KSCE Journal of Civil Engineering (2023) 27(4):1512-1525
DOI 10.1007/s12205-023-0817-2

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Direct Shear Characteristics of Enzymatically Cemented Sands

Mohammed Alwalan[a], **Abdullah Almajed**[a], **Kehinde Lemboye**[a], **and Ahmed Alnuaim**[a]

[a]*Dept. of Civil Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia*

ARTICLE HISTORY

Received 26 May 2022
Revised 27 September 2022
Accepted 27 January 2023
Published Online 1 March 2023

KEYWORDS

EICP
Shear strength
Sand
Application method
Interface
Direct shear test

ABSTRACT

A laboratory study was conducted to investigate the shear strength of bio cemented sands using enzyme-induced carbonate precipitation (EICP) via the direct shear test. Several specimens were prepared using four different application methods of EICP solution, namely spraying, mix-&-compact, percolation, and injection. Potential use of EICP for improving the sand-concrete interaction strength was also studied. Results indicated that the adopted application method of introducing the EICP solution to the soil affects the distribution pattern of $CaCO_3$ precipitation in the soil matrix, thereby shear strength. Each method yielded a different response when sheared compared to untreated sand. The injection method was found to achieve higher shear strength and interparticle cementation under controlled rate and distribution followed by percolation. The spraying and mix-&-compact methods produced specimens with weaker particles' bond and lower shear strength measurement but still showed relatively better performance than the untreated sands. Better cementation of soil grains was achieved in medium sand and when fine and organic materials were removed. Sands response to EICP-treatment was inferred to vary depending on the geotechnical characteristic of the soils. Moreover, the interfacial strength between sand and concrete was found to be enhanced after applying the EICP treatment as it coarsened soil particles.

1. Introduction

Problematic soil is typically stabilized to improve its engineering properties and performance to a desirable level, in order to meet the construction requirements. In general, soil stabilization may be accomplished using mechanical or chemical processes (Das, 2003). The former process densifies and compacts the soil medium by reducing the volume of voids, whereas the latter entails the application of additive materials to the soil (Makusa, 2012; Afrin, 2017). Over the years, soils with weak engineering properties have been chemically improved using mixing with Ordinary Portland Cement, OPC (e.g., Juran and Riccobono, 1991; Schnaid et al., 2001; Roy, 2017). Nonetheless, the environmental impact associated with OPC in the short- and long-term, put its use under question despite its mass availability and acceptance in practice (Disu and Kolay, 2021). This can be mainly attributed to its energy-intensive nature and significant carbon dioxide emissions (Zhang et al., 2013). Nonetheless, the consumption of cement is still increasing due to the high demand for new buildings and infrastructures as well as due to its frequent application for soil improvement, leading to the potential release of more carbon dioxide emissions (Almajed et al., 2021a).

As an alternative to OPC, bio cementation via enzyme-induced carbonate precipitation (EICP) offers a promising bio-technique for strengthening ground materials since it addresses numerous sustainability concerns (Hamdan, 2015). This technique utilizes free urease enzyme to form calcite ($CaCO_3$) by urea hydrolysis that binds soil particles together, increasing soil strength and stiffness (Hamdan and Kavazanjian, 2016). Generally, EICP is suitable for the stabilization of coarse-grained soils and the limitation of EICP occurs when a significant amount of fines are present in the soil due to the increase in surface area (Cao, 2018). The advantages and disadvantages of EICP treatment are available elsewhere (i.e., Almajed, 2017; Almajed et al., 2018; Arab et al., 2021a). Furthermore, a critical appraisal of the use of ECIP for geotechnical and geoenvironmental applications has been presented and discussed in research conducted by Almajed et al. (2021b).

The preparation of the EICP solution involves mixing urease enzyme obtained from agricultural sources with an aqueous

CORRESPONDENCE Ahmed Alnuaim ✉ alnuaim@ksu.edu.sa Dept. of Civil Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

solution consisting of urea and calcium chloride to initiate urea hydrolysis. A mixture of these ingredients is called the EICP baseline solution (Kavazanjian et al., 2017; Martin et al., 2021a; Almajed et al., 2021b). Also, additives such as non-fat milk powder, glutinous rice powder, or brown sugar (i.e., organic material) were incorporated to enhance the strengthening efficiency of EICP treatment (Almajed et al., 2019; Ossai et al., 2020; Yuan et al., 2020; Almajed et al., 2020a; Arab et al., 2021b; Martin et al., 2021b). These studies concluded that the inclusion of organic material, especially skim milk powder, promotes the formation and aggregation of concentrated clusters of calcium carbonate between the soil particles due to the presence of nucleation sites. This phenomenon caused the nearby clusters to merge, thereby, increasing the cementation effect of EICP treatment relative to the EICP baseline solution. Martin et al. (2021a) applied EICP solution modified by adding powdered milk to multiple granular material types. Their results indicated that the modified solution generates a stronger bond between soil particles as it increases the surface adhesion strength of the precipitated carbonate in comparison to those precipitated using the baseline solution. This observation could reduce the cost, quantity, and number of treatment cycles of the EICP technique in achieving the targeted strengths. In addition, Arab et al. (2021c) examined the durability of enzymatically-modified sand specimens and the results showed higher resistance against various environmental conditions, including temperature, wet-dry cycles, seawater, and sulfate contamination. Moreover, earlier investigations have also shown an improvement in the axial capacity of loose sands when treated with biogeochemical processes (Dejong et al., 2006). The challenges for the implementation of these processes on a field scale are addressed in (Dejong et al., 2013).

The mechanical response of bio cemented soils varies depending on the precipitation pattern of $CaCO_3$ in the treated soil mass (Ismail et al., 2002). Scanning electron microscopy (SEM) showed that the EICP treatment may induce calcite precipitation at the particle-to-particle contact points (i.e., cementation effect), onto the surfaces of grains (i.e., coating effect), or/and in the void spaces (i.e., filling effect) (Kavazanjian et al., 2017). Yasuhara et al. (2011) reported the filling effect, while the cementation effect was reported by Hamdan et al. (2013). Moreover, Almajed (2017) reported a coating effect. Nevertheless, a companion or combination of three effects within the same soil mass has yet not been observed (Lin et al., 2016). Furthermore, recently published studies have indicated that the prevalence of a specific pattern is dependent on several factors including the EICP recipe, soil types, surface microtexture and chemical characteristics of the soil, and distribution of calcite (Krishnan et al., 2021; Muhammed et al., 2021; Zehner et al., 2021; Ahenkorah et al., 2021a). However, Arab et al. (2021a) emphasized that a better bond between soil particles can be achieved in different granular soils provided that a proper application method of EICP-based solution is selected.

The method used to introduce the EICP solution to the soil (i.e., application methods) plays a crucial role in achieving the desired soil strength. It has been studied that improper introduction could result in the formation of non-uniform $CaCO_3$ precipitation and strength in treated soil (Mujah et al., 2017). Four application methods have been widely used in the literature, namely, injection, surface percolation, mix-&-compact, and spraying. Several studies, including Yasuhara et al. (2011, 2012), Neupane et al. (2013, 2015a), Kavazanjian et al. (2017), Kavazanjian and Hamdan (2015), and He et al. (2021) have promoted the use of the injection method of cementation solution as it yielded satisfactory outcomes contrary to other methods as long as the rate of calcium carbonate precipitation was well controlled. Otherwise, strongly localized cementation would form around the injection point leading to non-uniformity in both strength and calcite precipitation. Their microscopic analysis showed the precipitation of $CaCO_3$ on and between soil particles. Hamdan (2015), Almajed (2017), Almajed et al. (2018, 2020a), and Chandra and Ravi (2021) adopted the mix-&-compact method. They indicated that the pre-mixing method demonstrates a high rate of precipitating calcite more uniformly but can cause significant disturbance to the local soil. Their SEM images showed higher adherence of calcite crystals to the surface of soil particles than bridging particles together; however, the efficiency of particle cementation is highly dependent on the soil's relative density (Almajed, 2017). Mujah et al. (2017), Ossai et al. (2020), Krishnan et al. (2021), and Martin et al. (2021a) advocated for the surface percolation method. A reasonable homogeneous distribution of $CaCO_3$ and strength was achieved; however, cementation depth within the soil was found to be limited. Their imagery showed both the precipitation of $CaCO_3$ in the form of a scattered coating on the soil particle surface and the formations of compound clusters of $CaCO_3$ that connect soil particles as they grow, thus increasing the strength and cementation capability of the EICP technique. Nevertheless, heterogeneity in cementation patterns has been reported in large prepared samples due to the fast reaction/precipitation time in the EICP process (Ahenkorah et al., 2021b). Song et al. (2020) and Liu et al. (2021a) utilized the spraying technique to apply the EICP treatment. The researchers concluded that spraying of the EICP solution showed a significant improvement in the strength of near-surface soils. Their micro-level analysis displayed the formation of a thin layer of $CaCO_3$ coating on the soil particles.

The review of prior studies indicates a dispute on the most efficient application method and the resultant improvement levels in terms of strength and cementation capabilities. Such discrepancies could be attributed to the change in the ingredient concentration of EICP solution, the source of the extracted urease enzyme, or the different salt types. Comparisons of multiple methods are rarely conducted in similar settings, which puts forth the need for more investigation under similar testing settings considering only one optimized recipe of the EICP solution, based on efficiency and maximum amount of precipitated $CaCO_3$, before advocating for a specific method for the potential uses in-field application. As such should be performed to examine the effectiveness of enzymatic induce $CaCO_3$ precipitation for industrial/field applications (Ran and Kawasaki, 2016).

