Compressibility Behavior of MICP-Treated Sand Treated under Unsaturated Conditions

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ABSTRACT

Microbially induced calcium carbonate precipitation (MICP) is a soil improvement technique that has the potential to meet the expanding needs of society with marginal environmental consequences. In this method, biological activities of bacteria lead to formation of calcium carbonate at particle–particle contacts. Precipitated cementation links soil grains together and improves engineering behavior of soil. In recent years, the method has demonstrated promising results in a wide range of geotechnical applications where soil stabilization is mainly performed under unsaturated conditions. However, the deformation and compressibility behavior of unsaturated MICP-treated soil is yet to be investigated. A series of consolidation tests were performed on untreated and MICP-treated sand specimens. Specimens were treated by percolation in unsaturated conditions. Tests were performed in a modified consolidation setup equipped with bender element sensors. Consolidation test results indicated that unsaturated MICP-treatment significantly reduced compressibility of soils. A sudden collapse in shear wave velocity measurements with stress increment was observed in moderately cemented specimens that was less pronounced in lightly and heavily cemented specimens.

INTRODUCTION

Geotechnical structures such as tunnels, deep foundations, dams, retaining walls are among the infrastructures that provide support for urban development. These systems aim to support communities, reduce natural disaster casualties, and protect transportation and energy infrastructures. In recent years, aging structures and growing construction demands have prompted researchers to seek more versatile and environmental-friendly soil stabilization alternatives. Microbially induced calcium carbonate precipitation (MICP) has the potential to be a more sustainable and eco-friendly approach compared to the traditional soil improvement measures (e.g., application of Portland cement) (DeJong et al. 2010).

MICP is a natural biochemical process that results in the formation of $CaCO_3$ at particle-particle contacts (DeJong et al. 2006). In this method, either stimulated or augmented bacteria hydrolyze urea as a source of energy for metabolic activities and produce ammonium and carbonate ions (Khodadadi et al. 2017). Resulting carbonate ions bond with soluble calcium present in the soil system and precipitate $CaCO_3$. Precipitation may be formed on both soil grain surfaces and particle contact points (Feng and Montoya 2015). As a result, mechanical soil properties are enhanced by densification and cementation formation in soil matrix (DeJong et al. 2006).

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The application of MICP as a soil stabilization technique has confirmed significant improvement of mechanical soil properties in laboratory settings (Montoya and DeJong 2015; Lin et al. 2016). Numerical models have been developed to optimize treatment strategies for field implementations (Faeli et al. 2022). In addition, successful meter-scale and field trials have demonstrated that the technique is moving towards being an accepted practice in construction industry (van Paassen et al. 2010; Gomez et al. 2015, 2017; Lee et al. 2019; Do et al. 2020; Ghasemi and Montoya 2020; San Pablo et al. 2020; Terzis et al. 2020; Montoya et al. 2021). In actual field conditions, a soil element may likely undergo a k_0 loading path. Therefore, to perform settlement analyses, gaining an understanding of the deformation and oedometric behavior of MICP-treated soil is essential. Previous researchers have studied the effect of initial density and different cementation levels on the compressibility response of saturated MICP-treated sands (Feng and Montoya 2014; Lin et al. 2016). Results of the tests on specimens treated under saturated conditions exhibited lower deformations and compressibilities compared to the untreated sand. However, in many field implementations soil is not under saturated conditions and unsaturated conditions prevail. Therefore, it is necessary to have a clear understanding of the properties of the bio-cemented soil treated under unsaturated conditions.

In the study presented herein, a set of consolidation tests was performed on untreated and MICP-treated sand specimens. Specimens were treated with percolation under unsaturated conditions. During the treatment and consolidation phases, shear wave velocity measurements were carried out to assess the changes in stiffness due to cementation generation or degradation. Deformations and shear wave velocities were recorded with incremental loading and unloading. Results were then compared to the available data for specimens treated under saturated conditions.

MATERIALS AND METHODS

Tested material and specimen preparation. Specimens were prepared from silica sand excavated and transported from the South Jetty in Newport, OR. Soil comprised of subrounded and subangular particles and was classified as poorly graded sand (SP). The physical properties of the tested sand are shown in Table 1. All specimens were prepared by air-pluviation technique to a relative density of about 39%. Cylindrical columns were used to perform consolidation tests with a diameter and height of about 6.4 cm and 3.0 cm, respectively. Columns consisted of stainless steel walls and acrylic bottom and top caps equipped with a pair of bender elements. The use of stainless steel minimizes the lateral deformations of the specimens during loading. All specimens were kept under 30 kPa overburden during the MICP-treatments.

