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Review Article

# Review of Enzyme-Induced Calcite Precipitation as an Enhancement Technique for Weak Soils

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## Abstract

The swiftly expanded worldwide population has increased the demand for engineering solutions aimed to enhancing the geotechnical properties of weak soil, raising concerns about the sustainability of traditional approaches reliant on energy-intensive materials and methods from earlier times. Conventional ground enhancement methods such as compaction, preloading, vibration, and chemical grouting are often expensive and often have very high energy and carbon di-oxide emissions. Soil stabilization employing bio-enzymes has been viewed as a resilient and ecologically beneficial method for modifying the soil characteristics. Calcite-induced precipitation methods have recently emerged as effective strategies in geotechnical engineering for enhancing soils qualities. Among these, enzyme-induced carbonate precipitation (EICP) is distinguished as a notably efficient technique. This bio-inspired method emphasizes the precipitation of calcium carbonate to enhance the geomechanical soils characteristics. The CaCo3 functions in this process, in the capacity of cementitious agent which binding the grains of soil in the points of its contact, thereby raising the strength and stiffness of treated soils while simultaneously decrease the permeability and porosity. The enhancements obtained through EICP render it valuable for applications like ground enhancement, building materials, and erosion management, surpassing conventional binders. EICP particularly, has proven to be more effective since its application to all soils coarse and fine which have small pore size. This review thoroughly assesses the use of the EICP approach as a soil stabilization strategy conducted by different researchers. This review article studies urease and its implication on the properties of treated soil like shear strength, permeability and micro-structural changes.

**Keywords:** *EICP, Bio-cementation, Urease Enzyme, Environmental Technique, Engineering Properties.*

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## 1. Introduction

Rapid population growth and increasing their heightening demands have led to industrial development, intensive construction practices and mining, which represent primary sources of globally CO2 emissions are not eco-friendly activities may have degraded the land and caused great potential harm to the environment [1].

In the past decade, significant investigation was conducted to create environmentally eco-friend binders to enhancing soil. Among various soil binders, bio-cementation through carbonate precipitation was become a highly encouraging bio-inspired technique to enhancing the geo-mechanical properties of soil.

Several bio-mediated (i.e., bio-based material or biologically controlled) and bio-inspired (i.e., mimicked from biological process or systems) ground improvement methods have the potential to address multiple geotechnical challenges. Microbial-Induced Calcite Precipitation (MICP) and Enzyme-Induced Calcite Precipitation (EICP) are currently the most researched carbonate cementation techniques [2]. Soil enhancement means using MICP procedure was researched extensively [3]-[10].

Over the past few years, EICP involving urease has being contemplated as a replacement to MICP to overcome the limitations of MICP and the complexity of producing microbes used as in-situ soil stabilizers. EICP provides multiple advantages for soil enhancement, like promoting sustainability and delivering an item which is a reduced environment effect compared to conventional methods. On other hand, the crystals size of the enzyme urease which is very small (typically 12 nm) creates the process effective to all types of soil, incorporating grains of fine ones [11], as opposed to size of microorganisms comparatively large which its effect is relatively unsatisfactory for clay with generally small pores.

Moreover, EICP is a versatile therapy which could tailor for various applications of engineering. Even minor adjustments in the blend and level of solution concentration can lead to distinct result in relation to shear strength, permeability etc.

This paper presents an extensive literature review on the use of Enzyme-Induced Calcium Carbonate Precipitation (EICP) for improvement of weak/soft soil properties.

## 2. EICP Overview

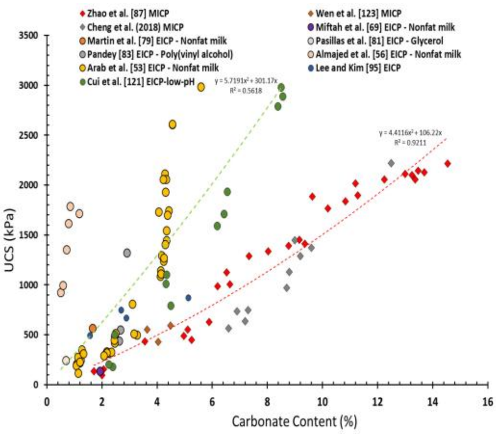
Interest in the EICP based enhancement geo-mechanical characteristics soil techniques has increased in recent years as it has demonstrated significant potential as a bio-inspired, eco-friendly compared to ground enhancement methods based cement.

