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ELECTROOSMOTIC TREATMENT OF SOFT CLAYS THROUGH THE INJECTION OF MICROORGANISM SOLUTIONS

Fuchen Teng [1], Shao-Chi Chien [2], and Yong-Cheng Sie [3*]

ABSTRACT

Electroosmotic chemical treatment (ECT) has been proven to satisfactorily improve the properties of soft clays, such as strength and stiffness. However, the use of chemical solutions is not preferable given their environmental impact. The study introduced a multidisciplinary advanced technology, electroosmotic biosolution treatment (EBT). The EBT included electroosmotic chemical treatment (ECT) and microbial induced calcite precipitation (MICP) technology. In this work, kaolinite specimens were injected with a bacterial solution through the electroosmotic technique, and their soil properties were characterized after treatment. The results showed that the microorganisms could be successfully injected into soft clays through the electroosmotic technique. After 360 hours of treatment, the cone resistance of the specimens peaked at 2,000 and 1,000 kPa in areas close to the anode and cathode, respectively (which were nearly ten and five times the pretreatment cone resistance, respectively). In the middle area, the cone resistance was 300 ~ 500 kPa (1.5 ~ 2.5 times the pretreatment cone resistance). Thus, the proposed approach can be used to inject bacterial solutions into low-permeability soft clays in order to enhance the electroosmotic effect.

Key words: Electroosmosis, soil improvement, microorganism, kaolinite.

1. INTRODUCTION

The electroosmotic technique uses the potential difference between electrodes inserted into soils to induce water flow from the anode to the cathode, from where the water is withdrawn. Electroosmotic chemical treatment (ECT) drains pore water in sands and clays through electroosmosis and simultaneously injects chemical solutions to improve the soil characteristics. The influence factors of ECT have been studied by some works. Li *et al.* (2011) and Estabragh *et al.* (2014) indicated the voltage gradient was positively related to the drainage volume and pH value. Ou *et al.* (2013) performed ECT tests with various analytes such as calcium chloride ($CaCl_2$) and sodium silicate (Na_2O + $nSiO_2$) on kaolinite and resulted in up to 3 MPa at the vicinity of anode by miniature CPT. Lin (2017) reported that injecting sodium silicate followed by KOH solution can effectively extend the improvement region. ECT—The effectiveness of which has been demonstrated through laboratory and field experiments by Chien *et al.* (2011 and 2015) and Teng *et al.* (2013)—can be used to uniformly distribute chemical solutions even in soft clays.

As noted by Karol (2003), the vast majority of macromolecular chemical grouts applied for improving soils are toxic, with sodium silicate being an exception; thus, environmentally friendly soil improvement methods are preferred. Bio-mediated soil improvement is an innovative and environmentally friendly soil improvement technique. This technique has been proven to be effective in improving fine sands and residual soils by Dejong (2006), Harkes (2010), and Soon (2014). Kile (2000) and Soon (2014) research the factors affecting the improvement of soils, such as pH and concentration of calcium ions and dissolved inorganic carbon, have been studied as well. In engineering applications, the type of soil layer typically requiring amelioration is soft clays, which typically have low strength and stiffness. For the bio-mediated soil improvement of soft clays, microorganisms and nutrients should be injected into the soil. However, the very low permeability of soft clays renders it difficult to inject such solutions, limiting the applicability of microbe-induced soil improvement of soft clays.

Bio-mediated soil improvement induces a series of chemical reactions, namely the generation of gas (biogas) and the precipitation of inorganic matter (biomineralization) and organic matter (biofilm). DeJong *et al.* (2013) comprehensively reviewed the latest literature on bio-mediated soil improvement.

An environmentally friendly approach for the improvement of soft clays that integrates electroosmosis and biosolutions is proposed in this study, which is called the electroosmotic biosolution treatment (EBT). EBT was used to inject microorganisms into soft clays. The used biosolution, which contained bacteria and the culture medium, had high electrical conductivity, enhancing the electroosmotic effect during treatment. Keykha *et al.* (2014) first tried using biosolution in the ECT. The results indicated the maximum strength improvement was 10 times to the untreated. Tain *et al.* (2021) applied the EBT to treat the settlement and reinforcement uniformity of marine clay. Li *et al.* (2021) studied fractal characteristics of pores of NAS reinforced by MICP under the control of electric field. The physical and chemical properties of the soils treated under various electroosmotic injection conditions were investigated. The results show the feasibility of improving consolidation soft clays through the electroosmotic injection of microorganisms.

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[1] Associate Professor, Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, No. 43, Keelung Rd., Sec. 4, Taipei, 10607, Taiwan.

[2] Professor, Departments of Visual Communication Design, Hsuan Chuang University, No. 48, Hsuan Chuang Rd., Hsinchu City, Taiwan.

[3*] Ph.D. candidate (corresponding author), Dept. of Civil and Construction Engineering, National Taiwan University of Science and Technology, No. 43, Keelung Rd., Sec. 4, Taipei, 10607, Taiwan (e-mail: D10905005@mail.ntust.edu.tw).

