

# Shear strength and stiffness characteristics of sands treated with biopolymer and enzyme-induced calcium carbonate precipitation: A comparative study

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**ABSTRACT:** Contemporary ground improvement techniques predominantly utilize cement; nevertheless, increasing efforts are being directed towards enhancing ground stability in an environmentally sustainable manner due to the ecological issues linked to cement usage. Biopolymer-based soil treatment (BPST) and enzyme-induced calcite precipitation (EICP) are getting greater consideration in the context of sustainable ground enhancement. Although numerous studies affirm the efficacy of BPST and EICP approaches, both possess limits that can be viewed as complementary. Recently, efforts have been made to overcome mutual restrictions by integrating BPST with EICP. This study has taken into consideration four situations of subsequent BPST-EICP combinations: 1) EICP, 2) BPST, 3) pre-EICP + post-BPST, and 4) pre-BPST + post-EICP. The shear strength characteristics of sand treated using the four procedures under consideration were evaluated. The stiffness properties of biologically treated soils were investigated by Bender Element Test (BET). The wave velocities (i.e., P- and S-wave) were measured using an oscilloscope, bender elements, and PZT plates. The experimental results showed that composite treatment exhibited higher performance than single treatment in terms of both shear strength and stiffness. Among the four conditions, pre-BPST + post-EICP (EAB) showed higher peak and residual shear strength, as well as P-wave and S-wave velocity, than pre-EICP + post-BPST (BAE). For BAE soils, stiffness improved progressively as the treatment cycle increased, but for EAB soils, stiffness maintained a consistently high level even after three or more cycles. In Poisson's ratio analysis based on elastic wave velocity, BAE was affected by both confining pressure and treatment cycle, while EAB was primarily influenced by confining pressure. Additionally, an empirical model predicting stiffness enhancement based on experimental data was proposed, and the model predictions showed high agreement with measured values. Overall, EAB is suitable for applications requiring high strength and volumetric strain resistance, while BAE is considered more suitable for achieving long-term gradual stiffness enhancement.

**KEYWORDS:** Biopolymer, EICP, Composite treatment, Shear strength, Stiffness, Elastic wave.

## 1 INTRODUCTION

Elastic wave-based testing is a key technique for non-destructively assessing the stiffness and dynamic behavior of soil. By measuring the propagation velocity of S-waves and P-waves using bender elements and PZT plates, it is possible to calculate the shear modulus ( $G$ ) and constrained modulus ( $M$ ), respectively (Andrus and Stokoe II, 2000; Richart et al., 1970). S-waves propagate only in solid media, reflecting the contact and arrangement states between soil particles, while P-waves pass through solids, liquids, and gases, making them sensitive to changes in moisture content and saturation (Chan, 2012). Due to these characteristics, S-waves are used for microstrain analysis, while P-waves are used for moisture condition monitoring. The reinforcement effect can be quantified by comparing changes in elastic wave velocity before and after improvement (Gu et al., 2015).

Traditionally, soil stabilization has primarily relied on ground improvement using cement-based materials, which offer significant advantages in terms of short-term strength and constructability. However, due to the high CO<sub>2</sub> emissions associated with the cement industry, bio-inspired geotechnics, which consider sustainability and environmental compatibility, have recently gained attention as an alternative (Chang et al., 2016; Zhang et al., 2024). This technology is an approach that mimics the structural formation principles and chemical reaction mechanisms found in nature to enhance the functionality of soil materials. Representative examples include Biopolymer-based Soil Treatment (BPST) and Enzyme-Induced Calcite Precipitation (EICP). BPST forms a biopolymer matrix between soil particles to increase shear strength (Chang and Cho, 2019), and EICP uses urease to precipitate calcite and strengthen particle bonding (Ahenkorah et al., 2021; Almajed et al., 2018). However, BPST is limited

by swelling issues due to hydrophilicity (Fatehi et al., 2021), and EICP is limited by the uneven distribution of calcium carbonate within pores (Martinez et al., 2013).