Table 1. Physical of the Tested Sand.

D_{50} (mm)	e_{min}	e_{max}	G_s	C_c	C_u
0.18	0.57	0.78	2.67	1.03	1.32

Treatment Process. *Sporosarcina pasteurii*, a common ureolytic soil bacterium, was used to catalyze MICP reactions. Bacteria culture was prepared using the procedure described by (Montoya et al. 2019). An ammonium-yeast extract medium was used to cultivate bacteria. Ingredients of the medium were autoclaved and sterilized separately and then mixed with the microbial stock culture. The solution was then incubated at 30°C with a 200 rpm speed for about

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20 hours to achieve an optical density (OD_{600}) of 0.8 to 1.2. The resulted culture was centrifuged in 15 ml vials at 4000 g for 15 min. The supernatant was then substituted with the fresh growth medium. Vials were centrifuged one more time and refrigerated at 4 °C for a maximum of 14 days.

Treatment solutions were applied using percolation on free-draining specimens, allowing soil to experience unsaturated conditions during treatment. A two-phased solution application procedure was used to treat the specimens. Treatments started with an introduction of biological solution and followed by four cementation treatments. This procedure was repeated until a target improvement level was obtained. Treatments were completed three times a day with 6-6-12 hour intervals. The biological solution consisted of 0.3 M urea and 10^7 cells/mL bacteria, and the cementation solution included 0.3 M urea and 0.1 M $CaCl_2$. These recipes have been successfully implemented in the previous laboratory and field-scale MICP experiments (Ghasemi et al. 2019; Ghasemi and Montoya 2020). Cementation cycles were repeated 24, 16, and 8 times to reach heavy, moderate, and light cementation levels, respectively. Initial and final shear wave velocities and carbonate contents are shown in Table 2. All specimens were saturated by passing 10 times pore volumes of deaired water using a pump. A burette filled with water was connected to the bottom of the specimens to ensure saturation during consolidation stages (Fig.1). Specimens were consolidated under 30, 60, 120, 240, 480, 960, and 1920 kPa vertical loads and were subjected to subsequent loading and unloading increments.

Table 2. Characteristics of the Tested Specimens.

Specimen	Cementation level	$(V_s)_{initial}$ (m/s)	$(V_s)_{final}$ (m/s)	Number of treatments	$CaCO_3$ content (%)
U	Untreated	134	-	0	0
L	Light	127	236	8	0.8
M	Moderate	125	598	16	1.4
H	Heavy	138	986	24	4.3

Shear Wave Velocity Measurement. Shear wave velocity was measured during treatments and consolidation loading/unloading increments. A pair of bender elements was placed in the top and bottom caps of a consolidation setup. Bender elements were fabricated following the approach presented by (Montoya et al. 2012). One of the benders was used to send a sine wave pulse (e.g., 10 kV, 10 Hz) through the specimen. The arrival time of the shear wave at the other bender element was used to calculate the shear wave velocity of the soil specimen.

Mass of $CaCO_3$ Measurement. Upon completion of the consolidation, acid washing was performed on specimens to determine the mass of carbonate associated with each cementation level. Soil samples were oven-dried for about 24 hours and then were soaked in 1 M HCl. After settlement of the sand particles, solution was substituted with fresh acid. This process was repeated until no more bubbles were observed in the specimens. Samples were then rinsed and oven-dried for 24 h. Mass of $CaCO_3$ was expressed as the weight loss during acid washing divided by the dry weight of untreated soil (Mortensen et al. 2011).

RESULTS AND DISCUSSION

Effect of Bio-cementation on Compressibility Behavior of Soil. The change in vertical strain with applied loading/unloading sequences for specimens treated to varying cementation

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levels is shown in Fig. 2. In this figure, untreated, lightly, moderately, and heavily cemented specimens are shown with "U", "L", "M", and "H", respectively. Untreated soil indicated a stress-strain behavior similar to that of disturbed clay with no clear point of maximum curvature. However, with the progress of cementation, the transition between compression and recompression paths became more pronounced. In addition, a gradual increase in measured preconsolidation stresses with cementation development was observed.