2. METHODS AND MATERIALS

2.1 Experimental Cell

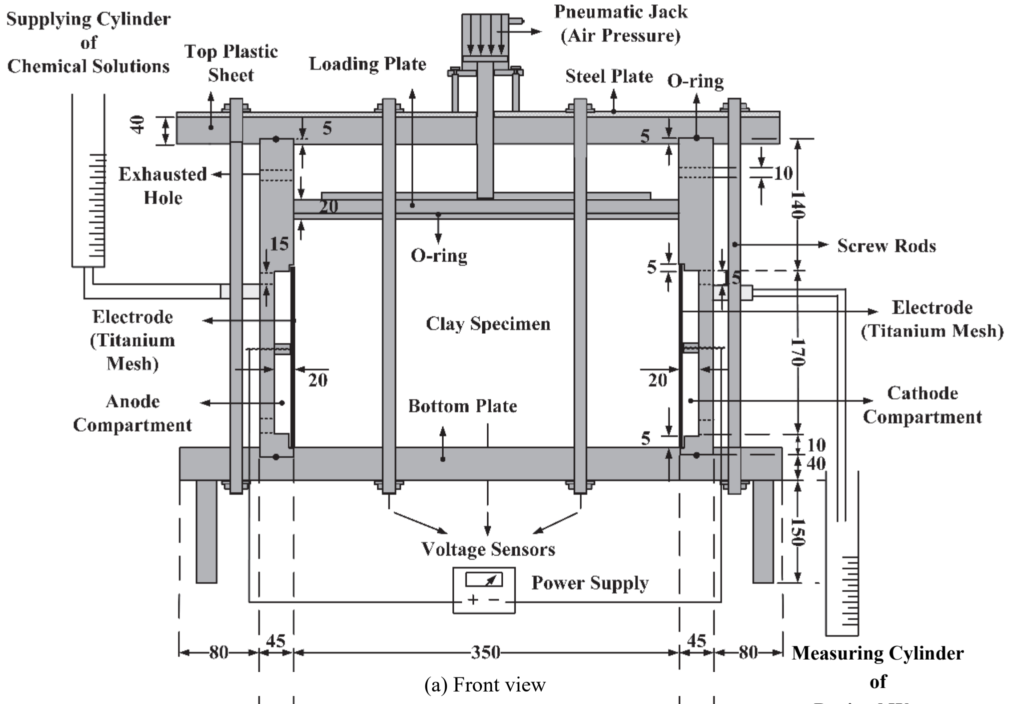
Figure 1 presents the experimental apparatus. The apparatus for the electroosmotic biosolution treatment (EBT) test comprised of plexiglass plates, solution cylinders, Pt-coated Ti meshed plates, air pressure system, and power supply device. The clay specimen size was 350mm (length) and 150mm (width). The height of the specimen depended on the consolidation pressure. In all tests, the anode and cathode were 350 mm wide Pt-coated Ti meshed plates, wired to a power supply device. This Pt-coated Ti composition of the anode could prevent metal ions from discharging into the soil following anode oxidization during electroosmosis. A minute amount of the biosolution to be injected was maintained in a 20 mm (width) × 150 mm (length) chamber attached to the anode; under an electric field, this setup facilitated the uniform injection of the solution into the soil samples. The drained water was collected in a similar chamber attached to the cathode, with a drainage tube for water discharge. The consolidation pressure specified to be exerted on the soil samples was provided by the top plate as well as the air pressure source.

2.2 Inductively Coupled Plasma Atomic Emission Spectrometry and pH Measurement

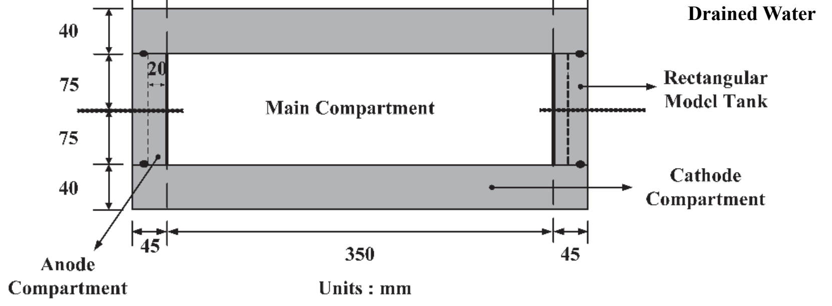
In the executed study, the soil samples (0.5 g) to be tested were digested on a hot plate at 110°C in 10 mL of aqua regia (HNO_3 : HCl = 1 : 3) for 3 hours. The residual product was then dissolved in 20 mL of 2% HNO_3, followed by filtering it via a Whatman No. 42 filter paper. The resulting filtrate was moved into a 100 mL standard flask, in which it was diluted using distilled water. Finally, the Ca^{2+} concentration of this solution was measured through an inductively coupled plasma atomic emission spectrometry instrument (JY 2000-2), and its pH was determined according to ASTM-D4972 by using a portable Mettler Toledo SG2-FK SevenGo pH meter.