To address this issue, a composite treatment (e.g., BAE, EAB) involving the sequential application of biopolymer and EICP has been proposed. Biopolymer-assisted EICP (BAE) utilizes the viscosity of biopolymer hydrogel to increase the retention time within the pore space, thereby enhancing sedimentation efficiency and achieving high compressive strength (Arab et al., 2021; Miyake et al., 2022). Additionally, enzyme-assisted biopolymer (EAB) reverses the order to induce different sedimentation behavior. Previous studies have mainly focused on BAE, and there are few cases that quantitatively compare the effects of changes in treatment order on soil shear strength, in elastic wave velocity, and stiffness development. Therefore, this study compares and investigates the shear strength and stiffness enhancement of composite treatment methods, BAE and EAB. Shear parameters of the soil are determined through direct shear tests, and elastic wave velocities are used for stiffness evaluation. In particular, the effects of treatment cycle and sequence, and confining pressure on stiffness enhancement behavior are discussed. The change characteristics of Poisson's ratio of composite treatment soils are analyzed, and an empirical Poisson's ratio prediction model utilizing confining pressure and treatment cycle is presented.

## 2 MATERIALS AND METHODS

### 2.1 Soil properties

In this study, sand without fine particles from Jumunjin was used, and it was determined to be SP according to the USCS soil classification method. In accordance with ASMT D 854, the specific gravity of the soil was determined to be 2.5. The

effective soil particle diameter ( $D_{10}$ ) is 0.46 mm, and the mean diameter of soil particles ( $D_{50}$ ) is 0.79 mm. The maximum and minimum void ratios were determined according to DIN 18126 and are 0.79 and 0.54, respectively. The relative density of the soil was set at 60%.

## 2.2 Test setup

A transparent acrylic cylindrical chamber with an inner diameter of 50 mm and a height of 100 mm was used for sample molding and processing for laboratory experiments. The chamber was designed with a sealed upper and lower structure to prevent contact with the outside air, thereby minimizing moisture loss and external interference factors. The target soil was compacted to a relative density of 60% to achieve a medium density state corresponding to field conditions.

The bender elements and PZT plates were mounted with the top cap and pedestal, respectively, enabling non-destructive stiffness evaluation based on elastic wave velocity. The system measures changes in P- and S-wave velocities resulting from composite treatment, enabling quantitative analysis of changes in soil stiffness. A square wave is input from the top via an oscilloscope. The elastic wave velocity is calculated based on the arrival time and measured waveform detected by the receiver sensor located at the bottom. This data is used to derive the stiffness of the soil under different treatment conditions.

Injection ports for solution injection were installed in the top cap and pedestal, enabling the injection of biopolymers and EICP solutions without disturbing the sample. The composite treatment solution was slowly injected from the top to minimize excess pore water pressure, and the effluent generated after the reaction was allowed to drain naturally to the bottom under gravity.

The sample treatment and loading conditions are shown in Figure 1. Three confining pressure conditions were applied to the composite-treated samples, set at 12.5 kPa, 25.0 kPa, and 50.0 kPa, respectively. The confining pressure was applied using a pneumatic cylinder, and the pressure accuracy was ensured by using a precision regulator and calibration process prior to the experiment.



Figure 1. Test setup for bio-treatment and elastic wave measurements.

## 2.3 Enzyme Induced Calcite Precipitation (EICP)

EICP (Enzyme-Induced Calcite Precipitation) is a method that utilizes urease to promote the hydrolysis of urea and precipitate calcium carbonate in soil pores. Urea,  $\text{CaCl}_2$ , and urease were used for EICP treatment. All were used in powder form at the research-grade level. The molar concentration of urea was set to 1 M, and that of calcium chloride to 0.67 M. The

concentration of urease was determined to be 3 g/L based on previous literature to promote the hydrolysis of urea, with a maximum activity of 1000 U/g. All components were mixed to create a biocementation solution, which was then injected into the soil. The amount injected into the soil was determined based on the soil's relative density, with 1 pore volume injected. The EICP solution was injected into the soil once a week, for a total of four injections.

