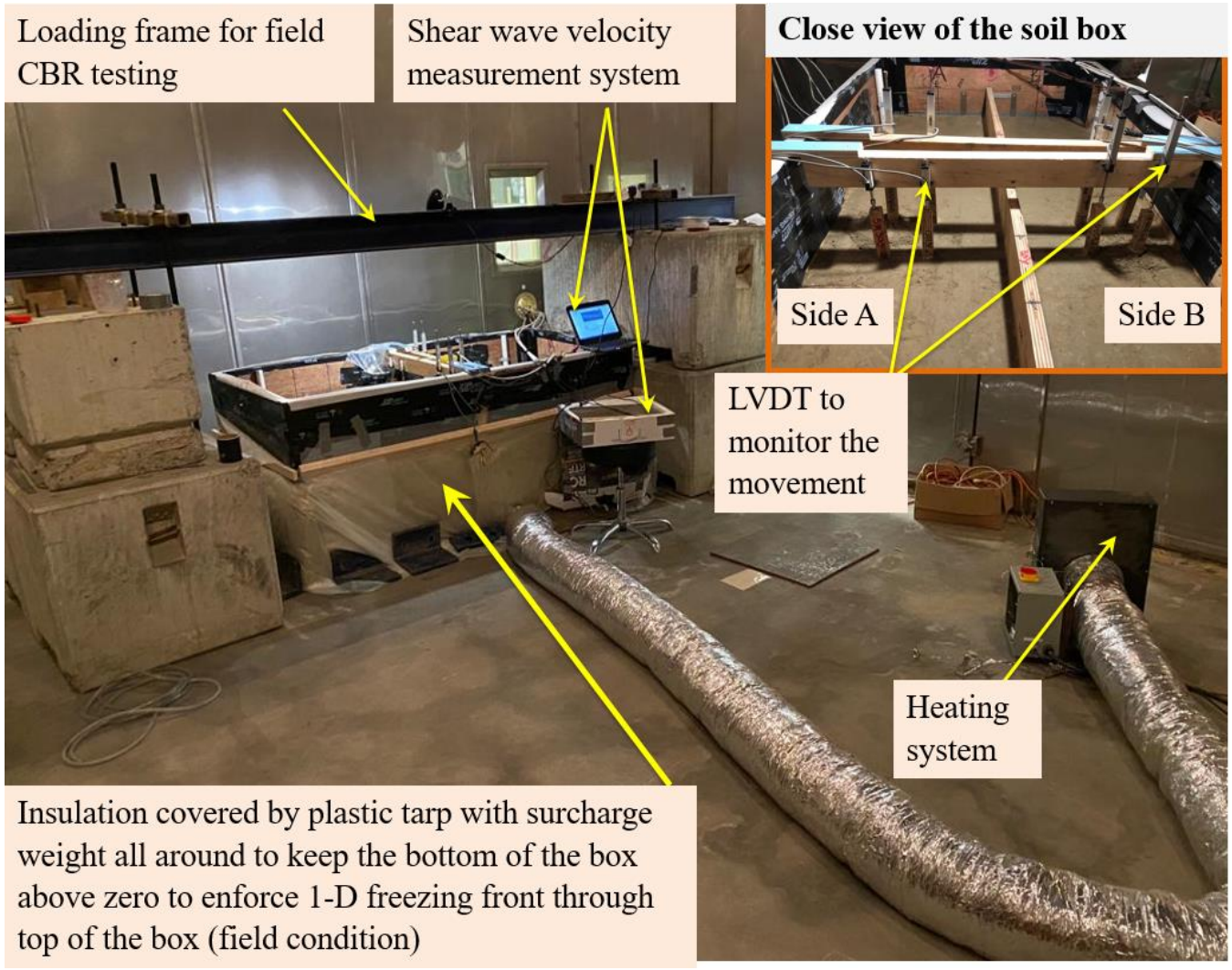

Figure 1. Experimental configuration for freeze-thaw durability testing of carbonated frost-susceptible soils in an environmental chamber.