Extensively utilizing EICP in several applications so far, like enhance soil strength: [12]-[21], permeability reduction [22]-[28], dust suppressant [29]-[32] and erosion mitigation [33]-[38].

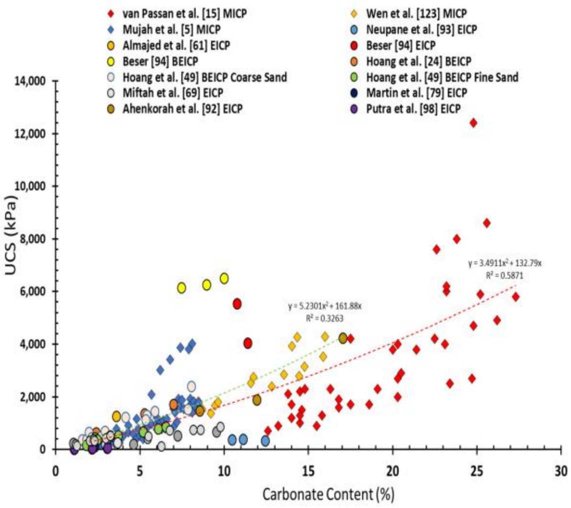
### 2.1. Urease Source

The EICP is a bio-cementation method utilizes an enzyme urease to catalyzing process of hydrolysis. Urease, a nickel containing enzyme, present in diverse organisms, vegetation, algae, fungi, and prokaryotes [39].

In general, both Microbial-Induced Carbonate Precipitation (MICP) and Enzyme-Induced Carbonate Precipitation (EICP) techniques utilize the enzyme urease for produce carbonate via urea hydrolyze in a calcium-rich solution, to induce precipitation of calcium carbonate in the pores of soil. Urease enzyme source is derived from bacteria in (MICP) whereas is primarily extracted from plants in (EICP). The enzyme can be obtained from various sources (agricultural, microbial, or fungal sources); several limitations in enhancing the soil properties in MICP utilizing urease source from cells bacterial have been observed to be resolved by EICP. Arab et. al., [40] compiled and summarized of UCS results and their carbonate content from multiple studies in the literature as shown in Fig.1.




(a)




(b)

**Figure 1.** A comparison of unconfined compressive strength (UCS) results based on various studies for both EICP and MICP samples' treated and their carbonate content (a) one treatment cycle; (b) multiple treatment cycles [40].

In general there are two major sources of the urease enzyme are:

The commercially available urease which is found to be extremely purified and costly/uneconomical, thus, it is used in delicate practices, including food industry, pharmaceutical company, and analytical chemistry [41].

The crude urease which extracted from some legumes/melon seeds [42] such as jack beans [43]-[44], soybeans [24], [31], [45] and watermelon seeds [14], [46].

The most prevalent crude urease source is extracted from soy bean [42], [44]. A procedure of extraction process of jack bean and soy bean crude ureases employed by researchers has been illustrated in Fig.2. Soy bean (Glycine max) and jack bean (Canavalia gladiate) were procured from the local marked for research purposes [47].

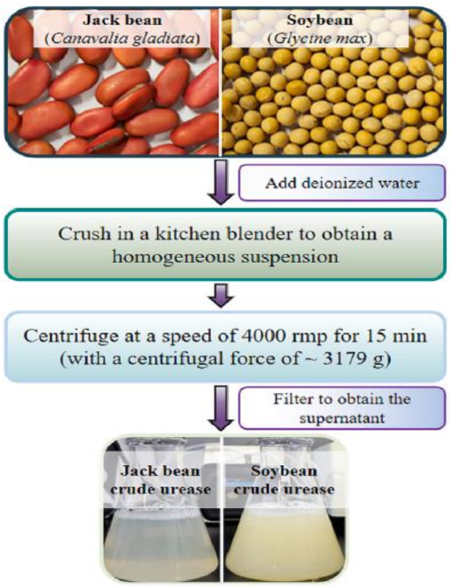



**Figure 2.** Detailed extraction process of soy bean and jack bean crude ureases [47].

## 2.2. Principle of EICP Process and Reaction

As mentioned earlier, EICP is a technique that employs the crude urease extract to catalyze urea hydrolysis. The urea solution is hydrolyzed into carbonate and ammonium ions in existence of calcium chloride leading to the creation of ammonium chloride and calcium carbonate. The calcium carbonate precipitate binding the grains of soil by filling the pores; generally the rise in carbonate content within pores of soil increases strength of soil. The precipitation process in soil through the utilization of the enzyme urease was shown in Fig.3, [48].