## 2.4 Biopolymer-based Soil Treatment (BPST)

BPST (Biopolymer-based Soil Treatment) is a technique that enhances the strength and stability of soil by coating soil particles with a biofilm using biopolymers or forming a matrix structure between soil particles. In this study, Xanthan Gum (XG) extracted from the *Xanthomonas campestris* was used as the biopolymer material for BPST. XG exhibits shear-thinning behavior, in which viscosity increases significantly when mixed with water, and shear stress decreases as shear strain increases. These rheological properties allow the EICP solution to remain in the pores between soil particles for a longer period, providing an environment in which calcium carbonate can precipitate more uniformly. In this study, the biopolymer concentration was set at 0.05% by weight of the soil, considering injectability and treatment efficiency. XG was manufactured into a homogeneous hydrogel form through a sufficient mixing process and then injected into the sample, followed by BPST treatment.

## 2.5 Biologically composite treatment

BPST fills the pores in the soil with hydrogel, reducing hydraulic conductivity due to the viscosity of the biopolymer and increasing shear strength. Meanwhile, EICP is a technology that increases strength by precipitating calcium carbonate between soil particles. However, BPST uses liquid-state biopolymers, which makes it difficult to ensure long-term structural stability due to biodegradability, and it has the limitation of not being able to exhibit sufficient shear strength in wet conditions. EICP also has the disadvantage of uncertainty in the precipitation location even when forming solid calcium carbonate, and ammonia gas is generated during the reaction process.

In this study, the concept of composite treatment is proposed to complement the limitations of BPST and EICP and combine their advantages. Composite treatment utilizes both XG biopolymer and EICP, and the two methods are distinguished by the treatment sequence. The first method, BAE (Biopolymer-Assisted EICP), involves first treating the soil with biopolymer hydrogel, then repeatedly injecting EICP solution to precipitate calcite in the pores. In this case, the viscosity of the biopolymer is expected to allow the EICP solution to remain in the pores for a long time, so that calcite will precipitate more uniformly while the solution is slowly injected. The second method, EAB (EICP-Assisted BPST), involves first forming sufficient calcium carbonate precipitation through EICP treatment, and then injecting biopolymer hydrogel. This method is expected to provide a permeability reduction effect by protecting the precipitated calcite with biopolymer and filling the pores with hydrogel, which has relatively high viscosity. This study aims to confirm how the sequence of composite treatment affects the strength and stiffness of soil.

# 3 TEST RESULTS

## 3.1 Shear strength parameters

The shear strength parameters of control soil (Jumunjin sand) and individually treated soils (BPST and EICP), composite

treated soils (BAE and EAB) were determined by direct shear tests. In the direct shear test, peak and residual shear parameters were determined using peak and final resistances generated by shear strain. Detailed experimental procedures and results are described in Park et al. (2024). The shear strength parameters for each condition are shown in Table 1.

The results of the direct shear test showed that the friction angle of the control sample at peak condition was 37.1°, while the friction angles of the BPST, EICP, and BAE-treated samples decreased by 26.4%, 19.4%, and 17.3%, respectively, to 27.3°, 29.9°, and 30.7°. In contrast, the friction angle increased by 5.1% to 39.0° after EAB treatment. Cohesion was measured at 0 kPa for the control sample, while it was 2.3 kPa, 7.4 kPa, 3.9 kPa, and 19.7 kPa for the BPST, EICP, BAE, and EAB treatments, respectively, with the EAB treatment showing the largest increase compared to the control sample.