Moreover, the majority of the published papers evaluated the strength characteristics of EICP-treated soils using the unconfined compressive strength (UCS) test due to its simplicity (Yasuhara et al., 2011; Yasuhara et al., 2012; Park et al., 2014; Hamdan, 2015; Kavazanjian and Hamdan, 2015; Putra et al., 2017; Almajed et al., 2018; Almajed et al., 2019; Rohy et al., 2019; Yuan et al., 2020; Chandra and Ravi, 2021; Muhammed et al., 2021; Krishnan et al., 2021; Yuan et al., 2021; Ahenkorah et al., 2021a; Arab et al., 2021c). However, only sporadic studies investigated the shearing parameters of EICP-based soil improvement, including friction angles and cohesion, despite the increasing interest in EICP (Hamdan et al., 2013; He et al., 2021). Apart from these two studies, the existing research body indicates an evident lack of investigations into shearing strength measurement and behavior of EICP-treated sand under various methods of solution application. Such investigation is necessary to assess the potential use of EICP to treat weak bearing stratum and quantify the available resistance offered against applied loads.

Accordingly, this study explores the shear behavior of EICP-treated sands via the direct shear test. The paper describes the injection, surface percolation, mix-&-compact, and spraying methods that were employed to prepare specimens utilizing the modified EICP solution at similar testing conditions. Determination of shear strength behavior, friction angle, and cohesion are then reported and discussed in the paper. Furthermore, interfacial strength and mechanical properties between EICP-treated sand and concrete are also investigated and discussed.

2. Materials

For the EICP solution, the modified version was considered herein. Cementation reagents, type of enzyme, and mixing procedure employed during the study were based on those described in Almajed et al. (2019). Furthermore, this study used two types of sand: clean silica and naturally occurring sands. The clean silica sand was purchased from a local manufacturer (i.e., Alrasheed Silica Plant). This type of sand was selected due to its local availability in abundance quantity. The particle size distribution curve is depicted in Fig. 1. As evident, most of the soil particles were medium-sized, ranging from 2 to 0.425 mm. The Unified Soil Classification System (USCS) designates the sand as poorly graded. The average specific gravity of the soil was 2.66, with a maximum and minimum dry density of 1.66 and 1.45 g/cm^3, respectively. The other sand type was natural red sand acquired from An Nafud desert, Saudi Arabia. The USCS classified the red sand as poorly graded fine sand. The particle size ranges between 0.425 to 0.0175 mm, as illustrated in Fig. 1. The natural red sand presented a specific gravity of about 2.65, with a maximum and minimum dry density of 1.83 and 1.60 g/cm^3, respectively. The images of particle shape and surface texture at different magnification levels are available in a study conducted by Almajed et al. (2020a).

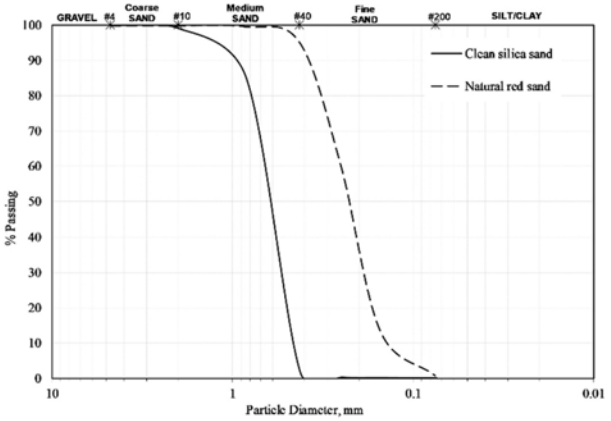


Fig. 1. Particle-Size Distribution Curves for Clean Silica and Natural Red Sands

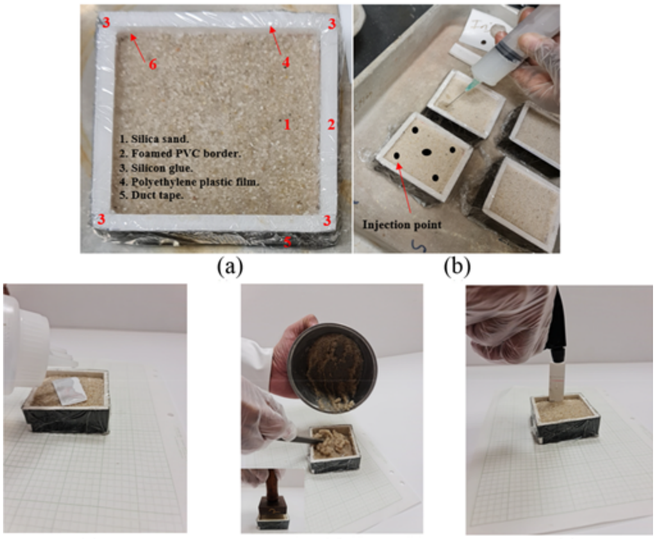
3. Experimental Procedure

3.1 Direct Shear Test

The shear strength behavior and properties of the EICP-treated sand specimens were investigated employing a strain-controlled direct shear test manufactured by VJ Tech Ltd. (model VJT2760), following ASTM-D3080 (ASTM, 2012). The apparatus has a maximum horizontal load capacity and a travel distance of 5 kN and 20 mm, respectively. The inner dimensions of the specimen inside the direct shear box were 63 × 63 × 21 mm^3. The tested specimens were sandwiched between two perforated plates followed by porous plates inside the box. Shearing loads were recorded by a load cell (ring), whereas a linear displacement transducer recorded the corresponding horizontal displacements. These measurements were logged continuously using a data acquisition system. During the shearing process, specimens were sheared up to a strain of 12% or failure at a shear strain rate of 0.6 mm/min (Das, 2001; Li et al., 2013), whichever occurred earlier. To define the shear strength envelope, three vertical pressure confinements were considered (i.e., 50, 100, and 200 kPa).

3.2 Sample Preparation

Several molds were fabricated to prepare specimens before conducting the direct shear test using foamed PVC borders. First, the molds were cut as per the direct shear required testing specimen size (i.e., 63 × 63 × 21 mm^3). Silicon glue was applied to form the molds, after which duct tape was used to strengthen the sides and the bottom of each mold, as shown in Fig. 2(a). Furthermore, polyethylene plastic film was placed in each mold to facilitate subsequent extraction and prevent the solution from leakage. Consequently, the clean silica sand was air pluviated into the molds by pouring through a funnel. The rate and height of falling were adjusted until a relative density of 40% was achieved, within a depth of 21 mm. The EICP solution was then applied per one pore volume (i.e., 26 ml), following different application methods as discussed below. After the treatment



(a) (b)

(c) (d) (e)

Fig. 2. Specimens Setup and Preparation via Different EICP Application Methods: (a) Mold's Components, (b) Injection Method, (c) Percolation Method, (d) Mix-&-Compact Method, (e) Spray Method

application, specimens were left for about seven days at room temperature for curing and dryness. A total of 24 direct shear samples were prepared using silica sand. Half of these were tested, while the other half were used to evaluate the reproducibility of the experiments and the integrity of each application method. For the natural red sand, none of the samples remained intact after extraction as they crumbled to pieces (i.e., did not form in one piece); thereby, testing could not be done. Further details are presented later in the text.

3.3 Application of EICP-Treatment Solution

3.3.1 Injection Method

A 20-gauge needle was used to inject the EICP solution within six pre-prepared sand specimens. Five injection points were selected of which four were near the mold's corners and one at the middle, as illustrated in Fig. 2(b). Each point was infused with an equal volume of the cementation solution (i.e., 6 ml). A slow rate of injection was maintained to prevent the formation of holes at the location of injection points. Notably, distribution of the injecting process was ensured with the purpose to avoid the formation of a strongly localized cementation that would form at the injection point.

3.3.2 Percolation Method

The soil was placed first in dry condition into the mold. Then, a one-pore volume of EICP solution was poured at the top of each specimen. The pouring was performed at a slow pace to eliminate spilling due to the accumulation of EICP solution above the surface. A total of six specimens were made to archive the objective of this study.

3.3.3 Mix-&-Compact Method

In the mix-&-compact, the sand weight required to be placed in the mold to achieve a relative density of 40% was placed in a bowl and quickly mixed with the EICP solution until a lump-free homogeneous paste was attained. Thereafter, the resultant mixture was immediately placed in six molds and lightly compacted to the desired height of 21 mm.

3.3.4 Spray Method

In this method, the EICP was applied by directly spraying the top of the sample's surface via a plastic spray bottle. The spraying was applied from a height of about 3 cm above the surface at a rate of 1 ml per stroke. The height was determined based on a trial-and-error method such that one stroke of spraying uniformly covered the sand surface. Accumulation of the EICP solution on the top of the samples was not allowed during application. In other meaning, there was a pause between strokes to allow the solution that wetted the surface to infiltrate the soil before the next stroke was applied. Again, a total of six specimens were made.

4. Results and Discussion

4.1 Apparent Characteristics

Figure 3(a) shows the number of specimens that remained intact upon extraction compared to damaged ones for each application method. As illustrated, four of the six specimens prepared via spraying were damaged. On average, the damaged specimens lost about 16% of their structure, especially at the bottom edges since these areas were not directly exposed to spraying, as shown in Fig. 3(b). During handling, extra care was taken for the remaining specimens as they were weakly cemented. The damaged spray specimens were easily disintegrated into large pieces by hand, as presented in Fig. 3(c). The results indicated the low efficiency of the spraying technique as it generated a weak EICP cementation in the soil matrix. This is in conformance with a study conducted by Song et al. (2020), in which spraying the EICP on the soil surface creates a weak bond between soil particles due to the scattered pattern of the $CaCO_3$ precipitation. However, the surface of the damaged specimens was relatively tough when pressed, which may be of interest in suppressing fugitive dust (Almajed et al., 2020b; Lemboye et al., 2021a). For the mix-&-compact technique, three of the six specimens were impaired. This is expected to occur as the cementation efficiency of EICP via the mix-&-compact treatment method is relatively low at lower initial relative density levels (Almajed, 2017). Nonetheless, a noticeable improvement in specimens' strength was observed compared to solution spraying, yet the specimens fell apart into intact chunks when thumb pressed as illustrated in Fig. 3(d).