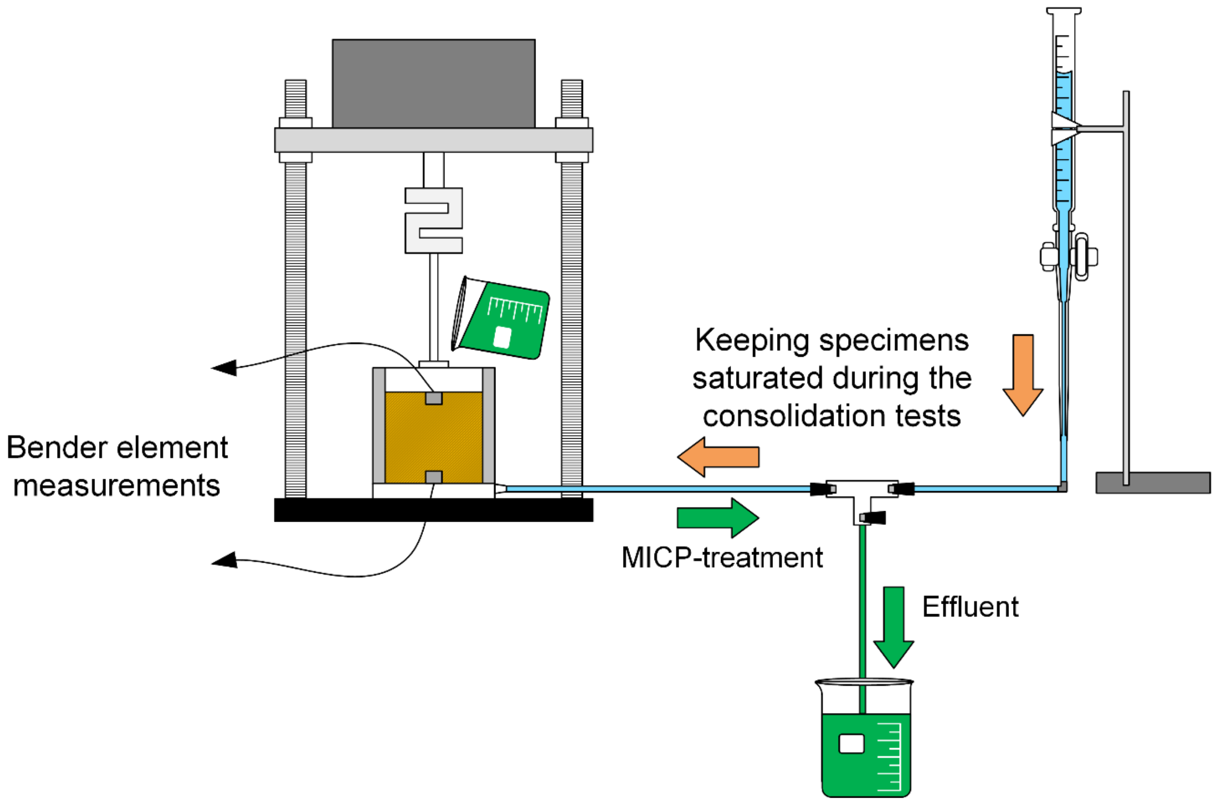

Figure 1. Treatment and consolidation setup sketch.

Under a similar loading, the maximum strain values were highest for untreated soil and decreased with an increase in cementation level. The observed behavior is a result of cementation bond formation that decreased the compressibility of the soil matrix. Densification and void ratio reduction resulting from the MICP-treatment further contribute to this behavior. Similar behavior has been reported by previous researchers (Feng and Montoya 2014; Lin et al. 2016).

With load removal during unloading, lower strain values were observed in all tests. The difference between strain during loading and unloading is an indication of the soil matrix's ability to recover the imposed strain. A narrower stress-strain curve at higher cementation levels demonstrates a greater ability to recover the strain during unloading. After several loading/unloading cycles, curves still exhibit a similar trend and values as the first unloading path. Such observations may imply that the majority of weaker cementation bonds have been degraded during the first loading/unloading path and the additional cycles have marginal effects on decementation of cemented bonds.