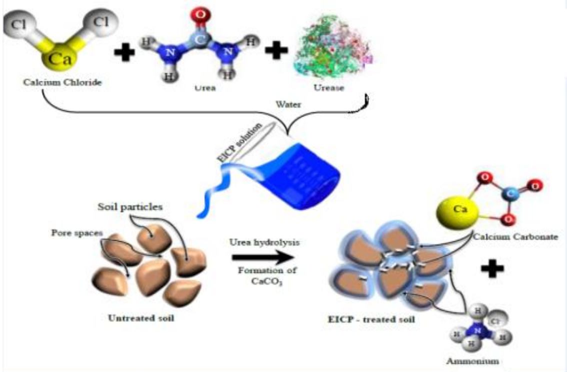



**Figure 3.** Schematic of calcite precipitation process [48].

An EICP process comprises of two phases: First) catalyzing ureolysis via enzyme urease CO(NH2)2 to carbon dioxide (CO2), ammonia (NH2) as shown in eq. (1); Second) calcium carbonate (calcite) is formed by the combination of calcium ions Ca2+, and carbonate ions CO32-, which gets precipitated. Calcium chloride dehydrate (CaCl22H2O), chosen for its effectiveness in CaCO3 precipitation as shown in eq. (2) and eq. (3) [49].

$$CO(NH_2)_2 + 2H_2O \xrightarrow{urease} 2NH_4^+ + CO_3^{2-} \qquad ...(1)$$

$$CaCl_2.2H_2O \rightarrow Ca^{2+} + 2Cl^- \qquad ...(2)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow precipitated \qquad ...(3)$$

The overall process for EICP involves carbonate precipitation, which occurs through the introduction of (CO3) ions and the alkalinity generated by ureolysis, EICP utilizes urease to catalyst the urea hydrolyses as well as acting as a mediator in the development of calcium carbonate precipitate [41].

## 2.3. Cementation Solution and EICP Mixing Procedure

The cementation solution consists of (urea-CaCl2) present at same or different molar concentrations. For urea, it is an organic material that dissolves easily in water, has odorless, no colour, does not cause toxicity, and plays a significant function in metabolsim compounds of nitrogen. As for calcium chloride, it has proven to be an effective source of calcium ions due to its strong ability to absorb moisture and its solubility in water.

Neupane et al., [50] investigated that the mixing procedure involves dissolving the entire quantity of urease in half of the total volume, in the remaining half, urea and calcium chloride are dissolved, these two portions combined to obtain the complete EICP solution. Fig.4 represents the precipitate formation by mixing the cementation solution and urease enzyme with water.

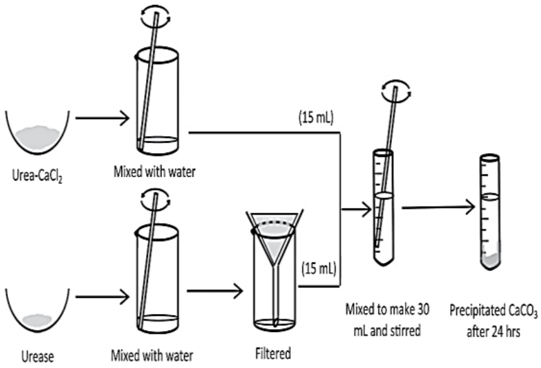



**Figure 4.** Illustration of precipitation test and mixing procedure [50].

One of the key factors influencing crystallization is the (urea-CaCl2) solution concentration. Also research on EICP emphasizes the necessity of determining the optimal urease concentration, as this optimization is crucial for achieving high hydrolyzing efficiency. Many researchers have focused on optimizing this process by increasing the precipitation ratio (PR %) calculated based on the EICP solution constituents. A summary shown in Fig.5 represent the alteration in concentration of enzyme vs. precipitation ratio (PR %) collected from several studies [40], [51].