Moreover, specimens extruded from molds treated with percolation preserved their structure except for one where damage was observed at the corner, as depicted in Fig. 3(b). Stronger and better-defined cementation was achieved. Evidence of a white precipitate (i.e., $CaCO_3$) was distinctly visible all

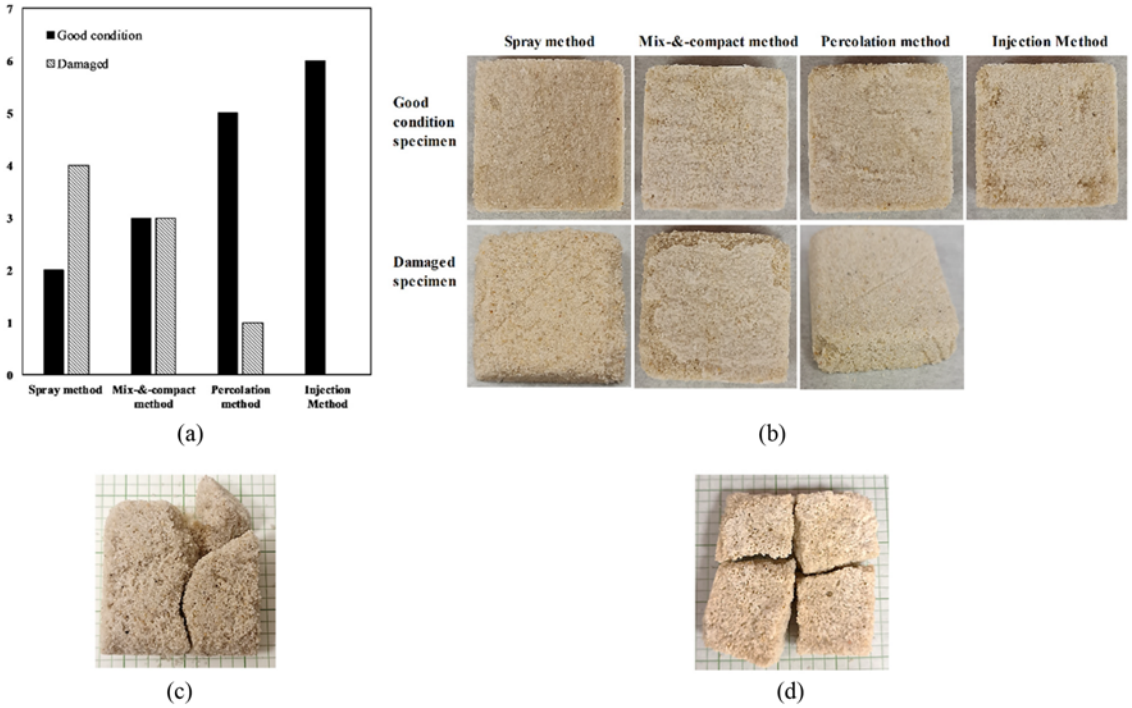


Fig. 3. Apparent Characteristics Post Treatment: (a) Specimen Condition after Extraction from Molds, (b) Representative Specimens of Good and Damaged Specimens after Extraction for Different Application Methods; and the Shape of Thump Pressed Specimens Treated by Spraying, (c) and Mix-&-Compact (d)

around the specimens, contrary to spraying where the color change was scarcely noticeable and different from the mix-&-compact where the largest amount of white precipitation occurred at the surface. Specimens from the percolation of the solution were found to be hardened and were almost impossible to split by hand. Sandpaper was used to level and shape the top and bottom of the specimens for direct shear testing due to irregularity and accumulation of white precipitation. Additionally, the specimens treated via injection were similar to those of percolation in terms of color but stiffer (i.e., splitting was not possible by hand). All six specimens made by injection maintained their shape upon removal from the mold. No damage was observed, indicating a better particle binding than any other method. Disturbance due to handling and installation in the direct shear box was not of concern. Therefore, it can be concluded that the injection technique increases the probability of particle binding occurrence within the soil matrix (i.e., could lead to a better particle-to-particle contact mechanism) under a controlled rate and distribution of injection. This agrees with the findings of the studies conducted by Yasuhara et al. (2011), Neupane et al. (2015b), Almajed (2017), Kavazanjian et al. (2017), and He et al. (2021). It should be highlighted that evidence of mineral precipitation is visually apparent with a different degree in all specimens as they turned white. However, the agglomeration of white precipitate varied depending on the application method being more visible in samples treated via injection followed by percolation.

4.2 Shear Strength Behavior

The direct shear test results on EICP-treated silica sand specimens prepared under various application methods are presented in Fig. 4, which compares the shear stress-strain curve behavior obtained for each method with the untreated sand specimens at vertical stresses of 50, 100, and 200 kPa. The figure clearly illustrates the influence of application methods in the response of silica sand during shearing under an equal concentration of treatment solution. As evident, there is a drastic improvement in the shearing behavior for the EICP-injected specimens followed by that of percolation. The increase in peak shear strengths was about 2.3 and 1.5 times (on average) that of untreated sand for injection and percolation methods, respectively. Such differential improvement is indicative of the development of an effective load-transfer mechanism at the particle-particle contacts. In contrast, the mix-&-compact and spraying methods showed slightly better behavior than the untreated sand at lower vertical stresses. As the vertical stress increases, the shear behavior of specimens treated via mix-&-compact and direct spraying are approximately similar. This could be attributed to the crashing of specimens caused by the applied vertical stresses before shearing, as they were weakly bonded as physically observed during setup. It seems that EICP treatment may have introduced more precipitation in the form of coating the surface of the grains or as independent crystalline solids in the voids rather than adequately cementing the sand particles together. Almajed et al. (2019) reported a similar observation and stated that such a participation pattern would occur in the mix-&-compact samples due to the continuous

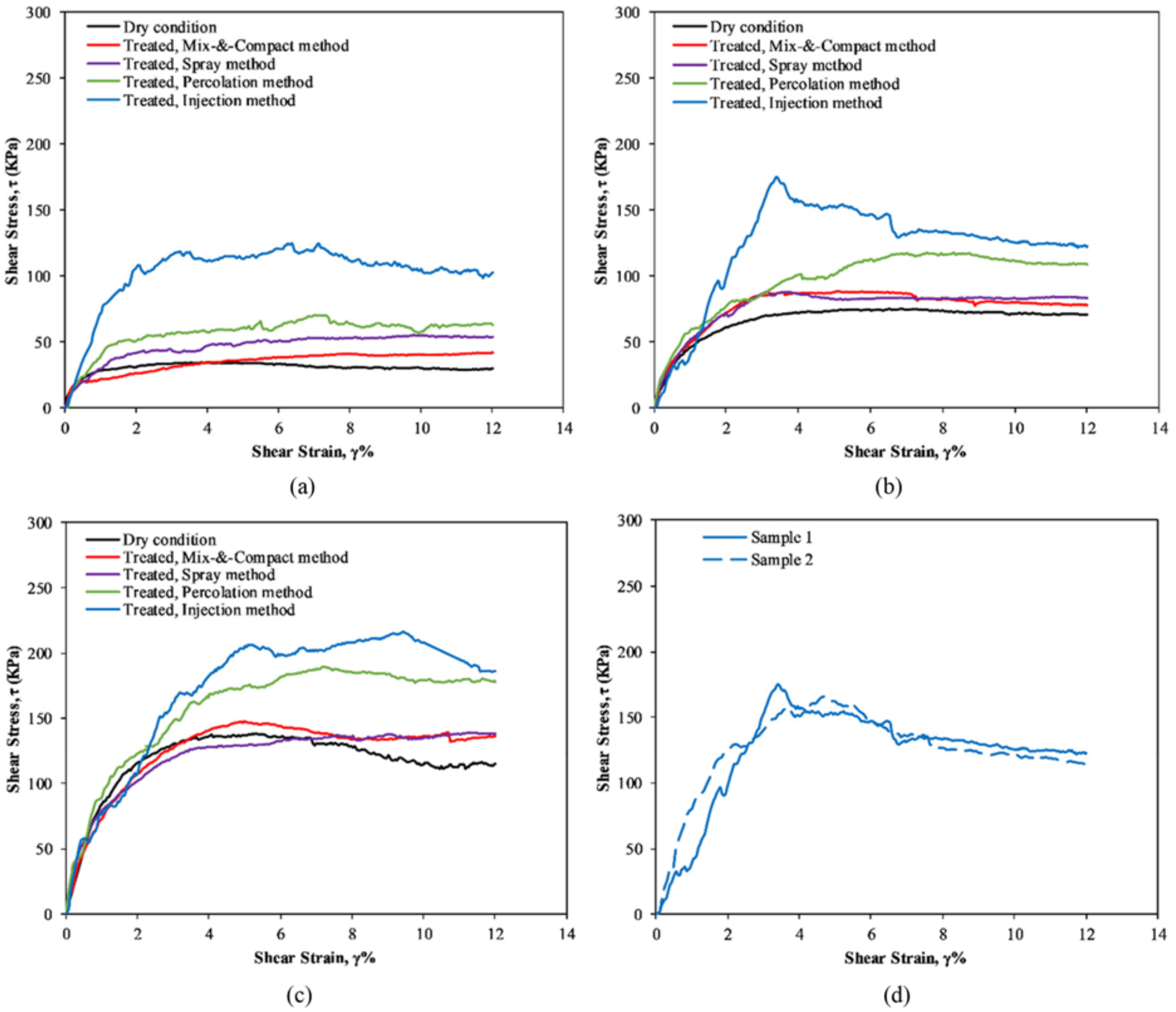


Fig. 4. Shear Stress-Strain Curves of EICP-Treated Silica Sand Specimen Using Various Application Methods at a Normal Stress of: (a) 50 kPa, (b) 100 kPa, (c) 200 kPa, (d) Compares Stress-Strain Curves of Two Samples Treated Via Injection of EICP Solution under Same Conditions

disturbance during preparation. Also, Song et al. (2020) observed the potential increase of a scattered pattern of $CaCO_3$ precipitation within the sand matrix once the solution is sprayed, especially at the surface of the particles rather than cementing the particles together. The mix-&-compact and spraying methods yielded peak shear strength values slightly higher than untreated sand, with an improved ratio of about 1.12.

