EPA Public Access

Author manuscript

J Appl Geophys. Author manuscript; available in PMC 2019 January 01.

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Published in final edited form as:

J Appl Geophys. 2018 ; 148: 234–244. doi:10.1016/j.jappgeo.2017.12.008.

Geophysical methods for monitoring soil stabilization processes

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Abstract

Soil stabilization involves methods used to turn unconsolidated and unstable soil into a stiffer, consolidated medium that could support engineered structures, alter permeability, change subsurface flow, or immobilize contamination through mineral precipitation. Among the variety of available methods carbonate precipitation is a very promising one, especially when it is being induced through common soil borne microbes (MICP – microbial induced carbonate precipitation). Such microbial mediated precipitation has the added benefit of not harming the environment as other methods can be environmentally detrimental. Carbonate precipitation, typically in the form of calcite, is a naturally occurring process that can be manipulated to deliver the expected soil strengthening results or permeability changes. This study investigates the ability of spectral induced polarization and shear-wave velocity for monitoring calcite driven soil strengthening processes. The results support the use of these geophysical methods as soil strengthening characterization and long term monitoring tools, which is a requirement for viable soil stabilization projects. Both tested methods are sensitive to calcite precipitation, with SIP offering additional information related to long term stability of precipitated carbonate. Carbonate precipitation has been confirmed with direct methods, such as direct sampling and scanning electron microscopy (SEM). This study advances our understanding of soil strengthening processes and permeability alterations, and is a crucial step for the use of geophysical methods as monitoring tools in microbial induced soil alterations through carbonate precipitation.

1 Introduction

Society is facing many challenges with ground quality, including soil stability, in densely populated areas [DeJong *et al.*, 2010]. The nature of soils, their use and induced changes (natural and/or anthropogenic) could lead to engineering problems [Dejong *et al.*, 2013]. Due to space limitations in densely populated areas, there is a need to enhance soil stiffness to address practical engineering problems, such as supporting standard foundations for building purposes [DeJong *et al.*, 2010], erosion prevention and dust control [Montoya *et al.*, 2013], crack remediation, and permeability reduction [Abo-El-Enein and Ali, 2012].

Soil stabilization methods, which increase soil stiffness and reduce permeability and porosity, have been introduced to address these engineering problems and risks to human health. *DeJong et al.*, 2010 discusses the cost of soil stabilization process and estimates US \$6 billion/year for more than 40,000 soil improvement projects worldwide. Common soil stabilization methods use materials such as cement, epoxy, acrylamide, phenoplasts, polyurethane, and glass water, which are all materials typically harmful to the environment. These materials commonly produce large amounts of CO₂ during production and leachate to groundwater resources can be poisonous (e.g. acrylamides) [*Worrell et al.*, 2001; *Karol*, 2003; *Chang et al.*, 2015]. Additionally, these methods are expensive, difficult to maintain over long periods of time, result in heterogeneous application, and could negatively impact soil properties [*Dejong et al.*, 2006].

Methods are needed that could offer enhanced soil stability, without the problems current approaches face. Microbial induced carbonate precipitation (MICP) offers an alternative soil stabilization approach and, if applied properly, can be a cost efficient, long term, and a relatively environmental friendly approach (e.g. uses less synthetic material and consumes CO₂ in cementation process) [*Ivanov and Chu*, 2008; *Anbu et al.*, 2016]. MICP typically involves the use of common soil borne microbes to promote calcite precipitation; calcite in return acts as the cementing agent for loose soils [*Dhami et al.*, 2013]. MICP's final result is similar to geochemical calcite precipitation (or lime injection soil stabilization), where both utilize calcite as the cementation agent. However, MICP is less expensive and more energy efficient because it requires less mechanical energy and man-made materials to apply [*DeJong et al.*, 2010]. Finally, the MICP application is non-disruptive to existing subsurface structures and can enhance the soil stiffness over larger areas due to low viscosity and injection pressure requirements [*Dejong et al.*, 2013].