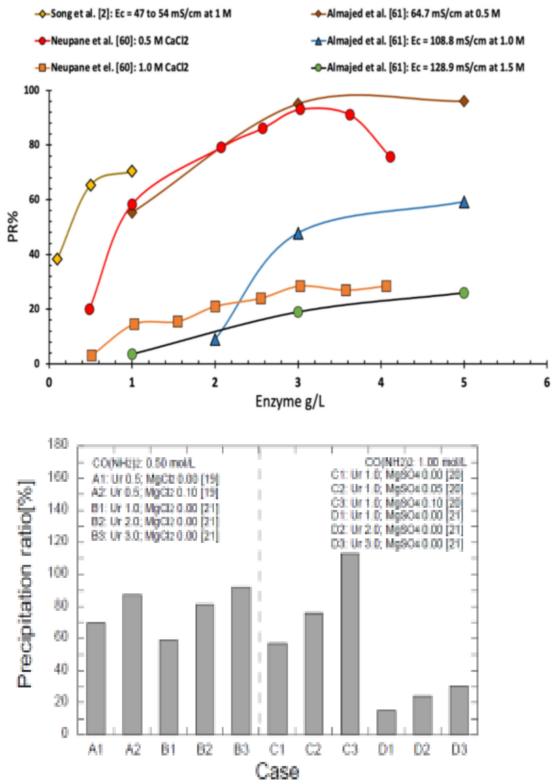



**Figure 5.** Summary of the results of precipitated tests in several studies [40], [51].

## 3. Soil Treatment via EICP and Application Methods

A number of studies which proved the effective implementation of EICP as a cementing binder are performed.

To introduce EICP enhancement solution in to the structure of soil, multiple ways have been suggested such as mix-compact method, injection method, surface percolation method, and spraying.

The soil to be treated by method (mix and compact) is mechanically mixed all together with the EICP cementing solution then compacted to the intended level of compaction. It is applicable in various fields, including pavement construction and targeted soil enhancement. Whereas the EICP spraying is commonly utilized when the treatment is focused on the surface strengthening, the cementing solution needs to stay on treated soil surface. So, this method is effective for enhancing water erosion resistance and controlling fugitive dust. The EICP cementing solution in surface percolation method is simply applied by pouring on the top surface of the soil.

Yasuhara et. al., [52] premixed Toyoura sand with powder of urease to obtain a uniform mixture prior to injection of EICP reagents into soil. The outcomes of UCS showed increase the strength, with range of (400kPa-1.6MPa). Using a similar method to [22] they also carried out to study the EICP treatment effect on the permeability of the specimen, and found out a compatible result. The study found that the permeability of treated specimen decreased in contrast to untreated sample. Their study also found that a single injection having dosage of injected solution (0.5-1mol/L) and urease content of 1-2g/300g of sand didn't have a notable change in permeability. The overall reduction observed in these tests is comparatively noteworthy, having a reduction of about one order of magnitude.

Knorr, [53] used the spray method on pans full of soil to control dust, two sprayers of enzyme and urea-calcium chloride solutions were used to spray 200ml of EICP cementing solution at a speed of 24.4m/sec without any separation in a wind tunnel test.

Hamdan, [13] tested four column Ottawa (20-30) silica sand specimens and observed that strength enhancement was proportional to carbonate concentration. When used the surface percolation method, the results of the treated soils for UCS test found with ranged from 38kPa to 220kPa, and when used the injection method the dry and saturated soil was injected, and the results of the treated soils for UCS test obtained spanning from 35kPa to 125kPa, also used the mix and compact method and obtained the results of compressive strength with range from 392kPa to 529kPa.

A significant increase in strength was observed for three sand columns specimen when a drained triaxial tests was performed by Hamdan [13], the cemented sand specimen before and after the triaxial test was shown in Fig.6.

**Figure 6.** Triaxial sand column standing without support with a weighted stainless steel top-cap (left), a large strongly cemented center and several broken pieces found after CD testing (right) [13].