2.3 Miniature Cone Penetration Test

The strength levels of the tested soil specimens were investigated by miniature cone penetration test (CPT), the apparatus was shown in Figs 2 and 3. CPT system's design was introduced according to ASTM D5778-12. The resistance of the soil was measured using a 60° and 66.5 mm^2 cone tip, which maximum capability load was 295 kg. The cone penetrated the soil at a constant rate of 20 mm/sec with the hydraulic cylinder. Experimental cell was fixed on the platform of the CPT apparatus and be penetrated at the positions specified in Fig. 4. The conversion factor, the maximum CPT cone resistance of unconfined compressive strength ($q_{c,\max}$/UCS), is approximately 15 (Teng *et al.* 2021). The test process for the CPT are presented in Fig. 5. To obtain the profile of soil strength, continuous cone resistance was monitored using a testing program.



(a) Front view



(b) Top view

Fig. 1 Schematic of the experiment setup

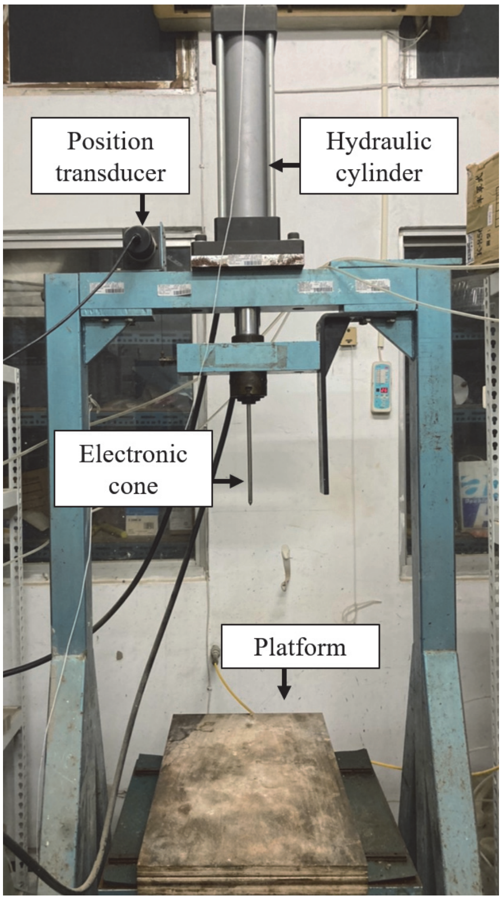


Fig. 2 Miniature CPT apparatus

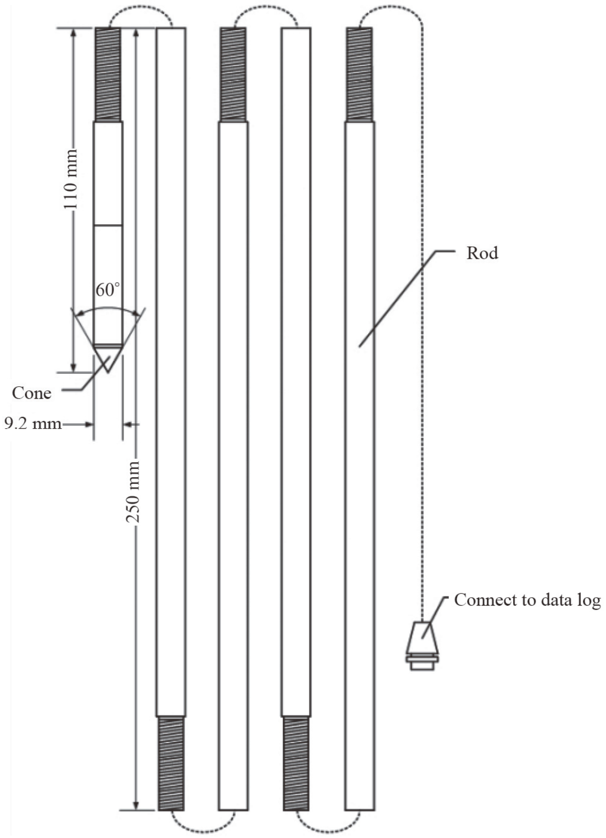


Fig. 3 Miniature CPT cone apparatus

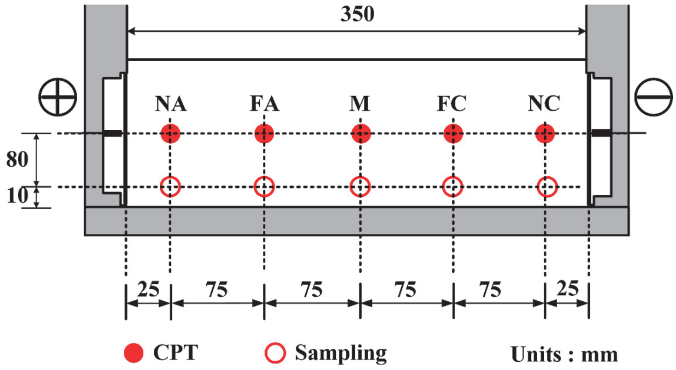


Fig. 4 Posttreatment CPT testing and sampling locations

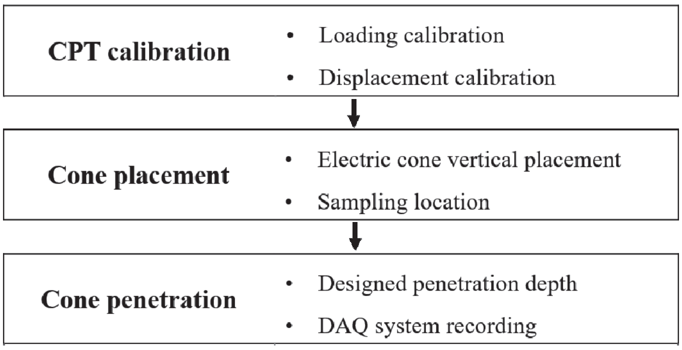


Fig. 5 Miniature CPT test process

2.4 Soil Specimen Preparation

Table 1 lists the chemical constituents of the kaolinite powder (liquid limit = 46; plastic limit = 25) tested in this study, and Table 2 presents its physical properties. The powder and distilled deionized water (60% water content) were mixed well. Subsequently, the mixed sample was transferred, in layers, to the experimental cell. Next, a filter paper was placed over the transferred sample, following which the anode and cathode were attached. Before the electroosmotic treatment, 30 kPa vertical consolidation stress was applied to the sample; the observed post-consolidation water content was approximately 51%.

Table 1 Chemical composition of the investigated kaolinite samples

Items of Analysis	Mean Percent by Weight (%)
Silicon Dioxide (SiO_2)	45.5
Aluminum Oxide (Al_2O_3)	38.00
Titanium Dioxide (TiO_2)	1.65
Iron Oxide (Fe_2O_3)	0.90
Calcium Oxide (CaO)	0.25
Magnesium Oxide (MgO)	0.03
Potassium Oxide (K_2O)	0.23
Sodium Oxide (Na_2O)	0.04
Loss on Ignition (L.O.I.)	13.40

Table 2 Fundamental physical characteristics of the investigated kaolinite samples

Liquid limit	46
Plastic limit	25
Plastic index	21
Specific gravity	2.61
Particle size (μm)	1.0 ~ 2.0