1.1 Monitoring process

Soil stabilization processes (such as MICP) are typically long term projects and require continuous, high resolution monitoring. Subsurface monitoring can be achieved through direct or indirect monitoring techniques. Direct monitoring involves high accuracy destructive sampling and analysis (e.g. SEM imaging, pH, microbial activity and chemical concentration changes) but the methods used are typically spatially limited, invasive, expensive, labor intensive and lacking in real-time monitoring capabilities. On the contrary, indirect measurements (e.g., geophysical methods) offer high temporal and spatial capability, cost efficiency, and noninvasiveness; but have accuracy limitations [*Weil et al.*, 2012]. Since biochemical processes during microbial activities (e.g., MICP) can alter subsurface physical and chemical properties, geophysical methods can be used as monitoring tools [*Atekwana and Slater*, 2009]. This is not uncommon since geophysical methods have been used for engineering and environmental purposes, such as ground quality characterization [*Arjwech and Everett*, 2015].

We utilize two geophysical methods, shear-wave velocity and spectral induced polarization (SIP) for this MICP experiment. Shear-wave velocity is chosen because shear-wave velocity is commonly used by engineers to measure soil stiffness for soil strengthening processes [*DeJong et al.*, 2010] and it has been shown to be sensitive to MICP [*Dejong et al.*, 2006].

Although shear-wave velocity measurements are sensitive to soil stiffness changes [DeJong *et al.*, 2010], long term implementation can be challenging. Furthermore, shear wave measurements provide information only on the soil properties, not on the biological processes, and this is not optimal for microbial induced treatments (such as MICP). SIP is an established geophysical method in mineral exploration, with multiple recent environmental applications due to its unique sensitivity to interfacial and bulk properties of earth media [Kemna *et al.*, 2012]. SIP is also shown to be sensitive to microbial cells [Ntarlagiannis *et al.*, 2005], biofilm formation [Davis *et al.*, 2006], and biogeochemical processes [Flores Orozco *et al.*, 2011]. As a result, SIP is an attractive candidate for the monitoring of soil strengthening processes since it is sensitive to MICP products and processes (e.g. calcite precipitation) [Wu *et al.*, 2010; Martinez *et al.*, 2013] and is suitable for long term, remote controlled, and autonomous operation [Slater and Sandberg, 2000].

2 Material and methods

The most important aspect of MICP is calcite precipitation. Hence, for the geophysical monitoring of MICP to be successful, it is necessary to characterize the geophysical signatures of calcite precipitation in common porous media. Wu *et al.* (2010) conducted a series of measurements on glass beads showing that calcite precipitation can be detected with SIP measurements. The research presented here builds on this previous successful research [Wu *et al.*, 2010] through increasing complexity by utilizing sand/clay mixtures as porous media in an attempt to replicate a closer approximation to field conditions and by measuring shear-wave velocity in order to assess possible seismic property alterations due to MICP.

2.1 Geochemistry

CaCl_2 and Na_2CO_3 are the two solutions required for precipitating calcite [Wu *et al.*, 2010]. Calcite will be precipitated upon contact of CaCl_2 with Na_2CO_3 (eq. 1) and the precipitation will continue along the solution mixing zone [Laabidi and Bouhlila, 2016]. Equation 2 shows the ionic reaction resulting in calcite precipitation. Chemical modeling [Gustafsson, 2016] suggests that the resulting solution of this mixture, under our experimental conditions, will be over saturated with a stable form of solid phase calcite. In addition, other unstable forms of calcium carbonate (e.g., Vaterite, Aragonite and Monohydrocalcite) could be precipitated (table 1).

2.2 Spectral induced polarization

Electrical current in the subsurface typically travels through electrolytic (σ_{ele}) and surface (σ_{surf}) conduction. Additionally, electronic (σ_{elec}) conduction occurs in the presence of interconnected metallic minerals. Both electrolytic and surface conduction pathways are ionic in nature, the former through the fluids in the interconnected pore space, and the latter through the electrical double layer (EDL) at the available solid – fluid interfaces [Binley and Kemna, 2005]. Electrolytic conduction is a purely real term whereas surface conduction is a complex one [Weller et al., 2010]. Fluid properties are captured through σ_{ele} , while σ_{surf} is primarily controlled by the surface properties (e.g. surface area, pore size distribution, surface charge density) and with less dependence on fluid properties [Lesmes and Frye, 2001; Binley and Kemna, 2005; Weller et al., 2013].