Hamdan and Kavazanjian, [29] employed four distinct treatment procedures across 56 soil pans with one of the treatment involving EICP. Thy examined these pan to analyse its efficacy in reducing the fugitive dust. The study used a hand-held plastic bottle sprayer to sprayed EICP solution on the surface of soil. They compared between these soil pans by separated them where, the first 29 soil pans were treated with EICP solution of 175ml for which sprayed continuously as 125ml of urea-$CaCl_2$ solution followed by 25ml of urease enzyme solution whereas the remain soil pans treated with 200ml of pre-mixed EICP solution in four applications each one of 50ml, with one minute between each application.

Almajed, [54] assessed the UCS of soil samples under various conditions and carbonate levels, and the strength of soil EICP-treated by mix-compact showed a greatly reliant on soil size grains and its relative density. Also found that the injection approach for treatment was surpass the two other treatment methods (mix-compact and percolation) in terms of strength enhancement, proving that the injection method enhances the soil strength. Almajed et al., [55] study wind erosion resistance on multiple types of soils by spraying method and achieved a substantial improvement when sprayed both EICP cementing solution and sodium alginate bio-polymer comparison to soils sprayed with EICP cementing solution alone. At the surface percolation method [56] showed that the UCS resulted in 100kPa at 1.2% $CaCO_3$ and one treatment cycle, whereas four treatment cycles led to 465kPa at 4.6% $CaCO_3$. Also, the SEM images Fig.7 of the treated soils demonstrated accumulation of precipitates between the particles of soil along the flow path of the cementing solution during percolation, and this probably mean the surface percolation facilitated the crystals calcite increase between the particles and hence, providing binding much compared to the mix and compact method.

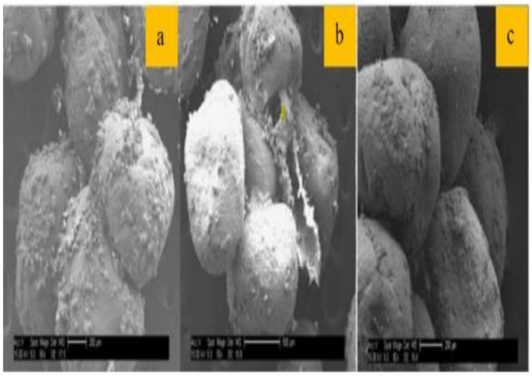



**Figure 7.** Distribution of precipitates calcium carbonate comparison according to implementation way (a) mix and compact-carbonate content 1.8%. (b)Percolation-carbonate content 1.79% and (c) injection- carbonate content 1.8%, [54].

Wu et al., [31] prepare EICP-treated solution by extracted urease from soya bean to spraying on coal dust generated from activities mining and the results success in suppressing it.

Lai et. al., [57] mixed urease solution with 2M cementation mix in 3:1 volume ratio to formulate the EICP solution, and used nine groups of sand columns which prepared in a Poly Vinyl Chloride tube (PVC), ethanol was also used from (0-60) % for the urease extraction. Hydrochloric acid (HCL) of 2M was added to modify the pH of the urease to (6.5).

Liu et. al., [47] tested two sets of treatment protocols to evaluate the stabilization of surface soil using jack bean and soya bean. In the first set, the urease solution was prepared with equal doses of crude ureases from jack bean and soya bean, while in the second set, crude urease with similar activity was used. The urease solution was then mixed with the stabilization mixture (urea and calcium chloride) in a 1:1 volume ratio to prepare the EICP treatment solution which was used by spraying onto the surface of sand soil specimen in a 1:3 volume ratio of sand volume. Their results presented in Fig.8, which shows the microstructure imaging of EICP-treated sand samples using SEM where various magnifications were utilized to detect the sediment bridging of precipitates between particles. In Fig.8-a, the large size of the crystals calcite is shown to be 12 micro-meters in the processed samples sand with jack-bean, while in Fig.8-b, samples processed with soy bean shows to be relatively smaller in size, ranging between 5-8 micro-meters.

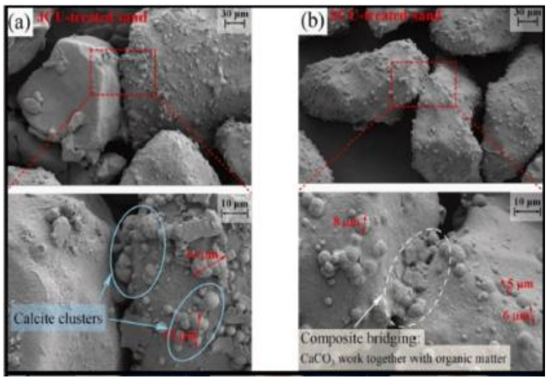



**Figure 8.** Microscopic crystals in treated sand by (a) jack bean (b) soya bean [47].

Furthermore, EICP is considered more suitable for field application due to the fact that the solution can be applied similarly to existing techniques and has a wider range of applicability in terms of soil particle size [19]. Fig.9 showed the pie chart classifying the number of research studies employing EICP in geo-technical engineering as well as construction and building materials classified by their applications [40].