Unified soil classification result	CL
Whiteness (GBE)	80
pH	6 ~ 8
Specific surface area (m^2/g)	24

2.5 Experimental Bacterial Species

Geobacillus, Sporosarcina, or Bacillus or a combination of two or more of these bacterial species was used to improve the strength of permeable soils. Bacillus smithii (strain number 14179; see Table 3 for details) were employed as the improvement agent. This agent was inoculated into previously sterilized culture vessels and then grown at 45°C in a solid-state culture medium (pH 7) comprising water, agar (15.0 g/L), beef extract (3.0 g/L), and peptone (5.0 g/L). The bacteria were subcultured on a monthly basis, with the bacterial colony being subsequently inoculated into sterilized culture vessels; the colony was then cultured in an aqueous culture medium (50 mL; pH 7) comprising peptone (5.0 g/L) and beef extract (3.0 g/L) and subsequently in a shake flask at 45°C and 100 rpm for 1 day. Finally, the colony was inoculated in a sterilized 5 L fermentation tank containing a similar aqueous medium for propagation and culture at 45°C for 2 days. These bacteria were finally harvested. All the aforementioned sterilizations were performed for 30 minutes at 121°C.

Table 3 Details of the experimental bacteria

Scientific Name	*Geobacillus stearothermophilus*
BCRC Number	14,179
Organism	*Bacillus smithii* Nakamura *et al.* 1988
Synonymy	*Bacillus stearothermophilus*
Author	Nakamura *et al.*
History	FIRDI, Y. K. Lo B1 (*Geobacillus stearothermophilus*)
Source	Soil
Others	1.16S rDNA sequence similarity was most closely related to Bacillus smithii (100%).
Growth Conditions	Temperature: 45°C, Oxygen Requirement: Aerobic
Biosafety Level	1
Nutrient Agar	DIFCO 0001
Beef extract	3 g
Peptone	5 g
Agar	15 g
Distilled water	1 L
Image	

2.6 Experiment

Six electroosmotic biosolution treatment tests were performed (Fig. 6 and Table 4). Per Mitchell (1993), a 50 V/m voltage gradient was applied in all the experiments. During the test, the injection of solutions relied on the electroosmotic effect only. To investigate the influence of injection duration, bacterial solutions containing *B. smithii* were injected from the anode, as suggested by Chien *et al.* (2011), into the experimental specimens through the electroosmotic process for 144, 360, 480, and 600 hours (hereinafter respectively referred to as B144, B360, B480, and B600). The pore fluid was determined to flow in the direction of the electrical current and accumulate at the cathode.