Spectral induced polarization is an extension of the commonly used DC resistivity method by allowing for measurement of the complex electrical properties of earth media [Binley and Kemna, 2005; Kemna et al., 2012]. For the application of SIP, the conductivity magnitude ($|\sigma|$) and phase (φ) are measured and then converted to the real (σ') and imaginary (σ'') components of complex conductivity (σ^*):

$$\sigma^* = |\sigma| e^{i\varphi} = \sigma' + i\sigma'' \quad (3)$$

$$\sigma' = |\sigma| \cos(\varphi) \quad (4)$$

$$\sigma'' = |\sigma| \sin(\varphi) \quad (5)$$

where $i^2 = -1$. Assuming a parallel conduction pathway [Waxman and Smits, 1968]:

$$\sigma' = \sigma'_{ele} + \sigma'_{surf} \quad (6)$$

$$\sigma'' = \sigma''_{surf} \quad (7)$$

In this model, σ' represents electromigration (energy loss), and σ'' represents charge polarization (energy storage).

Phenomenological models, such as Debye decomposition (DD) and Cole-Cole, are commonly used to describe the spectral shape of SIP data [Nordsiek and Weller, 2008; Ustra et al., 2016; Weigand and Kemna, 2016]. Debye relaxation, as applied on porous media, is related to the mineral grain charge transport properties, and could provide additional information on the rock - mineral matrix. Using DD models, the relaxation time distribution

(RTD) can be retrieved, from which the grain and pore size distribution can be estimated [Florsch et al., 2014; Ustra et al., 2016]. Since the dominant process of soil stabilization methods is the formation and evolution of a new mineral phase (e.g. calcite), RTD could be used to track precipitation and dissolution processes, especially over long periods of times.

2.3 Shear-wave velocity

Many soil properties (from an engineering perspective, e.g. stiffness) can be derived from small-strain shear modulus (G_{max}). The value of G_{max} can be obtained from shear-wave velocity measurement by the use of piezoelectric bender elements [Lee and Santamarina, 2005] through equation 8. A piezoelectric bender element is a thin, two-layer plate that can be installed in most soil cells [Lee and Santamarina, 2005] and is designed for shear-wave velocity measurements in laboratory scale experiments [Dejong et al., 2006].

Piezoelectricity results in deformation of a crystalline structure of the piezoelectric substance by applying an electrical field. Interestingly, even a different polarity of the electrical field can result in different deformations. Piezoelectric substances can produce polarized electricity by applying load (deformation of the crystalline structure) [Lee and Santamarina, 2005] which can be monitored by designated instruments.

$$V_s = (G/\rho)^{1/2} \quad (8)$$

Where V_s is the shear wave velocity, G is the shear modulus, and ρ is the soil density [Santamarina et al., 2001].

2.4 Column setup

Laboratory experiments were conducted in PVC sample holders that were optimized for both SIP and shear-wave velocity measurements (figure 1). The column is equipped with three ports (two for injection, one for outflow) allowing flow control and including an effluent fluid sample collector. Two bender elements were mounted at the top and bottom and two at the sides of column. Two electrodes (at top and bottom) were designated for current injection and two middle electrodes (at the sides) were designated for electrical potential measurements (figure 1). Non-polarizing Ag-Cl electrodes, placed outside the current flow, were used here to minimize any spurious polarization effects [Vanhala and Soininen, 1995]. SIP measurements on fluid filled samples holders confirmed that the non-conductive epoxy coated bender elements used do not interfere with the electrical signals.

2.5 Sample preparation

Two different types of porous media were evaluated: (1) Ottawa sand (Diameter: 0.6 – 0.85 mm), and (2) Ottawa sand - kaolinite mixture (95% by weight (BW) Ottawa sand, 5% BW kaolinite). The sand – kaolinite mixture was mechanically mixed, following standard laboratory procedures, for homogeneous mixing [Heenan et al., 2013]. Following the process described in Wu et al. (2010), a mixture of 20mM CaCl_2 and 20 mM Na_2CO_3 was used to precipitate calcite.

All columns were wet packed (where the soil was dumped slowly in the CaCl_2 solution and settled with gravitational forces, to minimize the chance of air bubble presence in the medium) by following identical packing procedures in an effort to minimize discrepancies between different columns. To ensure that the columns reached chemical equilibrium before the experiment commenced, we performed daily SIP and shear wave measurements on the packed columns until reaching consistent results [Personna et al., 2013].