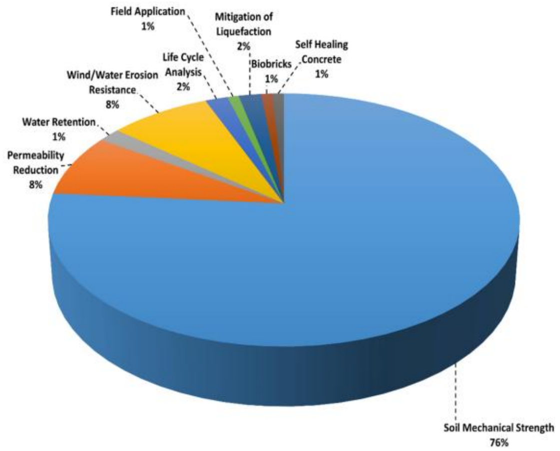



**Figure 9.** The research studies' no. using EICP in geotechnical engineering, construction, and building materials applications [40].

Table1 is presented overview of the studies in the literature that have used various sources of urease in enzymatic bio-mineralization in addition to the chemicals used in the process, as well as the additive used in some study to stabilize urease and improve the effectiveness of EICP soil treatment, also showing the effect of using this method on the properties of the soil including the unconfined compressive strength (UCS), permeability, others geo-mechanical and physical properties.

## 4. EICP Challenges for Soil Biocementation

### 4.1. Environmental Impact

The EICP process produces ammonium chloride (NH4Cl) as by-product, which may contamination the soil. Several promising methods have been introduced for ammonia removal. However, this issue is still under investigation and considers one of the major challenges that face the wide applications of these methods in the field.

### 4.2. Economic Impact

As previously mentioned in paragraph 2.1, there are two major sources of the urease enzyme. The commercially available, highly purified urease is found to be costly/uneconomical. It may be very costly if the application of EICP is performed on large scale. Hence, finding an alternative source to the urease enzyme is an essential task for reducing costs, and thus, promoting the simple and low-cost application of EICP for ground improvement. Several studies have shown that extracted urease from legumes/melon seeds such as jack bean, soybean, etc. that could be alternative method, that can be conducted in situ in a simplified process [14], [24], [31], [42], [43]-[44], [45], [46].

## 5. Conclusion

This review focused on the use of Enzyme Induced Carbonate Precipitation (EICP) technique/method in geotechnical engineering to enhance the engineering properties of soils that use urease enzymes extracted from different sources as an environmentally friendly option. The following conclusion could be obtained:

All studies presents in this review has examined the sustainability of the EICP method as ground improvement techniques. Some references proved that the EICP is the more one effective as it can be used in soils with pore size less than that of the bacteria, and efforts to enhance the EICP effectiveness as ground enhancing method have been validated.

Several studies was conducted the behavior of soil treated with EICP on a laboratory scale. Therefore, further studies that apply the EICP technique in real-world scenarios, up-scaling from the laboratory to field conditions should be prioritized to determine the best application methods and impact of complex environmental factors.

There are different methods of applying the treatment to improving weak/soft soil such as mixing, injection, spraying and percolation. Different molar concentrations of urea-calcium chloride for cementation solution preparation can be mixed with urease enzyme regardless the sources of urease. According to the indication of numerous researchers' studies, the permeability decreased on the EICP treated soils.

The UCS tests proved that application enhanced the strength soil particles. The triaxial tests on soil specimen revealed that EICP application enhanced the shear strength parameters. The micro-structural analysis comprising SEM, XRD, EDS, TOPAS, etc. demonstrated a large presence of calcite precipitate that bonded the soil particles together. The calcite distribution was found to be more uniform in EICP-treated soil, resulting in higher strength.