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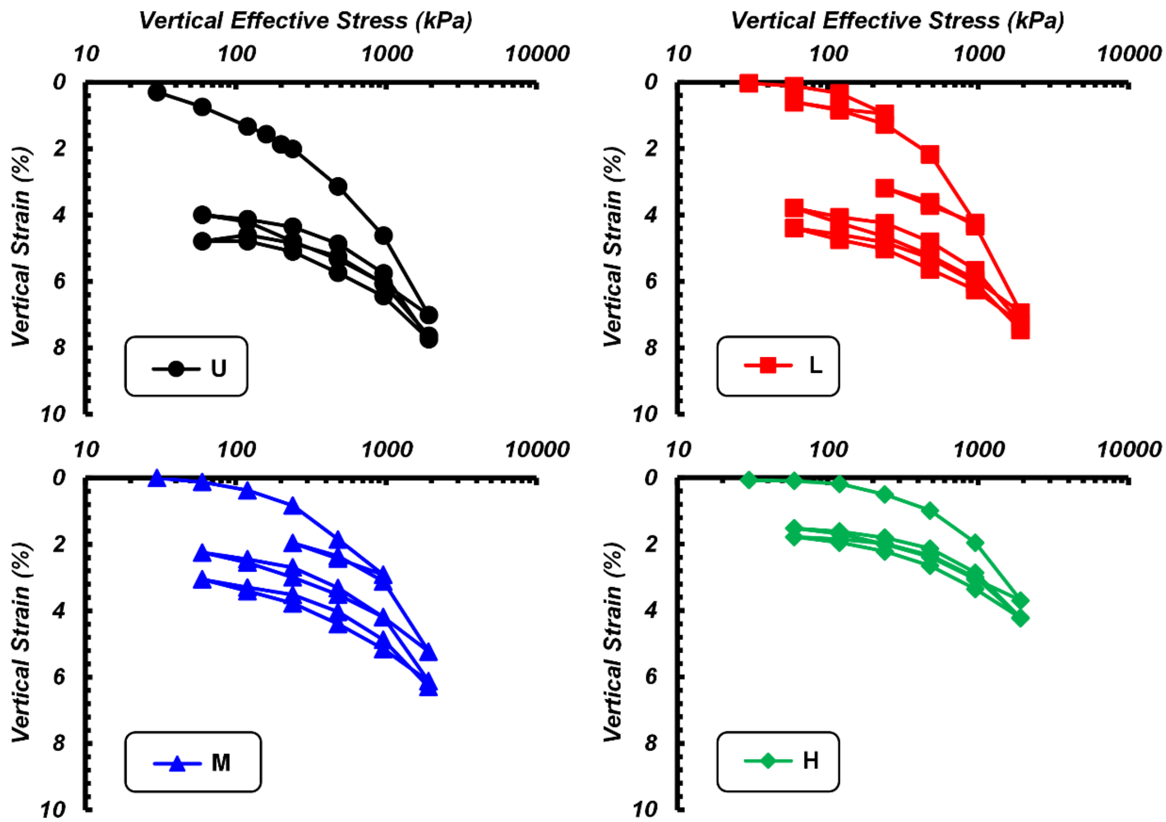

Figure 2. The Stress-strain behavior of specimens with varying cementation levels.

Effect of Loading/Unloading and Collapse Behavior. Shear wave velocity measurements during loading/unloading stress paths for various cementation levels are shown in Fig. 3. The untreated specimen demonstrated the lowest shear wave velocity and values increased for other specimens with an increase in cementation level. The untreated soil exhibited shear wave velocity increase during loading. At given stress, unloading shear wave velocities were slightly higher than their loading counterparts. This observation is in accordance with the uncemented sand's behavior reported by previous researchers (Yun and Santamarina 2005; Lin et al. 2016; Do et al. 2019).

Unlike the untreated soil, cemented specimens initially exhibited relatively constant shear wave velocities with stress increase. At low levels of confinements, cementation governs the soil matrix's stiffness (Yun and Santamarina 2005). Therefore, low levels of applied stresses were not sufficient to induce cementation bond degradation and shear wave velocity changes. In the moderately cemented specimen, a sudden stiffness loss (collapse behavior) at vertical stress of about 240 kPa was observed. Such observation could be a result of local bond degradation. With the further application of stress and beyond 480 kPa vertical load, shear wave velocity started to increase again. At higher load increments soil's behaviors becomes stress-controlled and shear wave velocities increased with loading increments. The collapse behavior was not pronounced in the lightly cemented specimen; the observed behavior could be the result of weaker and fewer cementation bonds that allows particle rearrangement and more ductile behavior compared to the moderately cemented specimen. In addition, the collapse in shear wave velocity might have happened around 120 kPa confinement (yield stress from the stress-strain curve) and rebounded

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quickly with load increase, therefore it is not perceivable with the applied load increments. This could be further investigated by performing tests with smaller load increments. No clear collapse behavior was detected for the case of the heavily cemented specimen where greater coordination numbers and stronger bonds linked soil particles together. This is relatively similar to the saturated MICP-treatment condition where collapse behavior was not identified by previous researchers (Lin et al. 2016; Montoya et al. 2019).