In the residual state, the friction angle of the control was 27.5°, which decreased by 17.1% and 8.7% in the BPST and BAE treatments, respectively, and by 38.5% in the EICP treatment. The EAB treatment showed a slight decrease (-2.9%) to 26.7°. Residual cohesion was 0 kPa for the control, while it was measured at 2.70 kPa, 7.73 kPa, 0.31 kPa, and 6.95 kPa for BPST, EICP, BAE, and EAB treatments, respectively, with EICP and EAB showing relatively high values.

Overall, EAB treatment showed a balanced improvement in friction angle and cohesion under both peak and residual conditions. In particular, peak cohesion increased by approximately 19.7 kPa in absolute terms compared to the control, showing the highest strength enhancement effect among all conditions. This indicates that EAB-treated soils are effective in both initial and residual strength.

Table 1. Shear strength parameters for each soil (Park et al., 2024).

State	Strength parameters	Control	BPST	EICP	BAE	EAB
Peak	Friction angle (°)	37.1	27.3	29.9	30.7	39.0
	Cohesion (kPa)	0	2.3	7.4	3.9	19.7
Residual	Friction angle (°)	27.5	22.8	16.9	25.1	26.7
	Cohesion (kPa)	0	2.70	7.73	0.31	6.95

### 3.2 Stiffness assessment using elastic wave velocities

Soil stiffness can be evaluated based on the elastic wave propagation behavior of the soil. In particular, the velocities of P-waves and S-waves propagating through the soil are used to quantitatively evaluate the stiffness enhancement effect of the treatment. P-waves can pass through liquids, gases, and solids, enabling tracking of changes in soil saturation and density, while S-waves can only pass through solids and are sensitive to changes in soil particle array states or interparticle contacts. In this study, soil stiffness changes under BPST, EICP, and composite treatment conditions were evaluated. Elastic wave velocities were measured at the end of each treatment cycle, and the stiffness enhancement effects under confining pressures ranging from 12.5 to 50 kPa were analyzed.

The changes in P-wave and S-wave velocities of BAE soils are shown in Figure 2 and Figure 3, respectively. In the case of P-wave velocities, higher velocities were measured in the same cycle as the confining pressure increased, and the velocities tended to increase progressively as the treatment cycle progressed. Notably, the largest increase rate compared to the initial biopolymer treatment was 49.91% under low confining pressure conditions (12.5 kPa), suggesting that composite treatment is more effective in enhancing stiffness under low-load conditions. S-wave velocities also exhibited a similar trend. Under the same cycle conditions, S-wave velocities increased

as the confining pressure increased, and the stiffness increase rate due to composite treatment was highest at 62.60% under low confining pressure conditions. These results can be interpreted as the stiffness gradually improving as calcite precipitation formed more uniformly due to the EICP solution remaining in the pore space for a long time by the prior injection of biopolymer.

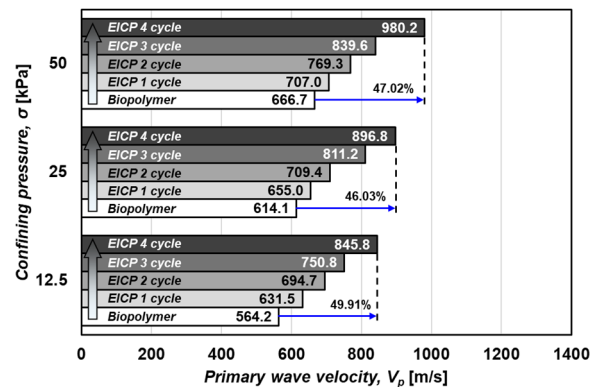


Figure 2. P-wave velocities of BAE depending on treatment cycles and confining pressures.