In addition, the smoothness of the shear stress-strain curves in Fig. 4 represents the roughness of the sample's shearing surface. For specimens treated via spraying and mix-&-compact, the shearing plane or sliding surface was found to be smooth as their shear stress-strain curve exhibited minimal skewed behavior when the shearing strain progressed, like the observed response of untreated silica sands. Those specimens entirely disintegrated into fragments after sharing, as shown in Fig. 5. Hence, the shearing pattern of spraying and mix-&-compact EICP-treated sands is closely akin to untreated conditions. On the other hand, percolation and injection treatment methods showed skewed behavior during shearing, as illustrated in Fig. 4. Continued breakage and disintegration within the specimens occurred, thus producing a tortuous response path, particularly if treatment was applied via injection despite the significant improvement compared to any method. Such a scenario makes behavior predictions of the EICP-treated soils more difficult to explain. Upon examining the percolation specimens after completion of the test, intact chunks were observed, as shown in Fig. 5. For injection, it seems that specimen (specimen 1) remained mostly intact, and only a small portion of the edges was sheared with the increase in the horizontal displacement.

Moreover, Fig. 4(d) presents the results of two different specimens (1 and 2) treated via injection at a vertical stress of 100 kPa. Deviation in response to shearing loads is distinctly apparent, with a difference of about 20%, even under constant treatment and testing methodology. The main variation occurred before the peak stress was reached. This may be attributed to the random patterns of calcite precipitation or to the random flow of the EICP solution, which adds to the complexity of predictions of the global shear behavior. When injection specimens were

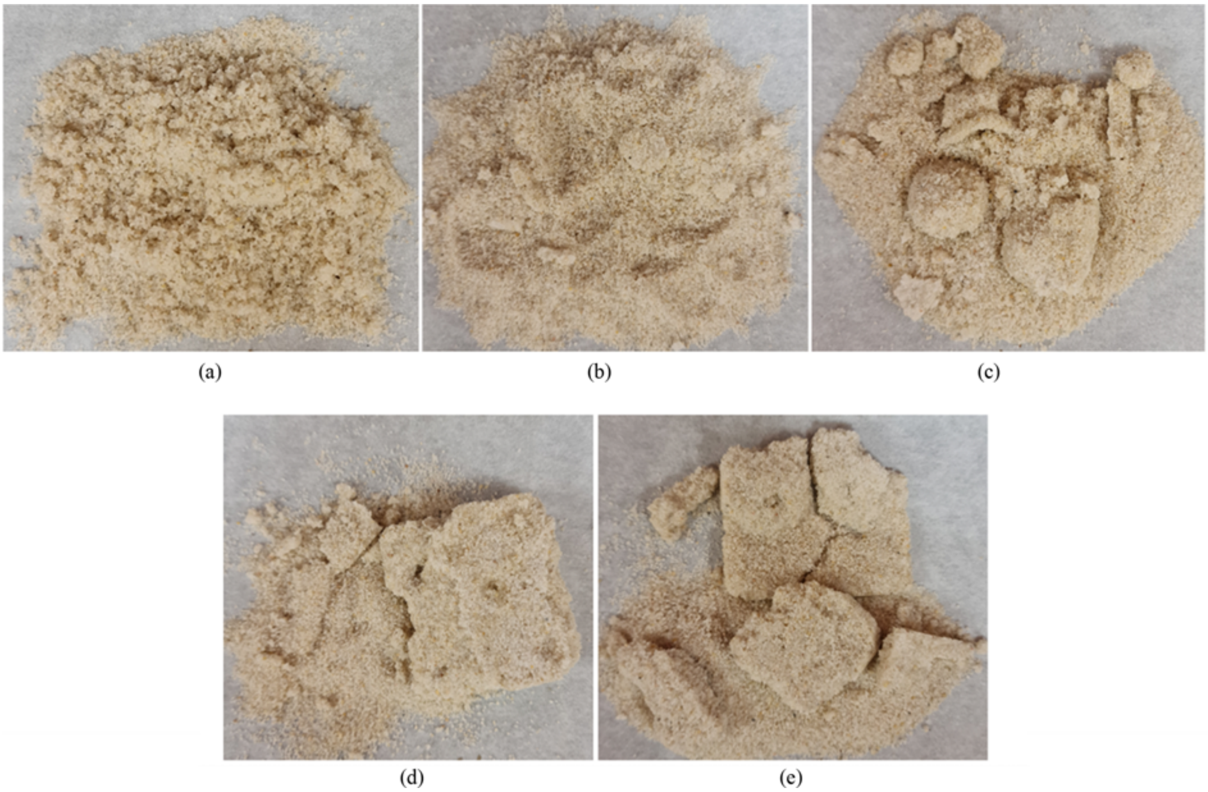


Fig. 5. A Representative Example of Specimen's Shape after Shearing for Each Method of EICP Solution Application: (a) Spray Method, (b) Mix-&-Compact Method, (c) Percolation Method, (d) Injection Method, Specimen 1, (e) Injection Method, Specimen 2

compared, the results did not show any specific pattern of disintegration or destruction behavior, as can be seen in Fig. 5.

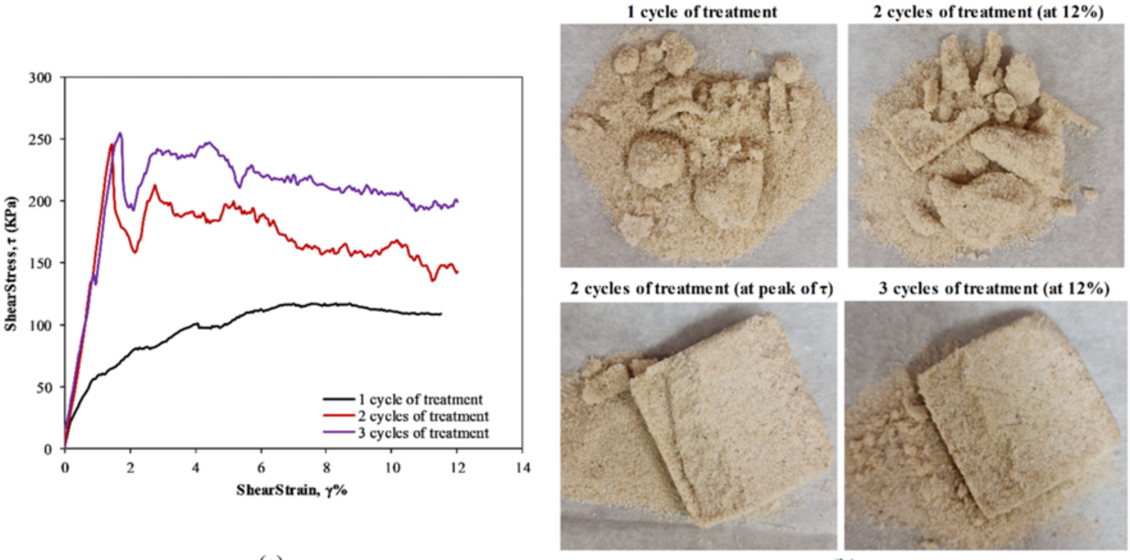
Figure 4 also shows that the residual shear strength was generally enhanced compared to untreated soil, being more pronounced in the injection and percolation of EICP solution. Moreover, it was observed that the shear strength of specimens treated via spraying and mix-&-compact remained constant at a value higher than untreated specimens despite their weak interparticle bound (i.e., cementation effect). This indicates that the presence of independent $CaCO_3$ particles or the co-existing of cementation and coating mechanisms within the soil matrix contributed to the increase in shear strength but at a lower degree than cemented soil mass. Such observation conforms with He et al. (2021), in which EICP treatment may improve soils even if the soil was partially cemented. For percolation and injection methods, a smooth sliding (i.e., no volume change) along the shear plane did not occur; hence, the residual strength is not reached as shear stresses experienced irregular patterns within the maximum shear strain. This probably indicates that the treated sand samples are being separated into fragments and chunks as creaking noise was observed. This was noticed upon examining the samples after shearing as evident in Fig. 5.