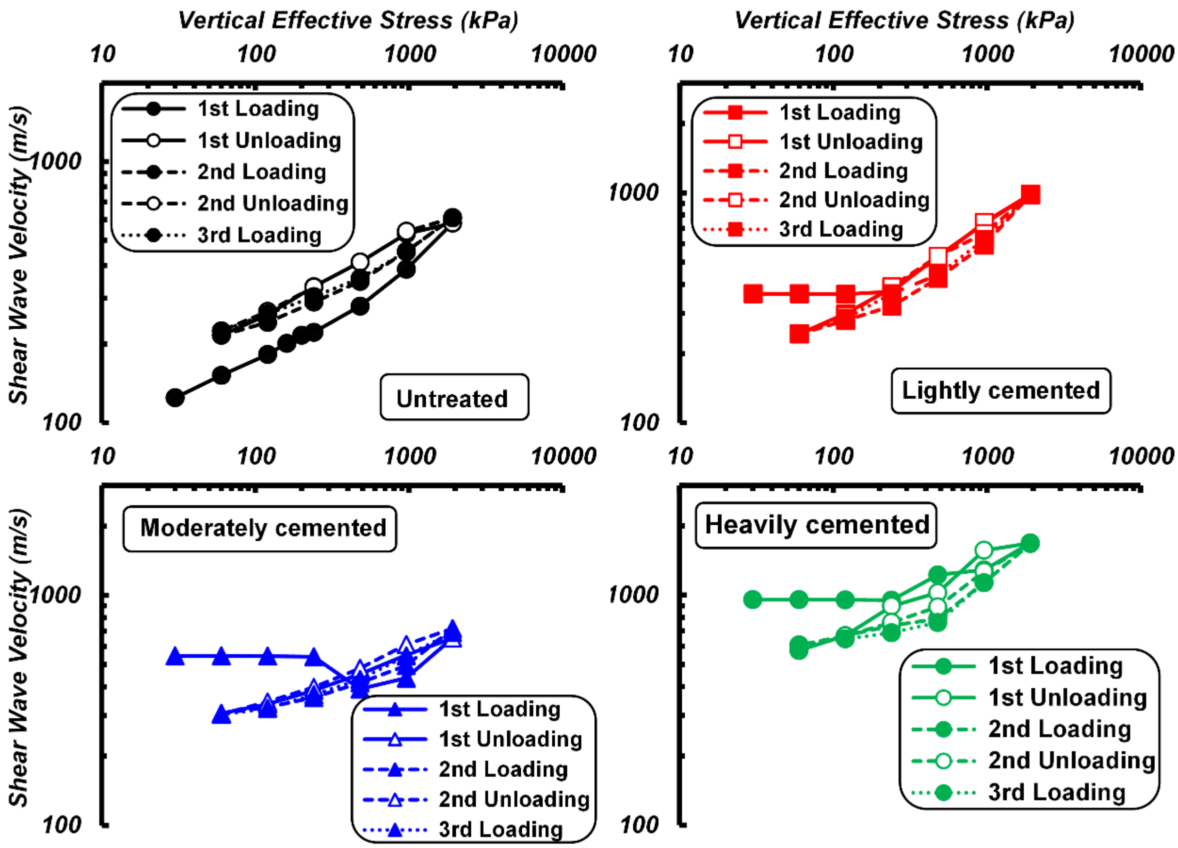

Figure 3. Treatment and consolidation for different cementation levels.

Cementation bond degradation and volume change behavior during consolidation tests could be assessed through V_s-e plot (Fig.4). The untreated soil presents a linear relationship between the increase in shear wave velocity and void ratio reduction. The concave upward path of moderately cemented soil indicates an initial bond degradation and softening followed by a hardening behavior. Unlike the moderately cemented soil, no clear concave path was observed for the case of lightly and heavily cemented specimens.

The behavior of a cemented soil matrix depends on curing stress, amount and cementation type, stress history, and density (Yun and Santamarina 2005). During unsaturated treatment and percolation, biological and cementation solution primarily exists in the form of menisci around the particle-particle contacts (Cheng et al. 2013). As a result of unsaturated MICP-treatment, cementation is mainly formed around the particle contacts. At light cementation levels, only small amounts of cementation are formed. However, the generated precipitations are not strong enough to prevent rearrangement of particles at yield stress. Therefore, no distinct collapse

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behavior in lightly cemented soils is observed. Conversely, in heavily cemented specimens, with the progression of cementation, more substantial precipitation is formed (e.g., Table 2). Therefore, formation of stronger cemented bonds prevents stiffness loss and collapse potential of the soil matrix.

