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INCREASING THE BEARING CAPACITY OF SQUARE FOUNDATIONS BASED ON SOYBEAN BIO-CEMENTATION

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Abstract

Sandy soils are commonly employed as the foundation for shallow footings. However, their relatively low bearing capacity often leads to excessive settlement and deformation. This study examines the potential application of the Enzyme-Induced Carbonate Precipitation (EICP) technique based on soybeans. Utilizing urease derived from soybeans to catalyze the crystallization of calcium carbonate ($CaCO_3$). This research investigates the impact of EICP-induced carbonate precipitation on the bearing capacity of sandy soil in square footings. 4 x 4 cm footing model was tested using the AIC-Innovation Loading Test apparatus. Direct shear additional tests were performed to assess differences in increase cohesion and shear angle. The results show 174.90% increase in bearing capacity, 73.47% reduction in settlement, 300.64% increase in cohesion from the shear test, and 202.46% increase from the loading test. The shear angle increased by 56.34%, and the dry unit weight increased by 36.5%. ANOVA analysis with a p-value of $2.03 \times 10^{-15} < 0.05$ confirmed that the increase in bearing capacity was not due to random variation but to the EICP treatment. These findings demonstrate that EICP proves to be a viable technique to enhance sandy soil and contributes to advancing of bio-cementation based on organic materials as a sustainable solution.

Keywords: EICP, Bearing Capacity, Sand, Soybean, Square Footing Foundation

Introduction

Sandy soil is frequently used as the foundation for shallow footings (Musílek et al., 2016). However, this type of soil exhibits relatively low bearing capacity (Raja et al., 2024). bearing capacity is influenced by several factors, including relative density ranging between 20% < Dr < 35%(Hatanaka & Feng, 2006), internal friction angle (25-35°) (Doumi et al., 2022; Mahmood et al., 2020), and negligible cohesion (Cardoza & Oka, 2020; Diana et al., 2024). Due to the minimal cohesion, the soil's stability heavily depends on the internal friction angle (Yousefi Samangani & Naderi, 2022). As a result, the soil is highly susceptible to excessive deformation and settlement under applied loads (Aleshaiqer & Azeez Alkifaee, 2024). Therefore, there is a need for effective soil improvement solutions to enhance the stability of the soil in supporting the foundation.

Various conventional methods, such as mechanical compaction (Zabrodskyi et al., 2021), chemical stabilization with cement or lime (Shooshpasha & Shirvani, 2015; Sinha et al., 2024), and the use of geosynthetics (Al-Subari et al., 2020), have been widely applied in soil improvement. However, these methods are often limited by environmental impacts, costs, and effectiveness (Mohamed et al., 2022; Prambauer et al., 2019; Zabrodskyi et al., 2021). These conditions necessitate the advancement of efficient and environmentally responsible soil improvement technologies. As a sustainable and low-cost solution. In recent geotechnical research, the use of EICP for soil bio-cementation has gained significant attention (Almajed et al., 2018; Dejong et al., 2013). The process relies on urease activity to catalyze urea ($CO(NH_2)_2$) and calcium chloride ($CaCl_2$), generating carbonate ions (CO_3^{2-}) and calcium ions (Ca^{2+}) (Hoang et al., 2020; Naveed et al., 2020). This reaction results in the crystallization of $CaCO_3$ within the soil matrix (Liu et al., 2021; Renjith et al., 2020). These minerals contribute to enhanced shear strength and stiffness by linking soil particles and decreasing void space (Gao et al., 2019). Soybean-based EICP is chosen due to its the metalloenzymes found in soybeans, which contain Ni^{2+} ions, are responsible for driving urease catalysis (Zambelli et al., 2013), environmentally friendly (Putra et al., 2025; Thakur et al., 2024), cost-effective urease enzyme source and low carbon footprint, minimizing the negative environmental impact (Kumar et al., 2023; Thrane et al., 2023).