Table 1. Shear Strength Parameters of EICP-Treated Sand Via Different Application Methods

Sample type	φ (°)	c (kPa)
Untreated	30	0
Treated, Spray method	32	9
Treated, Mix-&-compact method	32	14
Treated, Injection method	34	70
Treated, Percolation method	36	35

4.3 Shear Strength Parameters (c, φ)

Coulomb failure criterion was used to interpret shear strength parameters based on residual stresses. The friction angle, φ, and cohesion, c, values from each application method are tabulated in Table 1. An increase in specimen shear strength parameters can be observed regardless of the application methods. The mix-&-compact and spraying methods yielded comparable results in terms of φ and c, where a slight improvement was observed compared to the clean silica sand. Additionally, φ for EICP-treated sand via percolation indicated a 20% increase compared to the untreated sand but yielded lower c compared to treatment done via injection. The cohesion strength value reported herein is close to that reported by Hamdan et al. (2013) for EICP-treated Ottawa 20/30 silica sand. Meanwhile, the φ of specimens treated via injection exhibited an increase of about 14% with a significant cohesion strength compared to treatment done via percolation, suggesting the generation of a stronger bond between sand particles (i.e., induced precipitations mainly at the inter-particle



(a)

(b)

Fig. 6. Results of the Direct Shear Test: (a) Shear Stress Versus Shear Strain of Silica Sand Samples Treated with Different Cycles of EICP, (b) Samples Shape after the Completion of the Direct Shear Test

level). Microscopic analysis of He et al. (2021) showed that injecting EICP solution is more likely to generate $CaCO_3$ at the particle-particle contact regions. Their triaxial test results showed around a 20% increase in φ; however, c was marginally increased from 0 to 3.5 kPa, which is much lower than the value reported herein. This may be attributed to the dissimilarity in particle size and soil source (Krishnan et al., 2021).

4.4 Multiple Cycles of Treatment

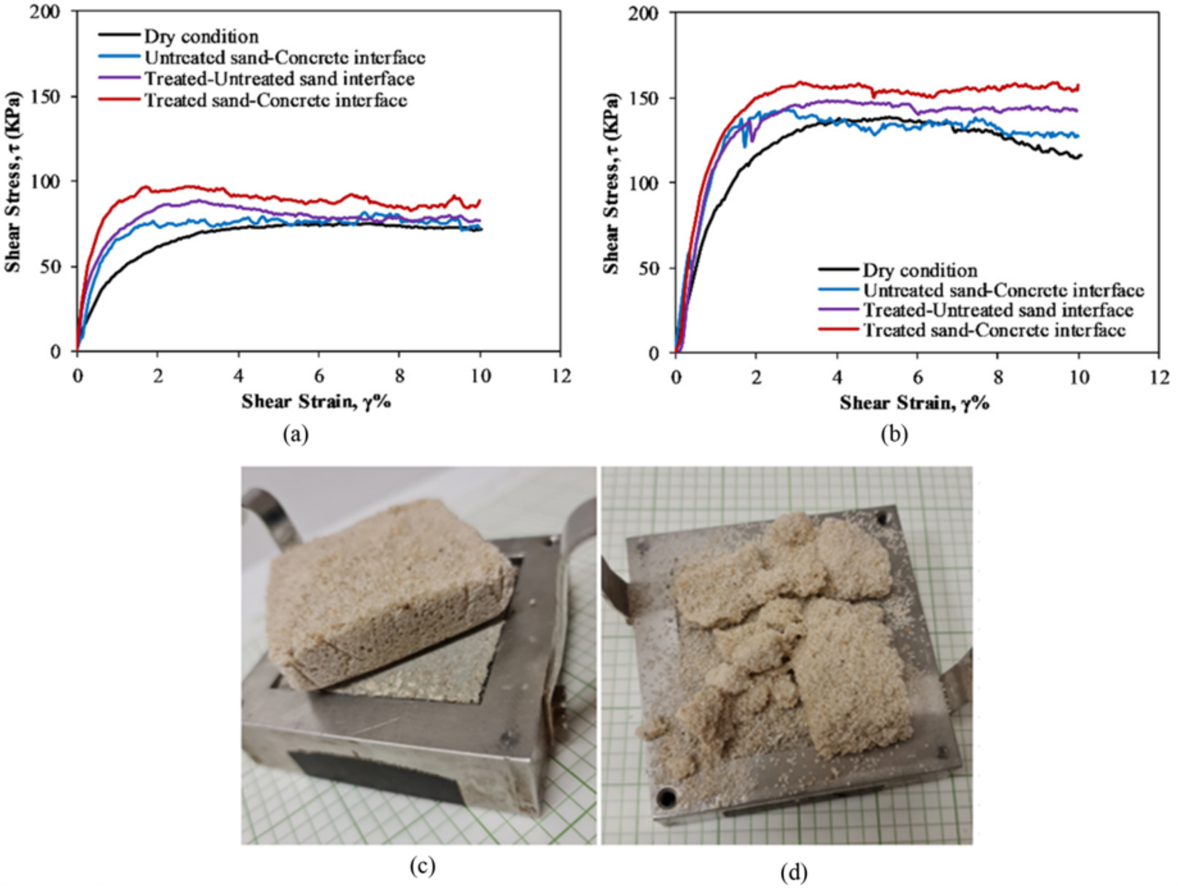
Two silica sand samples were prepared to investigate the effect of multiple cycles of EICP treatment on the shear stress-strain response. Mold setup and soil placement were maintained by using the same methodology as discussed previously. The percolation method was adopted. For each treatment cycle, a one-pore volume of cementation solution was poured over the surface. The curing period for each treatment cycle was 7 days.

Results of the direct shear tests on samples treated with 1, 2, and 3 cycles of treatment are shown in Fig. 6(a), in terms of shear stress versus shear strain at vertical stress of 100 kPa. As evident, the peak shear strength was found to be positively correlated with cycles of treatment. A significant improvement was observed in samples treated twice with EICP solution compared to a one-time treatment. However, a notable change in peak strength was not observed with a further increase in treatment cycles. After the peak, the samples experienced a sudden stress reduction followed by an irregular pattern of shear stresses when the shear strain increased. This could be attributed to the breakage of the samples as a creaking noise was noticed. Photographs of the samples during peak strength and after post-shearing are presented in Fig. 6(b).

The pattern of failure mode demonstrated a change with an increase in the multiple cycles of treatment. A similar mode of failure pattern was observed for the samples treated with 1 and 2 cycles of treatment. These samples were disintegrated into pieces; however, the sample treated by 2 cycles of treatment showed larger intact pieces. On the other hand, the sample treated by 3 cycles of treatment was observed to mostly maintain its structure. It seems that the sample was only sheared at the boundary where the shear load was applied. Loud cracking sounds were noticed post reaching its shear peak value, suggesting the continuous breakage of the developed cohesive bonds. Furthermore, the sample treated with 3 cycles of treatment showed a noticeable improvement in strength post-peak strength in comparison to the sample treated with 2 cycles of treatment. Hence, it can be safely inferred that multiple cycles of treatment improved residual shear strength despite the minimum improvement in peak strength. Nevertheless, it should be indicated that the multiple cycles of treatment conducted herein consumed a relatively large amount of enzyme and produced a strong ammonia odor. These two factors may hinder its application for field-scale treatments due to cost and sustainability concerns.

4.5 Interfacial Shear Strength

The interfacial shear strength is critical in analyzing the soil/structure interaction response in geotechnical engineering (i.e., influence capacity determination and interface skin resistance). As such, this section investigates the interfacial shear strength behavior between EICP-treated silica sand and rough concrete. A series of direct shear tests were conducted to explore the interface shearing behavior of the treated sand/concrete interface and treated/untreated-sand interface. The interaction of untreated sand/concrete was also studied for comparison purposes. The concrete block was made as per the dimension of the lower shear box. The concrete block surface was ensured to align with the surface of sliding, as illustrated in Fig. 7. After the treatments via



(a)

(b)

(c)

(d)

Fig. 7. Interfacial Shear Stress Versus Strain at a Vertical Stress of: (a) 100 kPa, (b) 200 kPa, (c) and (d) Depicts Sample Shape before and after Testing, Respectively

percolation, the pre-establish soil samples were inserted in the upper shear box, after which the shearing test was commenced with a shear strain of up to 10%.

The interface shear-strain curves at different vertical stresses of all interaction types are presented in Figs. 7(a) and 7(b). It can be seen that the interface shear stresses between EICP-treated sand and concrete were higher than shear stresses developed in the interface of untreated sand/concrete. In addition, sliding resistance between EICP-treated sand and untreated sand was observed to be higher than the sliding surface in raw sand with improvement in both the peak and residual strengths. Hence, precipitation produced by EICP treatment improved the interfacial strength of EICP-treated soils and concrete due to the roughening of soil particles. For the treated sand/concrete interface, the shear response exhibited a linear elastic behavior until the peak shear stress had been reached, followed by a relatively perfect plastic behavior with a residual strength plateau, especially as the vertical shear stresses increased. A representative sample of the treated sand/concrete before and after the test is shown in Figs. 7(c) and 7(d), respectively. Notably, the interface friction angle between two dissimilar materials is complex and difficult to predict for many reasons, including surface roughness, particle sizes, vertical stresses, and initial soil condition. Hence, the results presented herein are a preliminary investigation of the

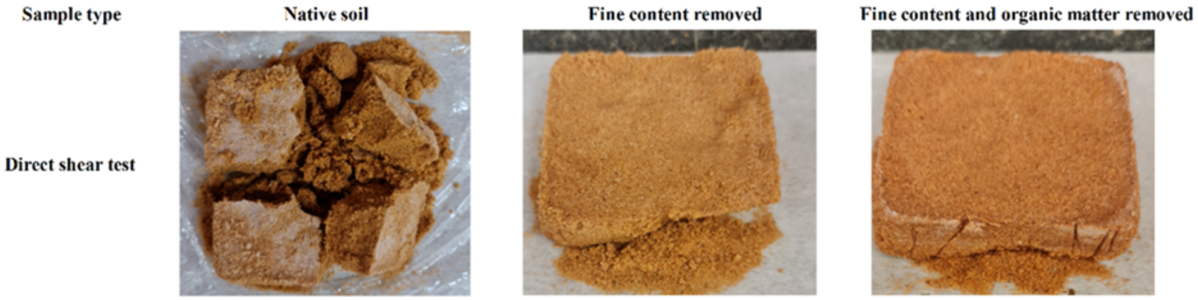


Fig. 8. Physical Appearance of EICP-Treated Natural Red Sand Samples after Treatment and Extractio