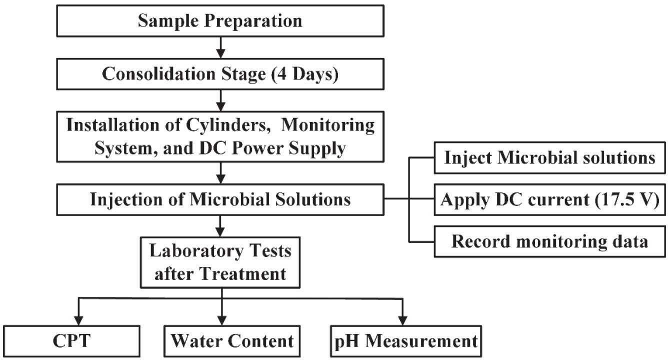


Fig. 6 Experimental flowchart

Table 4 Experimental details

Test notation	Electroosmotic time (hr)	Bacterial solution injection time (hr)	Deionized water injection time (hr)
H144	144	–	144
H360	360	–	360
B144	144	144	–
B360	360	360	–
B480	480	480	–
B600	600	600	–

To comparatively investigate the effect of injecting biosolutions, a second sequence of tests was conducted through distilled deionized water injection for periods of 144 and 360 hours (hereinafter, H144 and H360, respectively). The physical characteristics as well as chemical characteristics of the treated kaolinite were studied; Figure 4 indicates the sampling locations and CPT positions, namely near-anode (NA), near-cathode (NC), middle (M), far-anode (FA), and far-cathode (FC).

3. RESULTS AND DISCUSSIONS

In this work, bacterial solutions were injected into soft clay specimens through the electroosmotic technique, and the effects of injection duration on such properties as soil strength, water content, and concentration of calcium ions were investigated. Given the occurrence of the electrolytic phenomenon, alkaline, acidic, and neutral environments developed in the following regions: cathode, anode, and middle regions, respectively.

3.1 Effect of Injection of Microorganisms

3.1.1 CPT cone resistance

In this study, CPT cone resistance measurements were performed for the kaolinite samples treated with microorganisms (*i.e.*, B144 and B360) and with deionized water (*i.e.*, H144 and H360), and the measured resistances are presented in Fig. 7. The cone resistance of B144 and B360 increased in the NA area, and their soil strength increased significantly compared with that of H144 and H360. Sample B360 had a high cone resistance of 2000 kPa in the NA region, higher than that of B144. Similarly, in the NC region, B360 had a high cone resistance of more than 1000 kPa. However, in the other regions (*e.g.*, M and FC regions), the cone resistances of the treated kaolinite samples were less than 500 kPa. These findings indicate that injecting microorganisms through the electroosmotic technique can increase soil strength in regions near the anode and cathode and that this increase is proportional to the treatment duration.

3.1.2 Measurements of pH and drainage volume

This study also assessed the samples' pH, and the observed distribution of pH in the kaolinite samples B144, B360, H144, and H360 is shown in Fig. 8. In the microorganism-treated samples, the pH in the NA region was nearly 4.2 because of electroosmosis. Most regions of the samples, except for the NC region, were acidic. Sample B360 had the most basic environment, with a pH of almost 10.