2.6 Experiment procedure

Each soil sample involved duplicate active columns (promoting calcite precipitation), and a single control column (no calcite precipitation). All experiments started after the columns reached equilibrium, which was 72 hours under our experimental conditions. At time zero [0], background SIP and shear-wave velocity were measured as well as influent/effluent pH and conductivity. The fluids were also collected and properly stored for detailed chemical analysis. We used an open flow regime with a flowrate of 0.04 ml/min, which was chosen to mimic common ground water flow velocity in porous media and prevent particle loss from the column. Figure 2 schematically describes the experiment process (inside of the columns) highlighting the injection ports, and estimated area of precipitation.

We performed continuous SIP monitoring for the duration of the experiment using the following parameters: 4.5 hours' cycle, frequency range of 1 mHz to 24 KHz, with 5 measurements per logarithmic cycle. Shear wave velocity measurements were carried out daily. Fluid samples were collected daily, from the outflow sealed container. For the 100% sand sample we also conducted hydraulic conductivity (HC) measurements using the constant head method [Head, 1994] prior to injection and after the experiment. Unfortunately, due to the loss of clay in the process of HC measurement, we could not perform this experiment on the sand + clay samples. The entire experiment including all measurements, were performed in a temperature controlled laboratory (25° C, +/- 1° C).

At the end of the experiment, destructive sampling was performed on all columns (Figure 3). Columns were drained and core samples were taken for scanning electron microscope imaging (SEM). The core samples were oven dried to eliminate any moisture, as is required for SEM imaging.

3 Results

Mixing the two solutions (table 2) leads to observable change in conductivity and pH (figure 4a and b). For both active columns, the conductivity decreased, while the pH increased; changes observed in the control column are minimal, probably associated with the effect of flow, and small preparation differences within the saturation media (e.g. fluid temperature) [Akiya and Savage, 2002]. Inductively coupled plasma (ICP) analysis showed a decrease in effluent dissolved calcium concentration right after the injection started, although this decrease for the sand + clay sample was more dramatic at the beginning (figure 4c).

The hydraulic conductivity (K) of the sand sample was measured in two stages, immediately after packing, then before the injection of the mixing solutions, and again at the end of the

experiment (240 hours). K reduced an order of magnitude over that period; (table 3), while no changes in K were observed for the control column (table 3).

The imaginary component of the complex conductivity changed as the experiment progressed, presumably in response to calcite precipitation (figure 5). Although we monitored changes every 4.5 hours, we present a subset of the data that presents visually cleaner figures while preserves the trend observed (24 hour cycles). For both active samples, the magnitude of the imaginary conductivity response is developing two distinctive peaks at frequencies of 1 Hz and 1 mHz; the low frequency peak might not be fully captured since the lowest operating frequency of our system is 1 mHz. The sand sample imaginary conductivity at 1 mHz initially increased until time 72 hours (figure 5c) and after a small decrease, increased with a relatively slower trend until the end of the experiment (240 hours of injection). The 10 mHz peak behaved differently with maintaining a relatively constant value toward the end of the experiment (figure 5d). The sand + clay sample showed an initial increase until time 120 hours (figure 5a) and after a decrease, reached a constant value (at both 1 Hz and 1 mHz) until the end of the experiment (figure 5b).

The most dominant changes occur around 1 Hz and 1 mHz; for both active columns, where the same spectral and temporal behavior are observed (figures 5 and 6). In contrast, the control column does not show any noticeable changes (figures 6a and 6b). Although the observed trends are relatively similar for both samples, the magnitude of the observed change is greater, and with earlier peak response, for the sand only column (figure 6a).

Based on the imaginary conductivity trend (figures 5 and 6) we identified three different stages in the experimental progress, interpreted to be associated with calcite precipitation. Stage one represents background conditions with no calcite precipitation. Stage two occurs during the initial calcite addition with increasing precipitation and primarily occurs in the form of fine mineralization and subsequent aging primarily with increasing crystal growth. During stage three steady state is reached as the amount of calcite occurrence equals the amount of calcite precipitating as it is flushed due to flow or clogged pores, which prevents further mixing of the 2 solutions [see discussion for details].