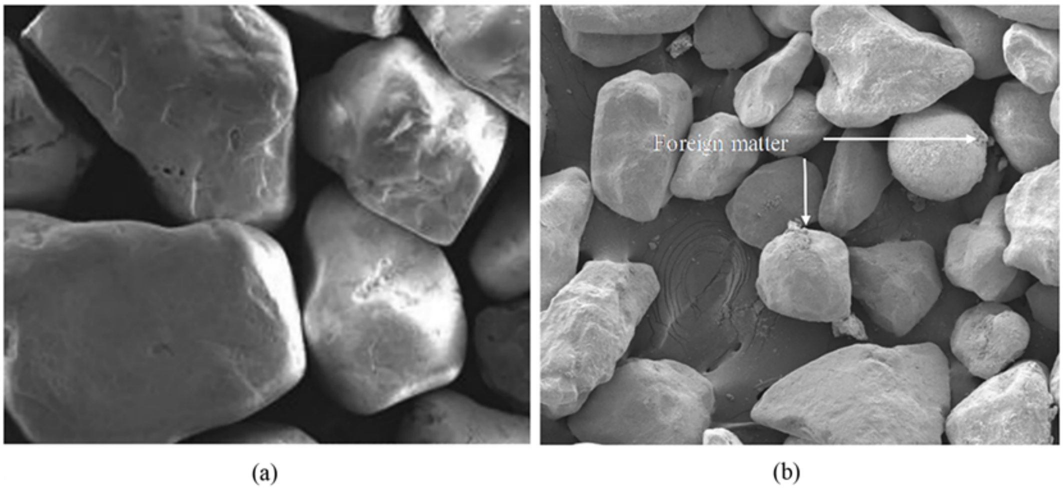


Fig. 9. SEM Images of: (a) Silica Sand (i.e., Alrasheed Silica Plant), (b) Natural Red Sand after (Almajed et al., 2020a)

matter. Further investigation is needed as studies on the between EICP-treated soil and other materials are still limited in the literature.

4.6 Natural Red Sand

Results after applying EICP treatment on a native natural red sand are demonstrated in Fig. 8, showing direct shear samples prepared at a relative density of 40%. The modified EICP treatment was found to be ineffective in cementing this native type of soil regardless of the application method. The sample ended up collapsing into individual pieces. Almajed et al. (2020a) have attributed this slumping of sample to the presence of fine content and organic matter that hinders the cementation effect of the EICP treatment as the resultant deposition of calcite does not adhere to particles. In line with this, an attempt was made to examine the effect of removing both fine and organic material on the integrity of the extracted natural red sand samples after EICP remediation. The fine content was removed by washing and sieving the native red sand on sieve #200. The retained sand was then oven-dried at 105°C for 24 hr. Fig. 8 shows the extracted sample of the red sand without fine content after treatment and curing. The level of EICP effectiveness was increased after the removal of fines. Notably, the sample mostly retained its shape but was easily damaged when moved. Furthermore, the fine-clean dry red sand was placed in a furnace with a temperature equal to 440 ± 40° (ASTM, 2020) for about 2hr, until a constant mass was achieved. The percentage of organic material was estimated to be approximately equal to 3.7% on average for three tests. After burning, the soil was placed in the designated mold and subjected to the EICP treatment. The extracted burned sample from the direct shear mold is presented in Fig. 8. The sample was found to hold its structure together as can be visually observed. It can be safely inferred that the EICP performed better in stabilizing the red sand after removing the fine and organic material compared to the native soil. However, the cementation strength appeared to be weak as samples were observed to easily fall apart when disturbed. Thus, direct shear could not be carried out. This result may shed some light on the influence of the co-existing fine and organic materials on the efficiency of the EICP treatment.

In corroboration of the imagery and particle shape analysis presented in studies conducted by Almajed et al. (2020a) and Lemboye et al. (2021b), Fig. 9 compares SEM images of silica sand and natural red sand samples before treatment. A close look at these images could provide insight into the effectiveness of EICP treatment in the sand of different particle sizes and shapes. It is clear that the silica sand particles are more rounded and uniform in shape while those of natural red sand particles are less uniform and with high angularity. The silica sand also appeared to be cleaner as there is no foreign matter attached to the soil particles compared to the red nature sand. These two factors could justify the poor performance of EICP treatment in angular sand particles despite the similarity in mineral composition. This is in agreement with Pandey (2018) in which irregular soil particles and angularity were identified as the main factors that contributed to the performance of the EICP solution in bridging the particles together. Hence, the more rounded shape of clean silica sand led to a more effective EICP treatment. Moreover, cohesionless soil's response to EICP-treatment could also be inferred to vary depending on the geotechnical characteristic of the soils. The response of sands to EICP cementation may vary if there is a variation in geotechnical characteristics even a consistent treatment procedures (Krishnan et al., 2021). Hence, the generalization of an optimum EICP recipe may not necessarily yield similar outcomes in all sands with the same geological formation implying the need for further research to quantify the reliability and other possible effects of EICP treatment.

5. Managerial Implications

Despite the tremendous effort done globally to reduce CO_2 emissions, the global production of cement has increased by about 154% in 2016 compared to 2000, and it is still growing due to the high demand for this material (Myhr et al., 2019). The increase in demand has already led to further emissions of CO_2 and a call for non-conventional approaches to sand stabilization is needed more than ever (Iftikhar et al., 2016; Almajed et al., 2021a). For instance, cement production in China has seen pecked output in recent years, which has grabbed the attention of both the public and academic sectors for possible remedies (Cao et al., 2016). It was reported that the emissions of CO_2 from the cement industry in China have significantly increased to about 627% within 25 years (Liu et al., 2021b). In the last decade or so, many research has been undertaken to develop eco-friendly binders for soil improvement due to the extensive use of ordinary Portland cement (OPC). Therefore, in supporting the global effort to reduce CO_2 emissions. The presented research advocates the use of bio-cementation via EICP as an alternative technique to general blend cement for soil stabilization. EICP technique is considered "environmentally friendly" due to its low-carbon benefits and has the potential to reduce the reliance on cement, thereby greening up the geotechnical industry (Yu et al., 2021; Wang and Yin, 2021). Nonetheless, the strength of sands stabilized by the EICP solution require an advance investigation before real field applications (Neupane et al., 2015a; Almajed et al., 2018; Almajed et al., 2019).

Furthermore, the following study provided important information regarding the performance of EICP-treated sands and EICP's potential use to strengthen weak bearing stratum via the estimation of shear strength characteristics. It also explored the most efficient method of EICP application that would lead to increased treatment efficacy and the developed strength within the treated soil matrix. Such outcomes provide geotechnical practicians' insight into the positive improvement in mechanical properties of EICP inhabited soil, and its capability in mimicking the natural or artificial cementing effect that occurs as a consequence of weathering processes or from general blending material, respectively, at minimal environmental impact and low embodied energy.

6. Study Limitations

The current work was carried out based on a bench-scale to provide a unique source for the shearing characteristic and engineering properties of EICP-treated sand and its interaction with adjusted soil and geotechnical elements. Such a study is needed to identify essential material properties, mechanical characteristics of bio-cementation via EICP, and the applicability of EICP to enhance bearing stratum before upscaling to larger-scale applications. Nonetheless, it is not a straightforward process to engage the lab testing results/findings in field application due to the complexity associated with the EICP treatment and its application techniques (Martin et al., 2021b), especially in soils of different types and characteristic (Krishnan et al., 2021), scale effects of direct shear tests (Cerato and Lutenegger, 2006). Thereby, the outcome of this paper could be utilized to derive the expected available resistance offered after the treatment or give researchers valuable insight into the load-transfer mechanisms at the macro-scales and foundation failures for further investigation. Herein, the main limitation of this research is as follows.

The application techniques are employed on a small scale and under controlled depth. Increasing the treatment depth may not result in uniform distribution of calcium carbonate in the sand as the bio cementation solution may not evenly spread when flowing through the sand mass compared to lab specimens. There are also concerns about using direct shear testing to characterize the behavior of a cemented material due to changes in mean stress during shearing, stress concentrations at the box boundaries, and defined shear failure plane. This may result in overestimating or underestimating the shear response of EICP-treated sands. Still, quantitative measurement of these concerns is not yet present in the existing literature. Moreover, the direct shear test results presented herein showed valuable benefits and critical issues for utilizing EICP as a ground improvement technique. There is still a need for optimization, especially in cases where the spatial variation of the soil properties exists. The presented study addressed the situation where the soil is uniformed; therefore, the results must be carefully examined in a situation where such a condition is not valid. Furthermore, the findings here promote the use of injection of EICP-solution into the soil as it yielded satisfactory outcomes contrary to other procedures. Herein, the best injection rate was determined based on the trial-and-error method during the preparation of the samples. The controlling factor was not to disturb the prepared sample or push the soil particles as the EICP solution was injected. However, the improper introduction could result in the formation of uneven precipitation within the soil mass. The soil zone around the injection point would be subjected to strongly localized cementation, causing strength within the soil mass to differ. This could also clog the voids preventing the EICP solution from further penetration into the soil as the reaction is faster than soil permeability. Hence, the scope of the present study is limited to bench-scale tests. Future studies using a larger scale should be performed to determine the effect of injection rate to verify the findings reported in this paper for application to field-scale conditions.