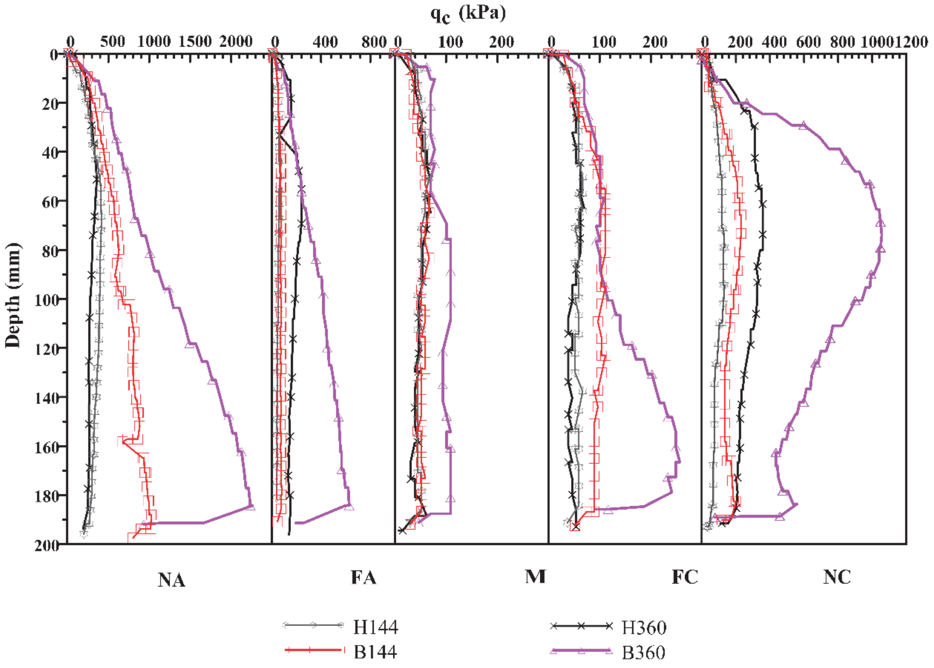


Fig. 7 Cone resistance of microorganism- and deionized water-treated samples

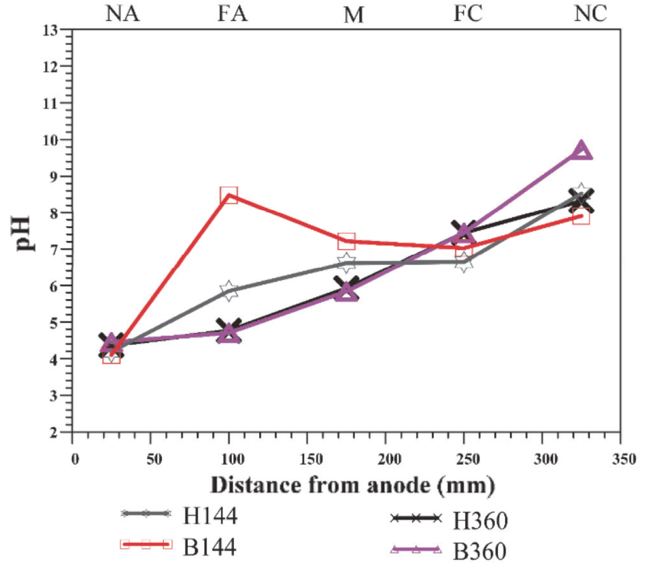


Fig. 8 pH distribution in kaolinite samples treated with microorganisms and deionized water

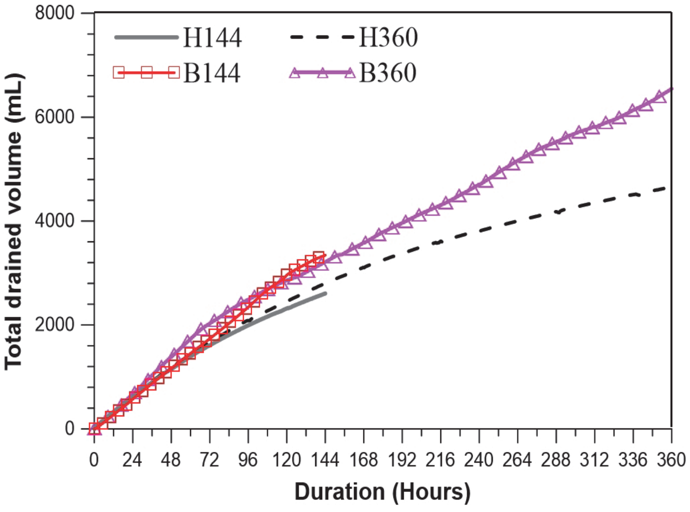


Fig. 9 Total drained volume

Figure 9 shows the drainage water volume for samples B144, B360, H144, and H360. The total drainage volume was higher when injecting biosolutions than when injecting pure water, which implies that the electroosmotic phenomenon is stronger in EBT tests because of the higher electrical conductivity of biosolutions.

3.2 Effect of Injection Duration

3.2.1 CPT Cone Resistance

The CPT data for samples treated for different durations (*i.e.*, B144, B360, B480, and B600) are shown in Fig. 10. The highest cone resistance (> 2,000 kPa) was observed in the NA region of the samples treated for 360 hours, approximately 10 times that of the untreated kaolinite samples (200 kPa). With an increase in treatment duration beyond 480 hours, the NA-region cone resistance of the treated samples decreased significantly, with the highest CPT cone resistance being less than 500 kPa for B480 and B600. This is likely due to the increase in the volume of the solution injected into the NA region at prolonged treatment durations, which hinders drainage at the cathode because of cementation; this is evident in Fig. 8, which shows an increase in strength in the NC region for B480 and B600.

Treatment for 360 hours yielded a rather high CPT cone resistance, which was 500 kPa, in the FA region. In the M and FC regions, the highest observed cone resistance was determined to be lower than 500 kPa, which further decreased when the treatment duration was increased to 600 hours. Regarding the NC region, the cone resistance increased significantly on treating the samples with the microorganism solution for over 360 hours, which yielded a high cone resistance of more than 1,000 kPa.