We used empirical DD models to processes all the complex conductivity data; the model fits the measured data very well (figures 7b and 8b) except stage 3 for the sand only experiment (figure 9b). The relaxation time distribution (RTD) peaks identified by DD show the development of unique and consistent peaks in response to calcite precipitation (figures 8a and 9a) as there is no such peaks in stage one (prior to injection, figure 7a). The observed RTD peaks do not move over time, with only the magnitude of the peak changing, which suggests no change in the polarization mechanisms over time. The change in peak magnitude might be due to changes in the polarization mechanism relative intensity. DD revealed two relatively (to background) distinct RTD peaks for the sand + clay sample, at 3×10^{-1} and 3×10^2 seconds (figures 8a and 9a, black line), similarly there are two large peaks in RTD for the sand sample at 30 and 3×10^2 seconds (figure 8a, blue line). No significant peaks were observed in the control column.

The changes in shear-wave velocity are shown in figure 10. We used the first observed peak in each measurement as the first arrival signal, as highlighted by the red line (figure 10a). The shear-wave velocity is increasing as the experiment progresses, presumably in response to calcite precipitation (figure 10b). The data presented are only for the clay samples. Unfortunately, due to receiver malfunction in the control column, data collection was impossible, so we do not have any additional data for direct comparison. Also during the sand experiment (which preceded the clay experiment), we used a suboptimal acquisition protocol that resulted in poor quality data.

At the end of the experiment all the columns underwent destructive sampling for SEM analysis. This SEM analysis confirmed calcite precipitation in the active columns, with clean round sand grains in the control columns, and (figures 11a to 11c) and calcite precipitation on the active ones (figures 11d to 11f).

4 Discussion

Visual observations and destructive sampling confirmed that direct mixing of the two solutions, Na_2CO_3 and CaCl_2 , induced calcite precipitation as expected (figure 11). Changes in the geochemical properties of the fluid and the reduction in K further support successful calcite precipitation under the experimental conditions (figure 4). ICP analysis on outflow solutions is also consistent with calcite precipitation since it shows reduction in dissolved calcium concentration. Based on the geochemical monitoring, and modeling (table 1), it is safe to assume that calcite precipitation is the dominant process in these experiments.

The presence of kaolinite in the “sand + clay” samples appears to have affected the availability of calcium ion for calcite formation. The ~120 ppm difference in initial effluent concentration of dissolved calcium between ‘sand only’ and ‘sand + clay’ samples (figure 4c) along with the dramatic drop in the effluent dissolved calcium concentration within the first 24 hours of the experiment (figure 4c), can be explained only with calcium sorption in kaolinite. In addition, the increase in effluent concentration of dissolved calcium in the sand + clay control column leads to the hypothesis that the clay structure is getting more and more saturated with calcium ions, hence more ions can reach the effluent. It is estimated that after 24 hours (figure 4c), all the calcium in the solution was available for calcite formation since the decreased rate has significantly slowed down (showing similar behavior as the “sand only” column ~75 hrs).

Calcite precipitation appears to have had a significant effect on geophysical signatures. The SIP and shear-wave measurements both showed changes as the calcite precipitation was progressing. Imaginary conductivity, heavily dependent on interfacial properties, appears to be an accurate marker of the calcite formation process. As discussed earlier, the magnitude of the signal and the signal shape changed over time. For both experiments, the imaginary conductivity trends are similar but vary in absolute magnitude, possibly due to calcium availability as a result of the interaction with kaolinite clay. The similar imaginary conductivity trends (figure 5) suggest the same dominant polarization mechanisms. This interpretation further supports that calcium availability, hence calcite precipitation, controls the signal magnitude. DD modeling is in direct agreement with this interpretation,

suggesting that the dominant polarization processes are the same in all experiments, but vary in contribution.