**Table 1.** Summary of the literature studies EICP technique.

| Ref. | Material Source and Dosage | Soil Type | Tests Performed | Application and Conclusion |
|---|---|---|---|---|
| Yasuhara et. al., 2012. [52] | Jack bean urease 0.5-1.5g/100mL, and (urea,CaCl2) 0.5-1.0 mol/L. | Sand | (UCS) Unconfined Compressive Strength permeability. | For improving soil compressive strength, and the results of UCS showed increased in the range of 400kPa-1.6Mpa, as well as a decrease in permeability coefficient from 10-1 to 10-3cm/sec. |
| Neupane et. al., 2013. [50] | Jack bean urease 2 and 15g/L, (urea,CaCl2) 0.5 and 1.0 mol/L | Sandy soil, silica sand soil. | UCS, permeability. | For improving soil compressive strength, and permeability reduction. The result of strength was 380kPa, and a decrease in porosity from 0.41 to 0.382. |
| Park et. al., 2014. [43] | Jack bean extract (0-5ml), Urea (5-25g /50ml), with (10/50g/ml) of three different salts. | River sand from Nakdon-g | UCS, SEM and XRD | For improving soil compressive strength, the results showed an increase ranging from (30-317)kPa. |
| Putra et. al., 2015. [51] | Jack bean (1g/L), (urea, CaCl2) of 0.5g/L for each. | Keisa sand | UCS, permeability. | For improving soil compressive strength, the results 60 kPa, at 3% carbonate precipitation was achieved, and a reduction in permeability coefficient less than 0.02 cm/sec. |
| Oliveira et. al., 2017. [58] | Jack bean of (4-8 kU/L) of activity 34,310U/g | Sand poor grade-d, organi-c, silty sands (two), and silt soils. | UCS, SEM. | For improving soil compressive strength and the gain strength for sandy, silty, and organic soils was: 25, 250, and 50kPa respectively. |
| Almajed et. al., 2017. [54] | Urease from jack bean of 3g/L, (urea, CaCl2) of (1M, 0.67M). Urease from jack bean of 0.85g/L, (urea of 0.875, 1.75 and 2.65M), and CaCl2 of 0.5, 1, and 1.5M), with 4g/L of dry non-fat milk. | Ottawa sand, and Ottawa silica sand | UCS, triaxial test. | For improving soil compressive strength and the results of UCS was 1461kPa when mixed a powder of xanthan gum with the soil. While effective stress cohesion and internal friction were achieved at cyclic triaxial test 332.96kPa, 34.58o respectively. |