3.2.2 Measurement of pH

The derived pH data are shown in Fig. 11. Bacterial treatment for 144 hours (B144) did not significantly affect the pH, apart from that of the NA region, wherein the inherently neutral environments of the bacterial solution and the soil were sustained. By contrast, after treatment for 360 hours, the pH decreased significantly in the FA and M regions, and these regions became acidic, whereas the pH increased in the FC and NC regions. This outcome is likely due to electrolysis. Moreover, on treating for 480 hours, the FC, M, FA, and NA regions became acidic. Thus, treatment for over 360 hours decreased the kaolinite samples' overall pH, except in the NC region, to acidic levels. These findings can be attributed to two potential causes. First, bacteria contained in the kaolinite consumed the oxygen in the water, releasing H^+ ions in the process. Second, when these bacteria died, their proteins disintegrated; consequently, the constituent amino acids released H^+ ions, decreasing the overall pH of the sample. The experimental data indicate that H^+ ions are released at higher rates when microbial solutions are injected for over 360 hours, which is a result of the increased oxygen consumption and amino acid decomposition. As a result, the pH of the FC and NC regions of the B600 and B480 samples decreased to around 8.0.

3.2.3 Water Content

Figure 12 presents data related to the water content of all samples. Regarding the NA region, B144 and B360 had the lowest water content of approximately 46%, the lowest among all samples. With increase in treatment duration, the observed water content increased to the initial value of 51% because of the continuous injection of the treatment solution. Water content levels in the NA and FA regions were significantly influenced by the injection of solutions, as evident from the data for B480 and B360. Regarding the NC region, which was determined to be near the drainage point, the water content levels of B360, B480, and B600 were similar.

3.2.4 Concentration of Calcium Ions

Calcium ion concentration in B144, B360, and B600 was measured through inductively coupled plasma atomic emission spectroscopy (Fig. 13). In all cases, the NA region had the lowest concentration of Ca^{2+}, which tended to decrease with an increase in the treatment duration. Furthermore, Ca^{2+} ions were concentrated in the FC and NC regions of the kaolinite samples treated for 360 hours. The Ca^{2+} concentration in the FC and NC regions of B600 were lower than those of B360, because the ions migrated to the cathode area, where they subsequently precipitated.

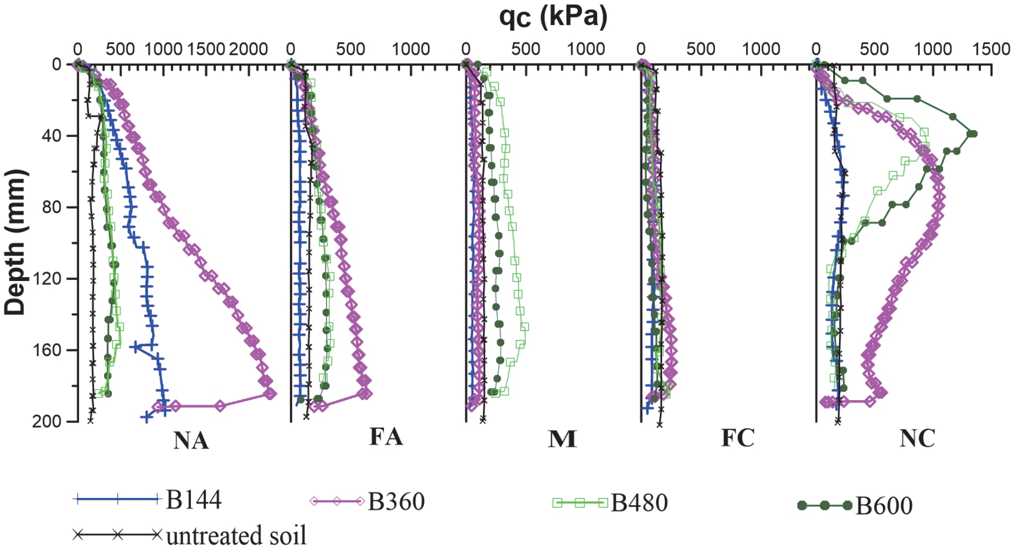


Fig. 10 Cone resistance (q_c) of kaolinite samples treated with microorganisms for different durations

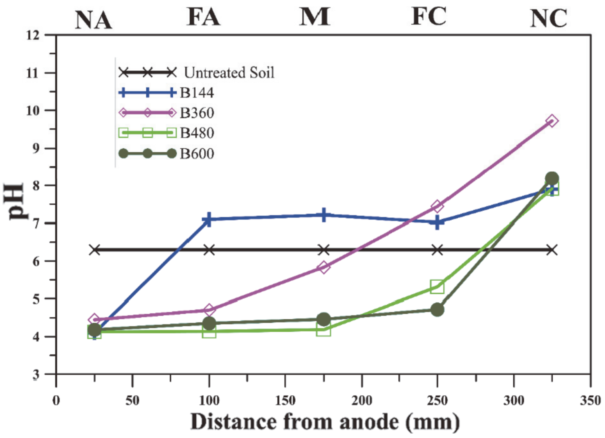


Fig. 11 pH distribution in kaolinite samples treated with microorganisms for different durations