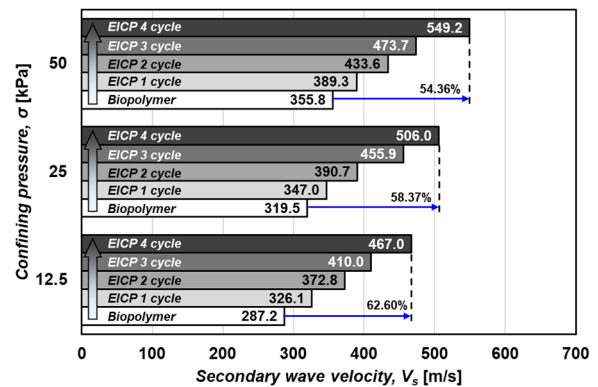


Figure 3. S-wave velocities of BAE depending on treatment cycles and confining pressures.

The changes in P-wave and S-wave velocities of EAB-treated soils are shown in Figure 4 and Figure 5, respectively. Similar to BAE, the elastic wave velocities increased with increasing confining pressure, and the P- and S-wave velocities of EAB soils were higher than those of BAE-treated soils in all cycles. The increase in P-wave velocity ranged from a minimum of 24.05% to a maximum of 43.97%, while the increase in S-wave velocity ranged from a minimum of 25.93% to a maximum of 44.08%. The velocity increase rate up to the initial stage of EAB treatment (after 4 cycles) was lower than that of BAE treatment. Considering the changes at each stage of EICP treatment, elastic wave velocities increased under all confining pressure conditions up to EICP 3 cycles, but no changes were observed under all conditions at 4 cycles. This indicates that the calcite precipitation efficiency reached its maximum at 3 cycles, and the precipitation efficiency decreased when additional solution was injected thereafter. Even when biopolymer was injected in the final stage, there was no change in elastic wave velocities.

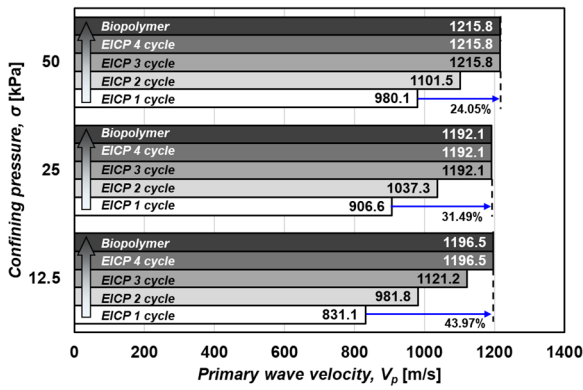


Figure 4. P-wave velocities of EAB depending on treatment cycles and confining pressures.

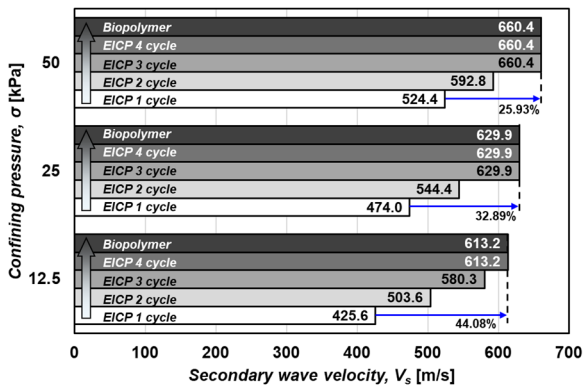


Figure 5. S-wave velocities of EAB depending on treatment cycles and confining pressures.

## 4 DISCUSSION

### 4.1 Effects of treatment cycles and confining pressure on soil stiffness

Poisson's ratio ( $\nu$ ) is defined as the ratio of transverse strain in the perpendicular direction to longitudinal strain in the direction of the applied load, and it has a positive value in tension and a negative value in compression. In this study,  $\nu$  was used to quantitatively assess the effects of confining pressure and treatment cycles on composite-treated soils. The  $\nu$  can be calculated based on elastic wave velocities (P-wave, S-wave), and the relationship is expressed as Equation (1).