7. Failure Pattern

Based on the results discussed above, it can be interpreted that different failure modes would occur during footings failure under enzymatically-modified sand on a macro scale. It is conceptualized that a triangular area of relatively large displacements would occur under the footing due to the continued breakage and disintegration of the weak developed particles' bond along the smooth plane or sliding surface when treatment has been done vis spraying and mix-&-compact method. The footing would penetrate the soil after reaching a specified level of load, like a pattern of punching shear mode of failure. For percolation or injection, it is postulated that a pattern of disintegration or destruction behavior (i.e., forming of lumped masses) would take place in the soil mass, causing a sudden stress reduction. Thereby cracks of irregular pattern form in the treated mass. The stress distribution under the footing is thereby non-uniform, as well as settlement of the footing. The results of Martinez and Dejong (2009) based on a 1g scaled shallow foundation model seated above bio-treated sand via injection showed a significant surface cracking, rotation, and surface heave of the footing upon failure. Nonetheless, a conclusive conclusion cannot be made as the foundation size, treatment zone under foundation, soil condition, depth of the footing, and surcharge at the ground surface affect the developed failure modes. Also, the results herein are derived based on maintaining the same treatment conditions, sand characteristics, and uniformity [i.e., D50, Cu, Cc, and same batch from the commercial vendor]. Hence, the exact nature, and shape of failure planes under enzymatically-modified sand need to be visually studied and there is a lack of research regarding such topics.

8. Conclusions

In the current study, several direct shear tests were performed with the purpose to investigate the shear strength behavior and parameters, and these tests included an assessment of the friction angle and cohesion of bio-cemented cohesionless soil via EICP. Wherein, a variety of application methods of introducing EICP solution to the soil were considered, as well as their potential to increase the soil shear strength was discussed. The current study also addressed the effect of sand sources on soil response to EICP treatment. Several significant conclusions as detailed below were obtained during this study:

1. The application methods of the EICP treatment to the soil matrix were found to play a crucial role in global shearing behavior.
2. EICP demonstrates the potential to improve the shear strength of cohesionless soils up to about 2.3 times that of untreated condition provided a proper application method is selected due to the fast precipitation rate (i.e., $CaCO_3$) in the EICP process. The results demonstrated that injecting the EICP solution into the soil at a controlled rate yielded a strong bonding force and higher resistance to shearing loads as a fresh EICP solution being induced at different injection points compared to any other method (i.e., percolation, spraying, and mix-&-compact methods). The sliding surface of specimens treated via the injection method was found to be rougher than specimens treated via other methods leading to more skewed shear stress-strain curve behavior. Such a scenario may render behavior predictions more challenging to explain and highly undesirable for in-field applications.
3. Minimal improvement in peak strength beyond two cycles of treatment was observed. Nonetheless, further increases in cycles of treatment showed an improvement in the residual shear strength despite the minimum improvement in peak strength.
4. EICP treatment technique was revealed to enhance the interfacial shear strength between sand and concrete due to the roughening of soil particles. The interfacial shear strength between treated sand and concrete was approximately 1.2 times higher than that of raw sand and concrete.
5. The performance of the EICP solution varied depending on the host sand despite the evident similarity in mineral composition. EICP was found to be insufficient to bind the particles of naturally occurring red sands as a single block. However, the EICP demonstrated a considerably well performance when the fine and organic materials were removed but was still found to be weak in strength properties. This phenomenon may be attributed to the variation in soil particle size, shapes, and angularity of the soil grains compared to 20/30 silica sand.

Acknowledgments

The authors would like to acknowledge the Researchers Supporting Project number (RSP2023R285), King Saud University, Riyadh, Saudi Arabia.

ORCID

Abdullah Almajed https://orcid.org/0000-0001-7230-9400
Kehinde Lemboye https://orcid.org/0000-0001-5320-3766
Ahmed Alnuaim https://orcid.org/0000-0003-0987-0603

References

Afrin H (2017) A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology* 3(2):19-24, DOI: 10.11648/j.ijtet.20170302.12

Ahenkorah I, Rahman MM, Karim MR, Beecham S (2021a) Optimisation of chemical constituents on enzyme-induced carbonate precipitation in test-tube and soil. *Geotechnical Research* 8(3):66-84, DOI: 10.1680/jgere.21.00006

Ahenkorah I, Rahman MM, Karim MR, Beecham S, Saint C (2021b) A review of enzyme induced carbonate precipitation (EICP): The role of enzyme kinetics. *Sustainable Chemistry* 2(1):92-114, DOI: 10.3390/suschem2010007

Almajed A (2017) Enzyme induced carbonate precipitation (EICP) for soil improvement. PhD Thesis, Arizona State University, Tempe, United States

Almajed A, Abbas H, Almusallam T, Al-Salloum Y (2021a) Stabilization of sand using energy efficient materials under normal and extreme hot weathers. *Journal of Cleaner Production* 285, DOI: 10.1016/j.jclepro.2020.124914

Almajed A, Abbas H, Arab MG, Alsabhan A, Hamid W, Al-Salloum Y (2020a) Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands. *Journal of Cleaner Production* 274:122627, DOI: 10.1016/j.jclepro.2020.122627

Almajed A, Lateef MA, Moghal AAB, Lemboye K (2021b) State-of-the-art review of the applicability and challenges of microbial-induced calcite precipitation (MICP) and enzyme-induced calcite precipitation (EICP) techniques for geotechnical and geoenvironmental applications. *Crystals* 11(4):370, DOI: 10.3390/cryst11040370

Almajed A, Lemboye K, Arab MG, Alnuaim A (2020b) Mitigating wind erosion of sand using biopolymer-assisted EICP technique. *Soils and Foundations* 60(2):356-371, DOI: 10.1016/j.sandf.2020.02.011

Almajed A, Tirkolaei HK, Kavazanjian E (2018) Baseline investigation on enzyme-induced calcium carbonate precipitation. *Journal of Geotechnical and Geoenvironmental Engineering* 144(11):04018081, DOI: 10.1061/(asce)gt.1943-5606.0001973

Almajed A, Tirkolaei HK, Kavazanjian E, Hamdan NM (2019) Enzyme induced biocementated sand with high strength at low carbonate content. *Scientific Reports* 9(1):1135, DOI: 10.1038/s41598-018-38361-1

Arab MG, Alsodi R, Almajed A, Yasuhara H, Zeiada W, Shahin MA (2021a) State-of-the-art review of enzyme-induced calcite precipitation (EICP) for ground improvement: Applications and prospects. *Geosciences* 11(12):492, DOI: 10.3390/geosciences11120492

Arab MG, Omar M, Almajed A, Elbaz Y, Ahmed AH (2021b) Hybrid technique to produce bio-bricks using enzyme-induced carbonate precipitation (EICP) and sodium alginate biopolymer. *Construction and Building Materials* 284:122846, DOI: 10.1016/j.conbuildmat.2021.122846

Arab MG, Rohy H, Zeiada W, Almajed A, Omar M (2021c) One-Phase EICP Biotreatment of sand exposed to various environmental conditions. *Journal of Materials in Civil Engineering* 33(3): 04020489, DOI: 10.1061/(asce)mt.1943-5533.0003596

ASTM (2020) Determining the water (moisture) content, ash content, and organic material of peat and other organic soils. https://www.astm.org/d2974-20e01.html

ASTM (2012) Standard test method for direct shear test of soils under consolidated drained conditions, https://www.astm.org/standards/d3080

Cao J (2018) Bio-Inspired Geomaterial Improvement and Development of Innovative Characterization Methods. PhD Thesis, Missouri University of Science and Technology, Parker Hall, United States

Cao Z, Shen L, Zhao J, Liu L, Zhong S, Sun Y, Yang Y (2016) Toward a better practice for estimating the CO_2 emission factors of cement production: An experience from China. *Journal of Cleaner Production* 139:527-539, DOI: 10.1016/j.jclepro.2016.08.070

Cerato AB, Lutenegger AJ (2006) Specimen size and scale effects of direct shear box tests of sands. *Geotechnical Testing Journal* 29(6):507-516, DOI: 10.1520/gtj100312

Chandra A, Ravi K (2021) Application of enzyme-induced carbonate precipitation (EICP) to improve the shear strength of different type of soils. *Lecture Notes in Civil Engineering* 88:617-632, DOI: 10.1007/978-981-15-6237-2_52

Das BM (2001) Soil Mechanics Laboratory Manual 6th Ed. Oxford University Press, USA., New York

Das BM (2003) Chemical and mechanical stabilization. *Transportation Research Board* http://onlinepubs.trb.org/onlinepubs/millennium/00018.pdf

Dejong JT, Fritzges MB, Nüsslein K (2006) Microbially induced cementation to control sand response to undrained shear. *Journal of Geotechnical and Geoenvironmental Engineering* 132(11):1381-1392, DOI: 10.1061/(ASCE)1090-0241(2006)132:11(1381)

Dejong JT, Soga K, Kavazanjian E, Burns S, van Paassen LA, AlQabany A, Aydilek A, Bang SS, Burbank M, Caslake LF, Chen CY, Cheng X, Chu J, Ciurli S, Esnault-Filet A, Fauriel S, Hamdan N, Hata T, Inagaki Y, Tsesarsky M (2013) Biogeochemical processes and geotechnical applications: Progress, opportunities and challenges. *Geotechnique* 63(4):287-301, DOI: 10.1680/geot.SIP13. P.017

Disu AA, Kolay PK (2021) A critical appraisal of soil stabilization using geopolymers: The past, present and future. *International Journal of Geosynthetics and Ground Engineering* 7(2), DOI: 10.1007/s40891-021-00267-w

Hamdan NM (2015) Applications of enzyme induced carbonate precipitation (EICP) for soil improvement. PhD Thesis, Arizona State University, Tempe, United States

Hamdan NM, Kavazanjian E (2016) Enzyme-induced carbonate mineral precipitation for fugitive dust control. *Geotechnique* 66(7):546-555. DOI: 10.1680/jgeot.15.P.168

Hamdan NM, Kavazanjian E, O'Donnell S (2013) Carbonate cementation via plant derived urease. *18th International Conference on Soil Mechanics and Geotechnical Engineering: Challenges and Innovations in Geotechnics, ICSMGE 2013* 3(480):2489-2492, Paris, France