The observed imaginary conductivity responses seem to track calcium carbonate precipitation progress in response to the mixing of the 2 injected fluids. Upon injection and subsequent mixing, calcite precipitates almost instantly and continues for the duration of the mixing. Carbonate precipitation due to mixing of highly concentrated solutions typically leads to the formation of isolated micro/nanometric crystals, or spherical/spheroidal aggregates and under lower concentrations carbonate minerals tend to grow on pre-existing surfaces as layers (laminae) [Van Driessche et al., 2017]. Imaginary conductivity is in direct agreement with this precipitation model. The 1 Hz data, representative of finer mineral grains, show that the new mineral phase forms at a higher rate in the early times of the experiment for the 'sand-only' column, as expected due to the increased availability of Ca, and then it reaches a steady state, as the column is Ca saturated. Conversely, the 'clay-sand' column exhibits different behavior, due to the calcium limitations previously described, and reaches a steady state earlier (figure 6). Changes in the 1 Hz data should reflect the amount of fine calcite present in the columns. The 1 mHz data can offer additional insight on calcite forming progress, since these data are sensitive to the presence of larger mineral grains. Since we established that the only process in our system is calcite formation, the lower frequency data suggest the formation of larger grains, or more accurately, the growth of existing grains due to the accumulation or addition of new layers. Broad spectrum SIP imaging appears to reveal the complete calcite precipitation story, with information not only on the precipitation process, but also on the calcite growth progress.

Shear-wave velocity measurements are in agreement with calcite precipitation and suggest increased soil stiffness (figure 10). Although both SIP and shear-wave measurement show that calcite is precipitating, the observed trends are different. Shear wave velocity keeps increasing, suggesting increasing stiffness with continuous fluid mixing. On the other hand, SIP reaches an early peak, followed by a small decline before reaching steady state conditions. Although seemingly different, the SIP trend supports continuous increasing stiffness. It is known SIP is sensitive to available surface area per pore volume. Due to the onset of calcite precipitation, the available surface area per volume rapidly increases up to a threshold value. Further precipitation begins to limit available surface area due to coagulation or pore blockage, until equilibrium is achieved. Furthermore, it is important to note that precipitation stage 2 has significantly higher SIP magnitude than pre-injection conditions (figure 12), suggesting that calcite is present and stable in the porous media. This observation could lead to the assumption that SIP is more sensitive to the cementation process and new mineral phase evolution.

Empirical models, such as DD, can be used to provide additional insight into the geophysical signal sources [Weigand and Kemna, 2016]. The DD based RTD approach used in our study further supports the development of two distinct polarization mechanisms – early time fine mineral precipitation, followed by late time mineral grain growth/layering – as a result of our experimental processes (figures 8a and 9a). The two processes seem to be complimentary and could be present in parallel; but each process is dominant during different stages of the experiment. A comparison between figures 8a and 9a for the sand sample (blue line) shows

the observed peak at 3×10^2 seconds for the middle injection stage (stage 2) is eliminated at stage two (the end of the experiment). This may be due to changes in the calcite formation type from initially powder form (fine structure), to a layered structure toward the end.

Furthermore, since the effluent properties (e.g. fluid conductivity) showed a stable trend shortly after the injection started, we assumed the electrolyte in the pore space is not changing significantly; therefore, the charge density, mobility, and thickness at the EDL, which is mostly controlled by pore fluid properties [Wu *et al.*, 2010], will not be changed toward the end of the experiment. Hence, we are assuming the only parameter that controls the polarization within our samples would be the surface area changes due to precipitation of the calcite within the pore space.

The main finding of our results is that joint shear wave and SIP measurements can provide comprehensive monitoring of calcite precipitation monitoring. Geophysical monitoring not only provides information on the overall stiffness, permeability, and porosity of the porous media, but also provides detailed information on the calcite forming stages.

This study conclusively shows that SIP is sensitive to calcite precipitation processes and can be used as a soil strengthening characterization tool. Furthermore, the ability to distinguish between different forms of calcite precipitation renders SIP as a promising monitoring tool. The monitoring capability of SIP could be especially beneficial for MICP field implementations where continuous long term assessment of the microbial performance on calcite formation is essential. However, further studies are required to investigate the efficiency of SIP in monitoring MICP processes, especially under complex field scale conditions.