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x} = \frac{\text{Radial strain}}{\text{Axial strain}} \quad (1)$$

In addition, it can be obtained using the  $V_s$  and  $V_p$  of porous media and is expressed by the Equation (2).

$$\nu = \frac{\frac{1}{2}\left(\frac{V_p}{V_s}\right)^2 - 1}{\left(\frac{V_p}{V_s}\right)^2 - 1} \quad (2)$$

The  $\nu$  value reflects the relative ratio of  $V_p$  to  $V_s$  ( $V_p/V_s$ ) rather than directly indicating the absolute stiffness of the material, as shown in Equation (2) above. In other words, the

smaller the  $\nu$  value, the greater the influence of the increase in  $V_s$ , and the larger the  $\nu$  value, the greater the relative proportion of  $V_p$ . In this study,  $V_p$  and  $V_s$  measured under each condition were used to assess the stiffness trend with changes in confining pressure and treatment cycle.

In the case of BAE soils (Figure 6), the  $\nu$  decreased with the increase in confining pressure in all treatment cycles, and the  $\nu$  further decreased with the increase in cycle under the same confining conditions. This indicates that the relative increase in  $V_s$  was more prominent than the increase in  $V_p$  in the BAE treatment, resulting in a decrease in the  $V_p/V_s$  ratio, which means that shear-dominant stiffness enhancement occurred. On the other hand, in the case of EAB soils (Figure 7), the  $\nu$  decreased with the increase in confining pressure, but the change in the  $\nu$  with the increase in the cycle was limited. This is explained by the fact that the relative increase in  $V_p$  was dominant over  $V_s$  during EAB treatment, and the  $V_p/V_s$  ratio was maintained relatively high. In conclusion, BAE tends to lower the  $\nu$  because the increase in  $V_s$  is relatively large, while EAB tends to maintain a high  $\nu$  because the increase in  $V_p$  is relatively large. Therefore, if the main objective is to improve shear deformation resistance, such as in the case of earthquakes, it is effective to apply BAE, while EAB may be more suitable for reducing volumetric compressibility and strengthening the skeleton.

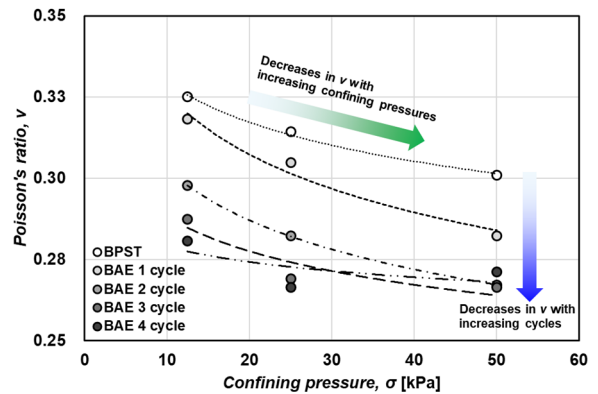


Figure 6. Poisson's ratio trends of BAE-treated soils.

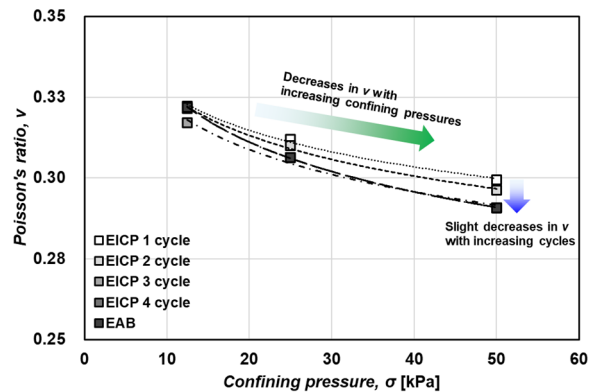


Figure 7. Poisson's ratio trends of EAB-treated soils.