The ability of EICP to enhance soil strength has been supported by multiple investigations, particularly through results obtained from UCS evaluations. J. Zhang et al., (2023) reported that the use of 20 grams/L of soybean powder in the EICP solution resulted in a UCS of 2.5 MPa. Conversely, Lai et al., (2023), Sun et al., (2024) and Xu et al., (2023) found that applying 100 g/L of soybean powder enhanced the UCS of silica sand to 2.8 MPa. Furthermore, Q. Zhang et al., (2023) reported that a mixture of 50 g/L resulted in a UCS of 6.28 MPa. Meanwhile, according to Martin et al. (2021), Shu et al. (2022), and Xue et al. (2024) a 60 g/L concentration significantly improved UCS to 4.1 MPa.

Based on the existing literature, EICP has demonstrated the ability to improve the strength characteristics of sand in multiple studies. However, the studies conducted thus far have been limited to UCS tests, without examining its application to square footings, which are more representative in evaluating the performance of shallow foundations in the field. This type of foundation is chosen due to its widespread use today, as well as its practicality and ease of fabrication. This study investigates the impact of soybean-based EICP regarding enhancement of bearing capacity in sandy soils supporting square shallow footings. The expected outcome is a soil stabilization method that cost-efficient and ecologically responsible, reducing the reliance on cement and synthetic chemicals, and contributing to the development of bio cementation techniques utilizing organic materials as a sustainable alternative for future geotechnical application.

Research Methods

This study uses SP-type sandy soil (Sand, Poorly Graded) from the Kediri region, exhibiting a relative density (Dr) of 34.29%, a measured dry weight per unit volume of 14.10 kN/m^3, and a porosity of 46%. Other physical characteristics include a D50 of 0.37 mm, the ratio of voids to solids (e) of 0.85, a specific gravity value (Gs) of 2.65, a (Cu) value of 2.93, and a coefficient of gradation (Cc) of 1.21. The soil was prepared in a test box measuring 35 × 27 × 20 cm using the water pluviation method to ensure uniform density (Mandolini, 2024).

Urease extract was obtained by dissolving 50 grams soybean powder into 1 liter of water (Q. Zhang et al., 2023), followed by stirring and filtration. The resulting was stored at 4°C for 72 hours (Shu et al., 2022). Cementation fluid was composed of 60 g/L urea combined with 110 g/L $CaCl_2$ in tap water (Q. Zhang et al., 2023). And was immediately applied to prevent premature reactions.

EICP solution was injected uniformly into the sand samples until saturation was achieved, with a total volume of approximately 9 liters. The specimens were cured under ambient conditions for a period of 3 days (approximately 25°C), and then dried for 2 days (J. Zhang et al., 2023). A total of three shear test samples were used for each loading test condition, with two loading conditions: one sample with EICP treatment and one sample without EICP treatment.

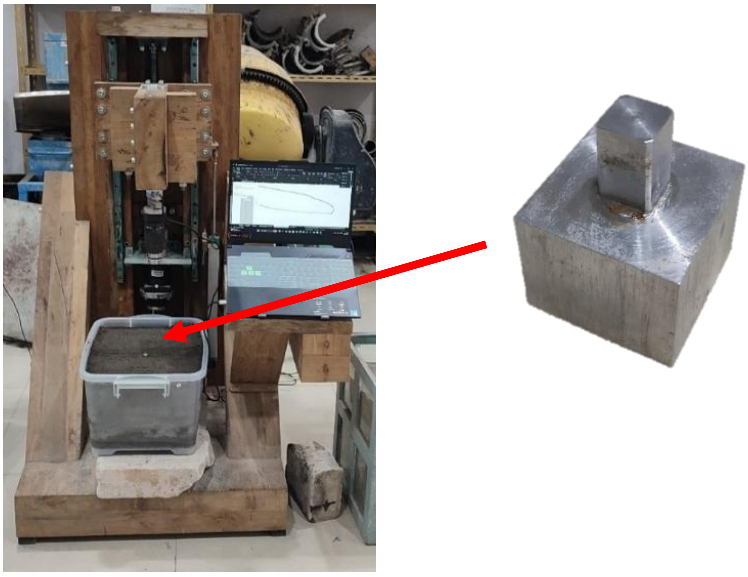

Figure 1. Loading Test Equipment AIC - Innovation

Direct shear method was employed to assess changes in (c) value and friction angle (φ) resulting from the treatment with test standards (ASTM D3080, 2011). The base bearing capacity test was performed using a square footing model measuring 4 × 4 cm, embedded to a depth of 4 cm. The AIC-Innovation loading system was applied to impose a vertical load exerted at a steady pace of 0.035 mm/s as illustrated in Figure 1. Applied force was recorded through a load cell, and corresponding settlement was captured using a linear position sensor. Testing continued until the settlement reached a maximum of 15% of the footing width(D1143/D1143M − 20, 2020). bearing capacity of the square footing was theoretically calculated using Terzaghi's formula (Karl Terzaghi, 1943)