5 Conclusion

The abiotic experiment on calcite precipitation as a cementing agent for soil strengthening, permeability, and porosity alterations clearly shows that SIP measurements can be an effective monitoring tool. SIP is sensitive to the calcite precipitation as well as aging and growth processes. SIP measurements are in direct agreement with shear-wave velocity, showing increased stiffness as precipitation progresses. Although both methods showed calcite is acting as a cementation agent, different types of information can be retrieved from each method since they respond to different physical properties. This idea could highlight that carbonate precipitation changes both the electrical and mechanical properties of the media as realized through the SIP and shear-wave measurements. This study provides the basis needed for a fundamental understanding of calcite based cementing processes and the use of geophysical monitoring for studying MICP in field and lab experiments whether the objective is to stiffen soil or reduce permeability for subsurface fluid flow alterations. SIP and shear-wave velocity measurements both are expected to be efficient non-destructive and indirect measurement for future MICP processes related to engineering or environmental purposes. Further experimentation of increasing complexity and field measurements are required to realize the full applicability and potential of geophysical measurements to achieve these ends.

Acknowledgments

Special thanks to Dr. Ashaki Rouff for providing us the opportunity to use ICP-OES device in her lab at Rutgers University – Newark (NSF grant #1530582). This project was funded by National Science Foundation grant #1363224. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. This document has been reviewed by the U.S. Environmental Protection Agency, Office of Research and Development, and approved for publication. Any mention of trade names, products, or services does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. The EPA does not endorse any commercial products, services, or enterprises.

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Figure 1.
Column setup, [a, c] Schematic setup, [b, d] Actual column

Figure 2. Schematic of injection process and estimated area of precipitation. A, B are current and M, N are potential electrodes.

Figure 3. Destructive sampling for SEM, [a] Taking a core sample by pushing an open (both sides) PVC tube in the soil, [b] the open hole not collapsing after soil sampling, suggests a stiff sand formation

Figure 4.

Evolution of saturating fluid over time sampled in the outflow; time = 0 hrs represents the injection zero [0] time. Two different porous media used, [a] sand + clay, [b] Sand only, [c] Effluent calcium concentration (ppm)

Figure 5.

Imaginary conductivity spectra, time = 0 hrs represents the background signal (prior to injection), [a] Initial increase phase for sand + clay sample, [b] late decrease and equilibrate phase for sand + clay sample, [c] Initial increase phase for sand sample, [d] late decrease and equilibrate phase for sand sample

Figure 6.

Imaginary conductivity behavior over time for two active and one control columns at two distinctive frequencies, time = 0 hrs represents the background signal (prior to injection) – red line separates the fine mineral formation stage from mineral growth stage, [a] Sand only sample, [b] Sand + clay sample

Figure 7. Debye Decomposition inversion at *stage one* (prior to injection), [a] RTD, [b] Imaginary conductivity observed (circles) and inverted (lines)

Figure 8.

Debye Decomposition inversion at *stage two* (50% of the experiment injection period was done), [a] RTD, [b] Imaginary conductivity observed (circles) and inverted (lines)

Figure 9. Debye Decomposition inversion at *stage three* (the end of the experiment), [a] RTD, [b] Imaginary conductivity observed (circles) and inverted (lines)

Figure 10.

Shear-wave measurement, time = 0 hrs represents the background signal (prior to injection), [a] Actual received wave forms (red line shows the first arrival peaks), [b] Shear-wave velocity (m/s) based on the identified first arrivals

Figure 11.
SEM imaging, [a, b, c] Control column, [d, e, f] Active columns

Figure 12.

Mineralization mechanism stages with arrows depicting increasing or decreasing measured parameter per carbonate precipitation stage. Stage 1: Background, no calcite precipitation. Stage 2: Increased precipitation, increased crystallization, σ'' increases to threshold value, shear-wave velocity increasing. Stage 3: Steady state conditions.

Table 1

Minerals resulting from CaCl_2 and Na_2CO_3 mixture based on geochemical modeling (Visual MINTEQ).

Mineral	Saturation index
Calcite	1.976
Aragonite	1.832
Other carbonate minerals	>1 (oversaturated)
Non-carbonate minerals	<1 (undersaturated)

Table 2

Inflow fluid properties

Solution	pH	Conductivity (S/m)	Concentration (mM)
CaCl ₂	4.9	0.289	20
Na ₂ CO ₃	10.9	0.374	20

Table 3

Hydraulic conductivity (K) changes

Sample	Initial K (cm/s)	Final K (cm/s)
100 % Sand	0.22	0.04
Control	0.23	0.23