### 4.2 Empirical equation for determining Poisson's ratio

An empirical prediction model was proposed to predict  $\nu$  based on changes in confining pressure and treatment cycle of BAE and EAB soils. The parameters of the prediction model are confining pressure and treatment cycle of EICP, and an exponential convergence model was applied. The proposed equation is shown in Equation (3).

$$v(\sigma, c) = v_{\infty} - (v_{\infty} - v_0) \cdot e^{-(a+c+b\sigma)} \quad (3)$$

Here,  $v_0$  is the initial state before composite treatment,  $v_{\infty}$  is the Poisson's ratio in the stable state after sufficient composite treatment,  $\sigma$  is the confining pressure,  $c$  is the treatment cycle of EICP,  $a$  and  $b$  represent the treatment cycle coefficient and confining pressure coefficient, respectively. In the case of  $c$  (treatment cycle), since the biopolymer treatment was found to have no effect on wave velocity change, the biopolymer treatment was not included in the treatment cycle. In the BAE treatment, the first biopolymer treatment cycle was set to 0, and in the EAB treatment, the last fifth biopolymer treatment was also set to 4 after a total of four EICP treatments. Each parameter determined by the prediction model is shown in Figure 8.

Except for the  $a$  parameter, the other parameters derived from the BAE and EAB prediction equations were determined similarly. This means that the decrease in the Poisson's ratio from the initial state to the steady state is similar for both treatment methods. In addition, the effect of confining pressure on the prediction model is minor, and the decrease in  $v$  with increasing confining pressure is also similar for both treatment methods. On the other hand, a clear difference was observed between the two treatment methods in the  $a$  parameter. The parameter  $a$  indicates sensitivity to the number of treatment cycles, and in the case of BAE, the  $v$  decreased rapidly as the number of cycles increased (Figure 6). This shows that the change in the  $v$  is large from the initial treatment to the long-term treatment. In contrast, in EAB, there was almost no change in the  $v$  with changes in the number of treatment cycles (Figure 7), which explains why the  $a$  value was small. In conclusion, while both treatment methods exhibit similar trends in the convergence of the  $v$  and changes in response to confining pressure over the long term, the influence of changes in the number of treatment cycles on the  $v$  is much greater in BAE, and this difference is well represented by the  $a$  parameter.

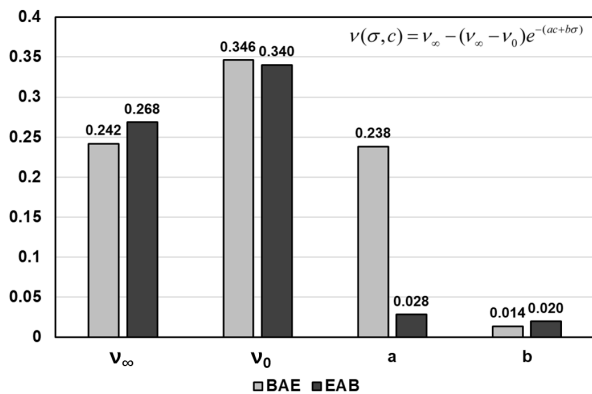


Figure 8. Comparison of prediction model parameters.

To verify the performance of the prediction model, the calculated  $v$  and predicted  $v$  were compared. In the case of BAE (Figure 9),  $R^2$  was 0.922 and RMSE (Root Mean Squared Error) was 0.00492, showing high prediction performance. In addition, in the case of EAB prediction model performance (Figure 10),  $R^2$  was 0.960 and RMSE was 0.0228, showing higher performance than BAE. This demonstrates that the empirical equation can provide a simple and physically interpretable  $v$  prediction even when confining pressure and treatment cycle change simultaneously. Both treatment methods showed high statistical agreement, suggesting that the empirical equation could be useful for designing and predicting the performance of

biological-geotechnical hybrid treatments. However, since the biopolymer and EICP solution concentrations applied in this study are under limited conditions, it is considered necessary to measure the elastic wave velocity of composite treated soils to apply them to other conditions.