$$Qu = (1.3 \times c \times Nc) + (\gamma \times Df \times Nq) + (0.4 \times \gamma \times B \times N\gamma). \qquad \text{(Equation 1)}$$

Statistical evaluation was performed through one-way ANOVA at a 5% significance level. When p-values fell below 0.05, the results indicated that EICP significantly contributed to improvements in the bearing capacity and mechanical characteristics

Research Results and Discussion

Bearing Capacity (Qu)

The performance of shallow foundations on sandy soils stabilized with Enzyme-Induced Carbonate Precipitation (EICP) can be evaluated through load-settlement relationship analysis. Figure 1 presents the experimental results of axial loading tests on a 4 x 4 cm square footing model, revealing how the EICP treatment simultaneously increases the ultimate bearing capacity while altering the soil deformation characteristics. This curve not only captures the magnitude of the load increase but also shows the change in soil stiffness through the observed settlement pattern, providing visual evidence of the effectiveness of the bio-cementation process in modifying the mechanical behavior of sandy soils.

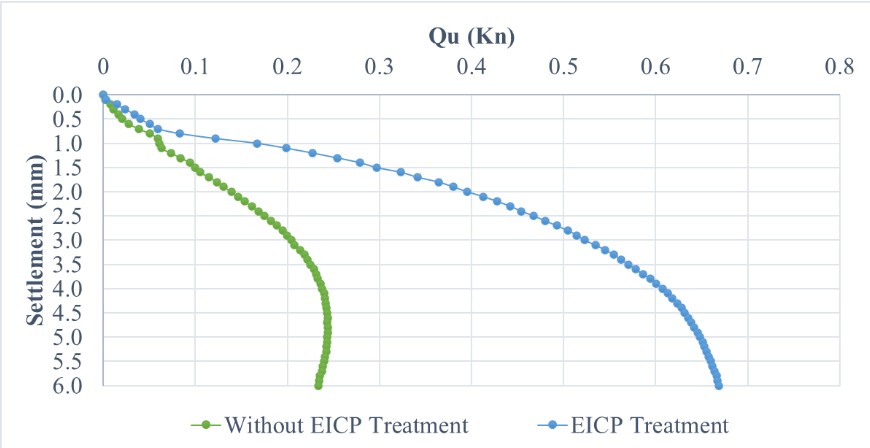

Figure 1. Effect of EICP on Soil Bearing Capacity

Figure 1 show the loading test results findings before the treatment phase indicated that, the maximum load (Qu) of 0.243 kN was achieved at a settlement of 4.9 mm, and load decreased to 0.226 kN when the settlement reached 15% of the footing width. After EICP treatment, the load of 0.243 kN was reached at a settlement of 1.3 mm. Value of Qu increased to 0.645 kN at a settlement of 4.9 mm and reached 0.668 kN at 15% settlement of the footing width. Maximum load increased by 174.90% compared to the untreated condition. The reduction in settlement at the same load was 73.47%. These results demonstrate that EICP improves the ability of sandy soil to resist vertical loading. The geotechnical implications of these findings are significant. The increase in Qu due to the formation of $CaCO_3$ deposits at the contact between sand grains improves grain interlocking and soil stiffness. Practically, this means that shallow foundations constructed on EICP-treated soils can be designed with smaller dimensions to support the same load. This results in design efficiencies in both foundation size and construction costs. Furthermore, the smaller settlement at a given load indicates improved long-term deformation performance, providing additional safety against potential excessive collapse. This is consistent with studies by (Meng et al., 2021; J. Zhang et al., 2023), which revealed that the development of $CaCO_3$ through enzymatic reactions improves intergranular contact and mechanical performance of sand.