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|---|---|---|---|---|
| Almajed et. al., 2018. [56] | Urease from jack bean of 3g/L, (urea, CaCl2) of (1M, 0.67M). | Ottawa sand | UCS | For improving soil compressive strength and the results of UCS was 1268kPa after four treatment cycles. |
| Geo et. al., 2019. [24] | Soybean of (40-130g/L), (urea, CaCl2) with 0.25 and 0.5mol/L for each | Sandy silty soil | Triaxial consolidation undrained tests. | Cyclic triaxial test was application at 15 treatments and higher peak axial stress of 250kPa was achieved, also an increase in the amount of precipitation without closing the pores means that this technique can be applied to fine grained soils. |
| Lee & Kim, 2020. [45] | (70-140g/L) solution of yellow soybean along with 0.75-3M (urea,CaCl2) | Clayey sand | (UCS)Unconfined Compressive Strength, SEM and EDS, Calcium carbonate precipitate. | For improving soil compressive strength, the results of UCS up to 870kPa and precipitate content up to 5.13%was achieved. |
| Almajed et. al., 2020a. [59] | Jack bean meal (1.5, 3,and 6g/L), (Urea:0.5,1,and 2M),(CaCl2:0.335,0.5, and1.34M), with 4g/L non-fat dry milk. | Ottawa sand, Saudi Arabia local sands. | UCS, SEM and EDX | To improve soil compressive strength where UCS values for sand treated by EICP achieved compressive strength more than 700kPa, which was higher than the sands treated by 10% OPC. |
| Cui et. al., 2020. [17] | Urease enzyme activity 40U/mL, (urea, CaCl2) of 1M. | Sand | Shear strength by PVC tube test molds, SEM. | To improve soil compressive strength, where EICP (one phase low ph) results was exhibit higher confined compressive strength of 3Mpa compared to (traditional two phase method) of 1Mpa at the same carbonate content. |
| Chaurasia et. al.,2020. [60] | 0.01, 0.02, and 0.03ml of Terrazyme. | India local soil, Black Cotton and Red soils | UCS, California bearing ratio (CBR) | To improve soil compressive strength where UCS and CBR results showed enhancement soils and improving properties with using terrazyme. |
| Zango et. al., 2021. [61] | Free urease enzyme from jack bean(3g/L), equimolar concentration of (urea,CaCl2) ranging (0.25-1.25M) | Natural residual soil | UCS, Tube tests, FESEM and EDX. | The results showed that the maximum shear strength of 728 kPa was achieved at 1M of (urea, CaCl2) and calcium carbonate content was yield to 4.33%. The highest precipitated mass of CaCo3 of 1.577g, 1.603g, and 1.603g was also obtained at 1M (urea,CaCl2) at 3, 7, and 14 days respectively. |
| Pratama et. al., 2021. [62] | Jack bean(20g/L), with0.5mol/L concentration of (urea,CaCl2). | Sand | UCS, SEM and XRD | To improve soil compressive strength where UCS values after three cycles of injection reached 600kPa, due to the precipitation of calcite crystals showed by SEM and XRD. |
| Baziar et. al., 2021. [32] | Jack bean soya bean enzyme for extraction two solution, (10-35)mL and (35-100)mL | Silty sand soil | UCS, SEM and XRD, and water, wind erosion tests. | To improve soil compressive strength where UCS results of both jack bean and soybean enzymes were exhibit higher compressive strength ranged from 1000kPa to 3500kPa depending on the density and treatment method. The results of erosion tests also showed resistance of treated soil to both water and wind erosion due to bonding between soil particles |

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| | | | | formed by precipitation of calcite, which appeared in SEM. |
| Putra et.al., 2021. [63] | Soya bean urease enzyme, of (5-50) g/L,(urea,CaCl2) of (0.5-1.5)M. | Organic Soil | UCS, Direct shear test, SEM and EDS. | To improve soil compressive strength where UCS results of treated organic soil was 148kPa, and cohesion of 50kPa. |
| Alotaibi et. al., 2022. [64] | Urease from jack bean of 0.091%, and (urea, CaCl2) of (1.82, 2.23) % by weight of dry sand soil. | Sand | Life Cycle Assessment LCA, UCS. | The LCA results proved that the use of EICP in soil treatment is less harmful and environmentally friendly compared to PC. Also the results suggested that, at lower UCS values, the EICP treated soils achieved less carbon footprint compared to PC treated soils. |
| Liu et. al., 2023c. [65] | Soya bean crude urease of 60g/L, with1.4mol/L (urea,CaCl2). | Sand | UCS, CaCo3 content. | The study proved that reusability of crude soybean urease by the multiple percolation of cementation solution at low concentrations led to an uniformly increasing CaCo3 content and improved UCS. |
| Almajed et. al., 2024. [21] | Jack bean (JICP), Soya bean (SICP) urease enzyme, of 3g/L,(urea,CaCl2) of (1M, 0.67M). | India local soil, Black Cotton soil as(CH) and Red soil as(CL). | UCS, Oedometer test, L.L & P.L. | To assess EICP-enhancer impact on strength and swell characteristics. The study revealed that the EICP notably increased the UCS values of soils used in the study at 21 days, reaching 450 kPa for red soil and the UCS of black cotton soil increased 11 times, also EICP proved effective in reducing swelling pressure by 60% for red soil and 67.5% for black cotton soil. |
| Zhanguo, Tong et. al., 2024. [66] | Soybean with vol. ratio 1:1 urease solution to (urea,CaCl2) of (0.5, 1, 1.5 and 2mol/L), Polypropylene fiber. | Loess from depth (2-3)m of building foundation excavation. | UCS, Direct shear test, Disintegration test and SEM. | The results indicating that the best reinforcing strength was achieved at fiber length15mm, and 0.6% content. The UCS and shear strength of fiber-reinforced loess reached its peak at 1.5mol/L EICP solution concentration. The findings showed improving in disintegration resistance of loess, and significantly decreased the porosity of the sample strengthened by EICP-FR. |

## 6. References:


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