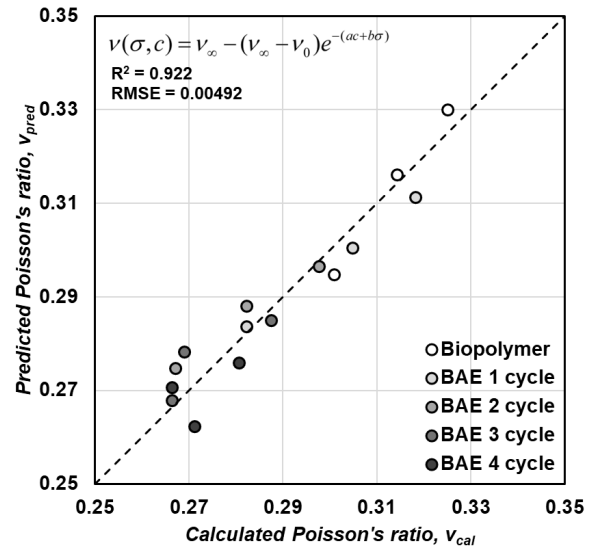


Figure 9. Verification results of prediction model of BAE.

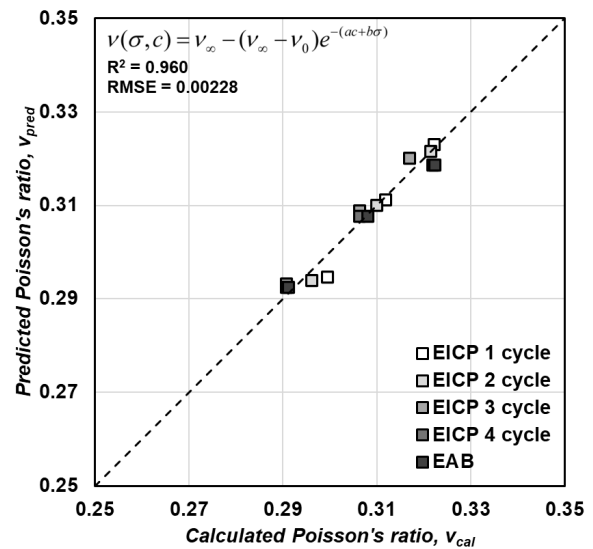


Figure 10. Verification results of prediction model of EAB.

## 5 CONCLUSIONS

The objective of this study is to comprehensively assess the shear strength and stiffness enhancement of composite treatment soils combining biopolymer and EICP. To this end, changes in soil strength and stiffness were compared and analyzed by the application sequences of XG hydrogel and EICP solution.

The results of the direct shear test showed that the shear strength parameters were generally higher in composite treatment soils than in single treatment (BPST or EICP) soils. In particular, EAB showed the highest peak and residual shear strength. The elastic wave velocity measurement results also showed that both  $V_s$  and  $V_p$  of EAB soils were higher than those of BAE soils. The changes in the treatment cycle showed

distinct differences between the two treatment methods. In the case of BAE soils, elastic wave velocities increased progressively as the treatment cycle increased, but in EAB soils, wave velocities tended to remain constant when the cycle exceeded three times.

Based on the  $v$  calculated using elastic wave velocities, the analysis results showed that both confining pressure and treatment cycle affected stiffness enhancement in BAE, whereas confining pressure was the main factor in EAB. These differences were also reflected in the parameters of the developed empirical equation, and except for parameter  $a$ , the other parameters were determined similarly for both treatment methods. The higher value of the  $a$  parameter in BAE compared to EAB is considered to be due to the sensitivity of the  $v$  in BAE soils to changes in the treatment cycle.

In summary, EAB treatment is proposed to be more effective in terms of shear strength and volumetric strain resistance. However, BAE treatment is more appropriate when aiming to achieve long-term, gradual shear stiffness enhancement.

## 6 ACKNOWLEDGEMENTS

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