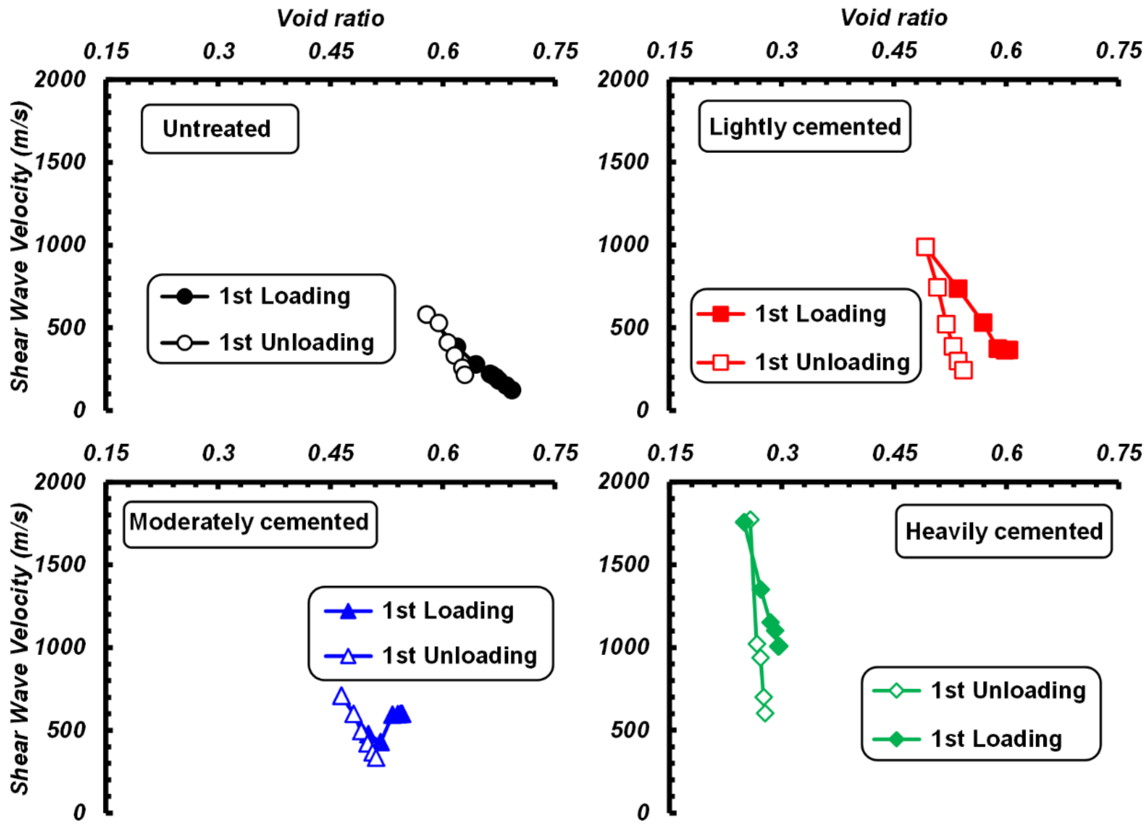

Figure 4. Shear wave velocity and void ratio measurements during loading/unloading paths for specimens treated to varying cementation levels.

CONCLUSION

This study presents the results of consolidation tests performed on unsaturated MICP-treated specimens with varying cementation levels. Similar to artificially cemented and MICP-treated soils under saturated conditions, specimens exhibited a significant decrease in compressibility behavior with an increase in cementation level. Compared to the untreated soil, preconsolidation stress increased and the peak strain significantly decreased as cementation increased. In addition, cemented specimens exhibited higher recoverable strain as cementation levels progressed.

In MICP-treated specimens measured shear wave velocities during consolidation tests initially exhibited a constant trend up to the yield stress value. With a further increase in applied stress, moderately cemented specimens experienced a drop in shear wave velocities. Shear wave velocity values increased again at higher levels of load application. The observed drop was less pronounced for lightly and heavily cemented soil specimens. Possible explanations for the observed behavior were discussed. Lightly cemented lacked sufficient cementation bonds between the particles allowing the immediate rearrangement of particles. Conversely, in heavily

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cemented specimens stronger cemented bonds prevented sudden stiffness loss of soil matrix. Further consolidation tests on different cementation levels are needed to verify the proposed hypothesis.

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