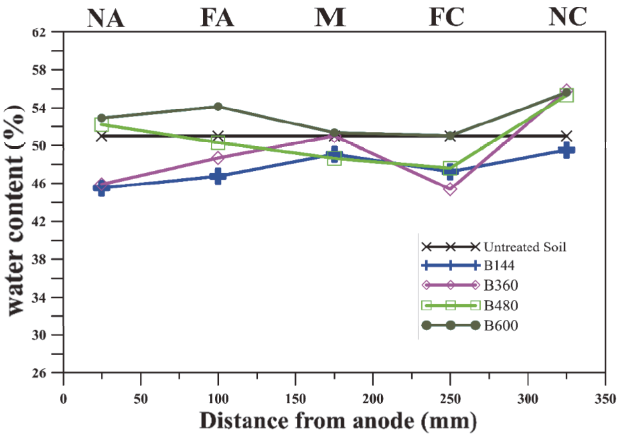


Fig. 12 Water content in kaolinite samples treated with microorganisms for different durations

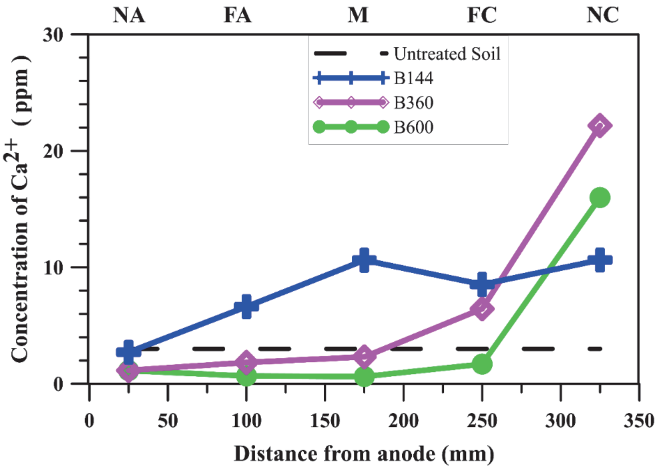


Fig. 13 Distribution of Ca^{2+} ion concentration in kaolinite samples treated with microorganisms for different durations

3.3 Mechanism of Improvement

The mechanisms of improvement of soil strength in the proposed method are complex and involve biochemical and electric-chemical reactions that occur during the electroosmotic process. The main source of this increase in strength is presumed to be the electroosmotic phenomenon, which occurs across the specimen, and the consequent precipitation at the cathode.

As clarified in Fig. 7, the cone resistance measured through Electroosmotic bacterial solution injection (EB) testing was higher than that measured through Electroosmotic deionized water injection (EH) testing. A comparison of the volume of the pore fluid drained (Fig. 9) in the EB and EH tests revealed that the EB test environment (*i.e.*, biosolution injection) had higher electroosmotic efficiency.

Soil strength in the NA region increased significantly for the B144 and B360 sample. A comparison of Figs. 7 and 10 indicates that a potential source of increase in strength could be the decrease in water content. Cone resistance in the NA region decreased with an increase in the treatment duration, which in turn increased the water content (~53% for B480 and B600) given the prolonged injection of biosolutions.

The potential source of the increase in soil strength in the NC region could be calcite precipitation, which occur in alkaline environments with sufficient calcium. This alkaline environment is produced by electro-kinetic reactions, which indicates that the high pH essential for calcite precipitation can be achieved even without the urea hydrolysis reaction. As shown in Figs. 10 and 11, the measured cone resistance in the NC region reached 1 MPa for B360, B480, and B600; the region's pH exceeded 8, and the region had adequate calcium ion concentration.

In the other region, the resistance reduced with increasing treatment time. The reason is related to water content. The more solution volume injection with the electroosmotic time increasing. The calcite clogs the voids in the NC region which causes the solution to accumulate. The resistance reduces with water content increasing as shown in Fig. 10. In order to make the EBT better, controlling the environment's pH and decreasing the water content are necessary.

4. CONCLUSIONS

This study proposed an innovative and environmentally friendly soil improvement method that involves the electroosmotic technique and the injection of microorganisms. The EBT technology used in the study, exert a strength improvement efficacy similar to ECT. The high electrical conductivity characteristic of biosolution, enhanced the electroosmotic effect during treatment. Experimental data confirmed that the electroosmotic injection of bacteria effectively improved the strength of kaolinite samples in the NA and NC regions. In addition, in contrast to electroosmotic chemical grouting, the proposed method produces a rather neutral pH, meaning that this approach has low environmental impacts. The study conclusions are listed herein:

1. Injecting bacterial solutions through the electroosmotic technique into soil samples for 360 hours improved soil strength, but only in the NA and NC regions (CPT cone resistance ≧ 2 MPa and > 1 MPa, respectively).
2. The electroosmotic injection of bacterial solutions, unlike electroosmotic chemical grouting, yields a comparatively neutral posttreatment environment.
3. The cone resistance of kaolinite samples in the NC region treated for 360 hours was comparable to that of samples subjected to electroosmotic chemical grouting.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY

Data for figures in this paper are available from the corresponding author upon reasonable request.

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