Cohesion

In the analysis of foundation bearing capacity, the cohesion parameter (c) plays a critical role as shown in equation 1. Figure 2 describes the impact of EICP stabilization on increasing soil cohesion values as measured through direct shear tests and loading tests. This increase in cohesion will directly affect the first component of the Terzaghi equation (1.3cN_c), where any increase in cohesion will be directly proportional to the increase in ultimate bearing capacity. This analysis is key to understanding the contribution of bio-cementation in improving the performance of shallow foundations on sandy soils.

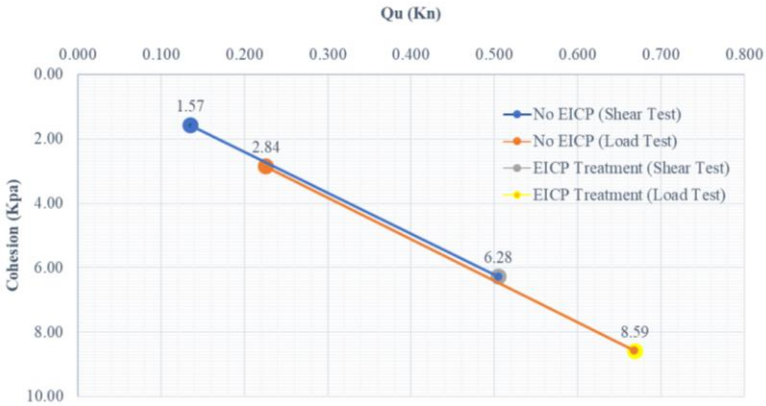

Figure 2. Effect of EICP on Cohesion

Figure 2 show the data obtained from the direct shear testing, where untreated soil exhibited a cohesion of 1.57 kPa, which increased to 6.28 kPa following treatment. Based on the loading test, the cohesion of the soil before treatment was 2.84 kPa, which increased to 8.59 kPa after treatment. The increase in cohesion from the shear test was 300.64%, and from the loading test, it was 202.46%. These results align with the findings presented by research (He et al., 2022) reveals that the use of EICP in sandy soils can lead to a cohesion increase of up to 3.5 kPa. This is further corroborated by Shu et al. (2022) which demonstrated that the formation of calcium carbonate from the chemical process involving soybean urease, urea and $CaCl_2$ results in a binder between soil particles, reducing internal shearing in sandy soil. This bond leads to an increased resistance to compressive load and shear forces.

Shear Angle

The internal friction angle (φ) is a key factor in assessing the bearing capacity of shallow foundations, which affects the bearing capacity. Terzaghi's bearing capacity formula in equation 1 estimates the ultimate bearing capacity by considering the factors Nc, Nq, and Nγ, which depend on soil properties, including the internal friction angle. Increasing the internal friction angle through Enzyme-Induced Carbonate Precipitation (EICP) treatment can increase the bearing capacity of foundations. Therefore, optimizing the internal friction angle is crucial to improve the stability and bearing capacity of foundations on sandy soils.

Figure 3. Effect of EICP on Shear Angle

Figure 3 show the increase in shear angle following EICP treatment. Prior to treatment, the internal friction angle was 29.13°, which rose to 45.54° after treatment, reflecting a 56.34% improvement. The observed increase influences the values of Nc, Nq, and Nγ used in estimating the ultimate bearing capacity of shallow foundations. An increase in the internal friction angle improves soil resistance to shear stress and contributes to greater bearing capacity of the foundation. This finding is consistent with the results obtained by Ye et al. (2024) documented a 27.09% improvement in the shear angle due to EICP stabilization in sandy soil.

Unit Weight

Soil unit weight is an important parameter in calculating foundation bearing capacity, as it affects the γDf and γB components in Terzaghi's bearing capacity formula in equation 1. An increase in soil unit weight indicates a decrease in porosity and an increase in soil density due to pore filling by $CaCO_3$ precipitation. Therefore, changes in soil unit weight play a significant role in increasing soil bearing capacity, especially in sandy soils.