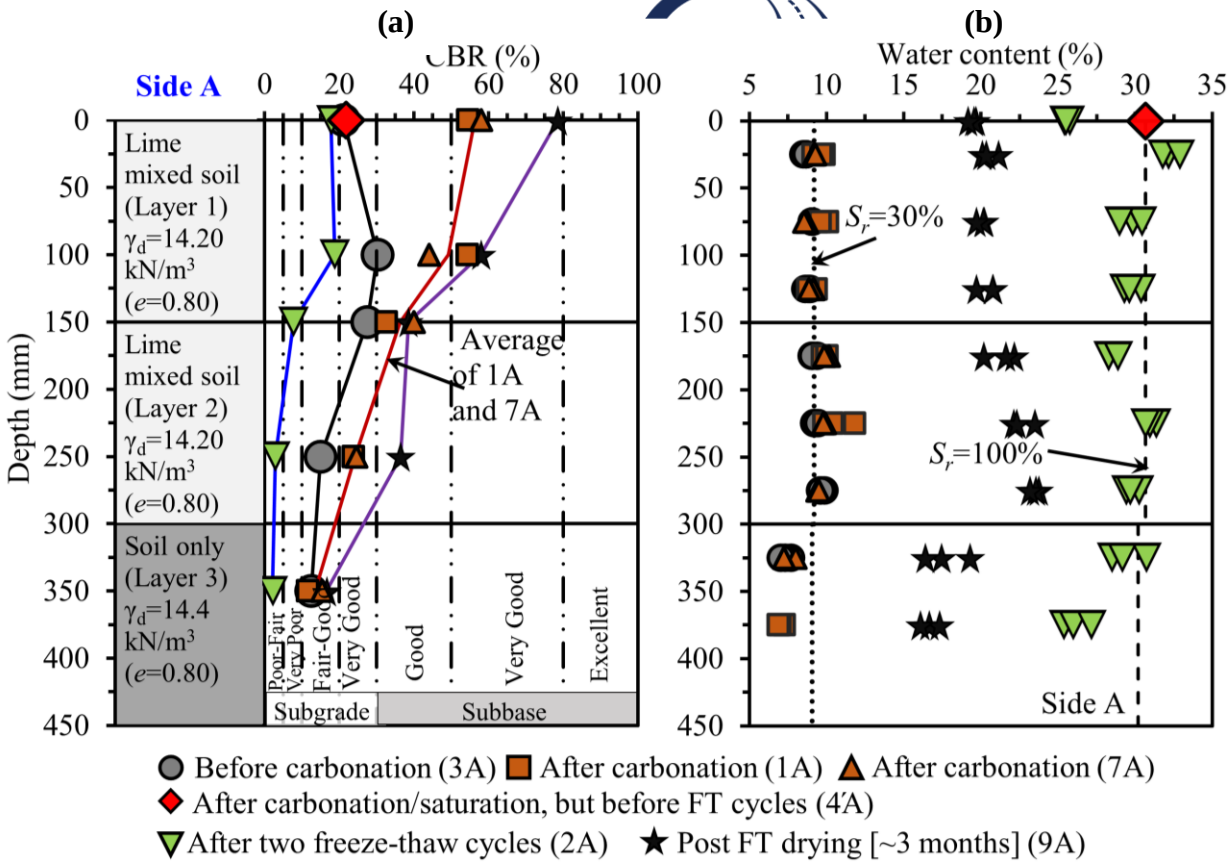

Figure 2. a.) California Bearing Ratio (CBR), and b.) water content. Variation of soil stiffness and strength and the associated water content profile for the soil box at various stages of testing are shown. The soil was carbonated in the upper 150 mm. After carbonating the soils were saturated and exposed to two freeze-thaw cycles. The CBR remained elevated, relative to post-saturation levels, after being exposed to freeze-thaw cycles. The lower layers dropped significantly (comparison of red diamond and blue line with green triangles). After drying, the CBR increased to or supassed values that were measured prior to environmental testing, thus demonstrating the durability of carbonated soil. [Notes: number in the legend shows the testing location in the soil box]

Describe any additional activities involving the dissemination of research results not listed above under the following headings:

Outputs:
Definition: Any new or improved process, practice, technology, software, training aid, or other tangible product resulting from research and development activities. They are used to improve the efficiency, effectiveness, and safety of transportation systems. List any outputs accomplished during this reporting period:

An innovative ground improvement technique, soil carbonation, has been shown to be a potential method to stabilize subgrade materials. When deployed under the correct conditions, it can stabilize soil efficiently and consumes carbon dioxide during the process, significantly reducing the carbon footprint relative to conventional chemical stabilization methods for soil.

Outcomes:
Definition: The application of outputs; any changes made to the transportation system, or its regulatory, legislative, or policy framework resulting from research and development activities. List any outcomes accomplished during this reporting period:

Impacts:
Definition: The effects of the outcomes on the transportation system such as reduced fatalities, decreased capital or operating costs, community impacts, or environmental benefits. The reported impacts from UTCs are used for the assessment of each UTC and to make a case for Federal funding of research and education by demonstrating the impacts that UTC funding has had on technology and education. NOTE: The U.S. DOT uses this information to assess how the research and education programs (a) improve the operation and safety of the transportation system; (b) increase the body of knowledge and technologies; (c) enlarge the pool of people trained to develop knowledge and utilize technologies; and (d) improves the physical, institutional, and information resources that enable people to have access to training and new technologies. List any outcomes accomplished during this reporting period:

This project has demonstrated that soil carbonation has the potential to be scaled and utilized as a method to stabilize poor subgrade materials, which would enhance the durability and increase the longevity of pavement systems. The project has resulted in an intimate understanding of the conditions required to efficiently deploy this soil stabilization technique that may be adopted by contractors and practitioners. It has been demonstrated that carbonated frost-susceptible materials are durable under freeze-thaw conditions. Additionally, the consumption of carbon dioxide during the carbonation process has the potential to nearly eliminate the carbon footprint associated with process-based emission of lime, which was used as the alkali additive (a significant advantage over conventional lime stabilization for soil).

Participants and Collaborators:

Use the table below to list individuals (compensated or not) who have worked on the project other than students.

Table 6: Active Principal Investigators, faculty, administrators, and Management Team Members				
Individual Name & Title	**Dates involved**	**Email Address**	**Department**	**Role in Research**
Aaron Gallant, PhD, PE	09/2018-09/2022	aaron.gallant@maine.edu	Civil Engineering, University of Maine	PI
Warda Ashraf, PhD	09/2018-09/2022	warda.ashraf@uta.edu	Civil Engineering, UT Arlington	Co-PI

*Use the table below to list **all** students who have participated in the project during the reporting period. (This includes all paid, unpaid, intern, independent study, or any other student that participated in this project.) **ALL FIELDS ARE REQUIRED.***

Table 7: Student Participants during the reporting period								
Student Name	**Start Date**	**End Date**	**Advisor**	**Email Address**	**Level**	**Major**	**Funding Source**	**Role in research**
SK Belal Hossen, EI	09/2018	-	Aaron Gallant, PhD, PE Warda Ashraf, PhD		PhD	Civil and geotechnical engineering	TIDC & UMaine	Graduate Research Assistant
Temitope Omokinde	06/2022	-	Aaron Gallant, PhD		MS	Civil Engineering	TIDC	Graduate Research Assistant

Use the table below to list any students who worked on this project and graduated or received a certificate during this reporting period. Include information about the student's accepted employment during the reporting period (i.e. the student is now working at MaineDOT) or if they are continuing their students through an advanced degree (list the degree and where they are attending).

Table 8: Students who Graduated During the Reporting Period			
Student Name	**Degree/Certificate Earned**	**Graduation/Certification Date**	**Did the student enter the transportation field or continue another degree at your university?**
			Please list the organization or degree
N/A			

Use the table below to list any students that participated in Industrial Internships during the reporting period:

Table 9: Industrial Internships			
Student Name	**Degree/Certificate Earned**	**Graduation/Certification Date**	**Did the student enter the transportation field or continue another degree at your university?**
			Please list the organization or degree
N/A			

*Use the table below to list **organizations** that have been involved as partners on this project and their contribution to the project during the reporting period.*

Table 10: Research Project Collaborators during the reporting period						
Organization	**Location**	**Contribution to the Project**				
		Financial Support	**In-Kind Support**	**Facilities**	**Collaborative Research**	**Personnel Exchanges**
		List the amount	List the amount	Mark with an "x" where appropriate		
N/A						

*Use the table below to list **individuals** that have been involved as partners on this project and their contribution to the project during the reporting period. (**List your technical champion(s) in this table.** This also includes collaborations within the lead or partner universities who are not already listed as PIs; especially interdepartmental or interdisciplinary collaborations.)*

Table 11: Other Collaborators				
Collaborator Name and Title	**Contact Information**	**Organization and Department**	**Date(s) Involved**	**Contribution to Research**
	For internal use only			(i.e. technical champion, technical advisory board, test samples, on-site equipment, data, etc.)
N/A				

Use the following table to list any transportation related course that were taught or led by researchers associated with this research project during the reporting period:

Table 12: Course List						
Course Code	**Course Title**	**Level**	**University**	**Professor**	**Semester**	**# of Students**
i.e. CE 123		Grad or undergrad?	Where was the course taught?	Who taught the course?	Enter Spring, Fall, Summer, Winter and the year	How many students were enrolled in the class?
N/A						

Changes:

List any actual or anticipated problems or delays and actions or plans to resolve them (list no-cost extension requests here)…

N/A

List any changes in approach and the reasons for the change…

N/A

Planned Activities:

List the activities planned during the next quarter.

- To quantify the carbonate binder content via thermogravimetric analyses (TGA) on samples subjected to F-T cycles and post F-T drying (long term).
- Drafting two technical manuscripts on novel carbonation technique to stabilize the subgrade soils and its freeze-thaw performance.
- Preparation of the final report.