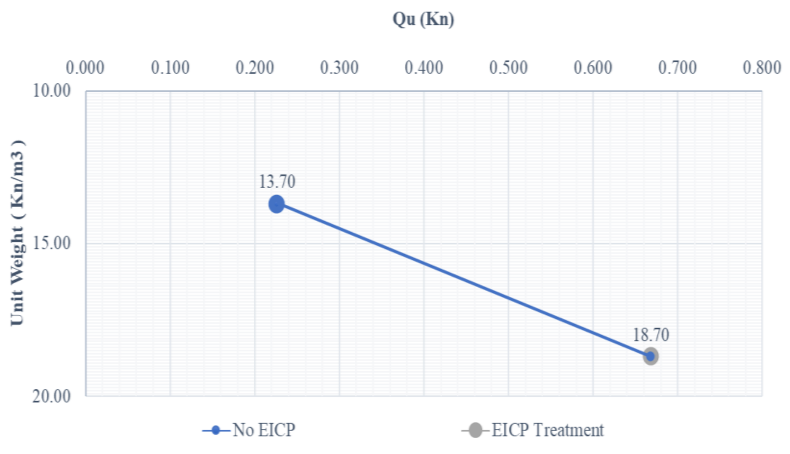

Figure 4. Effect of EICP on Unit Weight

Figure 4 Show soil samples exhibited a dry mass per unit volume of 13.70 kN/m³ prior to EICP treatment. After treatment, the unit weight increased to 18.70 kN/m³, representing a 36.5% increase. This increase in unit weight indicates a reduction in porosity due to pore filling by $CaCO_3$ precipitation. The soil becomes denser, leading to an increase in the γDf and γB components in Terzaghi's bearing capacity formula.

ANOVA Test

Table 1. One-way ANOVA Test

F Table	F Value	P-value
3.92	83.34	2.03E-15

One-way ANOVA was employed to evaluate the variation in bearing capacity between untreated and EICP-treated soil. Statistical evaluation yielded an F-value of 83.34, while the tabulated F-Table was 3.92 at a significance level of $\alpha = 0.05$. The p-value was 2.03×10^{-15}, which is smaller than 0.05. These results indicate that the difference between the conditions before and after treatment is statistically significant. The increase in bearing capacity was not due to random variation, but rather a result of the EICP treatment.

Parameter Integration

The increase in Qu is in line with the parameter components that influence it, including cohesion, friction angle, and unit weight, showing a mutually supportive relationship. The formation of particle bonds enhances cohesion and shear angle, while pore filling increases the unit weight. The enhancement in cohesion contributes directly to the c component in Terzaghi's bearing capacity equation, while a greater internal friction angle elevates the values of Nc, Nq, and $N\gamma$, thereby increasing the foundation's load- bearing capacity. Additionally, the increase in unit weight enhances the γDf and γB factors, effectively enhancing the ultimate bearing capacity of footings placed on sand. These combined improvements have a significant impact on enhancing the load-bearing capability of foundations on sand soils

Conclusion

This study shows that EICP treatment with soybean urease significantly increases the bearing capacity of square footings on sandy soil by 174.90%, reduces settlement by 73.47%, and increases cohesion by 300.64% in shear tests and 202.46% in loading tests. The internal friction angle increases by 56.34%, and the unit weight by 36.5%. ANOVA analysis ($p = 2.03 \times 10^{-15}$) confirms that these improvements are due to the EICP treatment, not due to random variation. The geotechnical implications of these findings are clear. The increase in ultimate bearing capacity (Qu) directly impacts the efficiency of shallow foundation design, as foundation dimensions can be reduced to support the same load without reducing the safety factor. In addition, smaller settlements indicate improved deformation performance, so structures built on EICP-treated sandy soil will be more stable. It provides an economical and environmentally friendly alternative solution, reducing dependence on conventional materials such as cement and lime for sandy soil improvement. Further research is recommended to test the use of EICP on other soil types and to optimize the use of other organic materials to accelerate and improve the effectiveness of the bio cementation process. Long-term evaluation of the durability of the resulting bio cementation is also important to identify potential degradation due to weather changes and microbial activity. These findings support the development of bio cementation techniques using organic materials as a sustainable alternative for future geotechnical applications.

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