He J, Yang F, Qi YS, Fang CH, Yan BY, Zhang Y, Hang L, Gao YF (2021) Improvement in silty sand with enzyme-induced carbonate precipitation: Laboratory model experiment. *Acta Geotechnica* 17:2895-2905, DOI: 10.1007/s11440-021-01361-z

Iftikhar Y, He W, Wang Z (2016) Energy and CO_2 emissions efficiency of major economies: A non-parametric analysis. *Journal of Cleaner Production* 139:779-787, DOI: 10.1016/j.jclepro.2016.08.072

Ismail MA, Joer HA, Randolph MF, Meritt A (2002) Cementation of porous materials using calcite. *Geotechnique* 52(5):313-324, DOI: 10.1680/geot.2002.52.5.313

Juran I, Riccobono O (1991) Reinforcing soft soils with artificially cemented compacted-sand columns. *Journal of Geotechnical Engineering* 117(7):1042-1060, DOI: 10.1061/(ASCE)0733-9410(1991)117:7(1042)

Kavazanjian E, Almajed A, Hamdan NM (2017) Bio-inspired soil improvement using EICP soil columns and soil nails. *Grouting 2017* 13-22, DOI: 10.1061/9780784480793.002

Kavazanjian E, Hamdan NM (2015) Enzyme induced carbonate precipitation (EICP) columns for ground improvement. IFCEE 2015, March 17-21, San Antonio, Texas, DOI: 10.1061/9780784479087.209

Krishnan V, Tirkolaei HK, Martin KK, Hamdan NM, van Paassen LA, Kavazanjian E (2021) Variability in the unconfined compressive strength of EICP-treated "Standard" sand. *Journal of Geotechnical and Geoenvironmental Engineering* 147(4):06021001, DOI: 10.1061/(asce)gt.1943-5606.0002480

Lemboye K, Almajed A, Alnuaim A, Arab M, Alshibli K (2021a) Improving sand wind erosion resistance using renewable agriculturally derived biopolymers. *Aeolian Research* 49:100663, DOI: 10.1016/j.aeolia.2020.100663

Lemboye K, Almajed A, Hamid W, Arab MG (2021b) Permeability investigation on sand treated using enzyme-induced carbonate precipitation and biopolymers. *Innovative Infrastructure Solutions* 6(3), DOI: 10.1007/s41062-021-00530-z

Li Y, Chan LS, Yeung AT, Xiang X (2013) Effects of test conditions on shear behaviour of composite soil. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering* 166(3):310-320, DOI: 10.1680/geng.11.00013

Lin H, Suleiman MT, Brown DG, Kavazanjian E (2016) Mechanical behavior of sands treated by microbially induced carbonate precipitation. *Journal of Geotechnical and Geoenvironmental Engineering* 142(2):04015066, DOI: 10.1061/(ASCE)GT.1943-5606.0001383

Liu KW, Jiang NJ, Qin JD, Wang YJ, Tang CS, Han XL (2021a) An experimental study of mitigating coastal sand dune erosion by microbial- and enzymatic-induced carbonate precipitation. *Acta Geotechnica*

16(2):467-480, DOI: 10.1007/s11440-020-01046-z

Liu J, Tong D, Zheng Y, Cheng J, Qin X, Shi Q, Yan L, Lei Y, Zhang Q (2021b) Carbon and air pollutant emissions from China's cement industry 1990-2015: Trends, evolution of technologies, and drivers. *Atmospheric Chemistry and Physics* 21(3):1627-1647, DOI: 10.5194/acp-21-1627-2021

Makusa GP (2012) Soil stabilization methods and materials in engineering practice. Luleå tekniska universitet, Luleå, Sweden

Martin KK, Tirkolaei HK, Kavazanjian E (2021a) Enhancing the strength of granular material with a modified enzyme-induced carbonate precipitation (EICP) treatment solution. *Construction and Building Materials*, 271:121529, DOI: 10.1016/j.conbuildmat. 2020.121529

Martin KK, Tirkolaei HK, Kavazanjian E (2021b) Mid-scale biocemented soil columns via enzyme-induced carbonate precipitation (EICP). *Soils and Foundations* 61(6):1529-1542, DOI: 10.1016/j.sandf.2021.09.001

Martinez BC, Dejong JT (2009) Bio-mediated soil improvement: Load transfer mechanisms at the micro- and macro- scales. *Advances in Ground Improvement*, American Society of Civil Engineers, Reston, VA, DOI: 10.1061/41025(338)26

Muhammed AS, Kassim KA, Zango MU, Ahmad K, Makinda J (2021) Enhancing the strength of sandy soil through enzyme-induced calcite precipitation. *International Journal of Geosynthetics and Ground Engineering* 7(2):1-10, DOI: 10.1007/s40891-021-00289-4

Mujah D, Shahin MA, Cheng L (2017) State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP) for soil stabilization. *Geomicrobiology Journal* 34(6):524-537, DOI: 10.1080/01490451.2016.1225866

Myhr A, Røyne F, Brandtsegg AS, Bjerkseter C, Throne-Holst H, Borch A, Wentzel A, Røyne A (2019) Towards a low CO_2 emission building material employing bacterial metabolism (2/2): Prospects for global warming potential reduction in the concrete industry. *PLoS One* 14(4), DOI: 10.1371/journal.pone.0208643

Neupane D, Yasuhara H, Kinoshita N, Ando Y (2015a) Distribution of mineralized carbonate and its quantification method in enzyme mediated calcite precipitation technique. *Soils and Foundations* 55(2):447-457, DOI: 10.1016/j.sandf.2015.02.018

Neupane D, Yasuhara H, Kinoshita N, Putra H (2015b) Distribution of grout material within 1-m sand column in insitu calcite precipitation technique. *Soils and Foundations* 55(6):1512-1518, DOI: 10.1016/j.sandf.2015.10.015

Neupane D, Yasuhara H, Kinoshita N, Unno T (2013) Applicability of enzymatic calcium carbonate precipitation as a soil-strengthening technique. *Journal of Geotechnical and Geoenvironmental Engineering* 139(12):2201-2211, DOI: 10.1061/(asce)gt.1943-5606.0000959

Ossai R, Rivera L, Bandini P (2020) Experimental study to determine an EICP application method feasible for field treatment for soil erosion control. *Geo-Congress 2020*, American Society of Civil Engineers, Reston, VA, DOI: 10.1061/9780784482834.023

Pandey G (2018) Feasibility study of water based / polymer modified EICP for soil improvement involving recycled glass aggregate. MSc Thesis, University of Akron, United States

Park SS, Choi SG, Nam IH (2014) Effect of plant-induced calcite precipitation on the strength of sand. *Journal of Materials in Civil Engineering* 26(8):06014017, DOI: 10.1061/(asce)mt.1943-5533.0001029

Putra H, Yasuhara H, Kinoshita N (2017) Optimum condition for the application of enzyme-mediated calcite precipitation technique as soil improvement method. *International Journal on Advanced Science, Engineering and Information Technology* 7(8):2145-2151, DOI: 10.18517/ijaseit.7.6.3425

Ran D, Kawasaki S (2016) Effective use of plant-derived urease in the field of geoenvironmental/geotechnical engineering. *Journal of Civil & Environmental Engineering* 6(1):1-13, DOI: 10.4172/2165-784X.1000207

Rohy H, Arab MG, Zeiada W, Omar M, Almajed A, Tahmaz A (2019) One phase soil bio-cementation with eicp-soil mixing. *World Congress on Civil, Structural, and Environmental Engineering*, DOI: 10.11159/icgre19.164

Roy A (2017) Soil Stabilization using Rice Husk Ash and Cement. *International Research Journal of Engineering and Technology (IRJET)* 4(2):49-54

Schnaid F, Prietto PDM, Consoli NC (2001) Characterization of cemented sand in triaxial compression. *Journal of Geotechnical and Geoenvironmental Engineering* 127(10):857-868, DOI: 10.1061/(ASCE)1090-0241(2001)127:10(857)

Song JY, Sim Y, Jang J, Hong WT, Yun TS (2020) Near-surface soil stabilization by enzyme-induced carbonate precipitation for fugitive dust suppression. *Acta Geotechnica* 15(7):1967-1980, DOI: 10.1007/s11440-019-00881-z

Wang HL, Yin ZY (2021) Unconfined compressive strength of bio-cemented sand: state-of-the-art review and MEP-MC-based model development. *Journal of Cleaner Production* 315, DOI: 10.1016/j.jclepro.2021.128205

Yasuhara H, Hayashi K, Okamura M (2011) Evolution in mechanical and hydraulic properties of calcite-cemented sand mediated by biocatalyst. *Geo-Frontiers 2011*, American Society of Civil Engineers, Reston, VA, DOI: 10.1061/41165(397)407

Yasuhara H, Neupane D, Hayashi K, Okamura M (2012) Experiments and predictions of physical properties of sand cemented by enzymatically-induced carbonate precipitation. *Soils and Foundations* 52(3):539-549, DOI: 10.1016/j.sandf.2012.05.011

Yu X, Chu J, Yang Y, Qian C (2021) Reduction of ammonia production in the biocementation process for sand using a new biocement. *Journal of Cleaner Production* 286, DOI: 10.1016/j.jclepro.2020.124928

Yuan H, Ren G, Liu K, Zhao Z (2021) Effect of incorporating polyvinyl alcohol fiber on the mechanical properties of eicp-treated sand. *Materials* 14(11), DOI: 10.3390/ma14112765

Yuan H, Ren G, Liu K, Zheng W, Zhao Z (2020) Experimental study of EICP combined with organic materials for silt improvement in the yellow river flood area. *Applied Sciences* 10(21):7678, DOI: 10.3390/app10217678

Zehner J, Røyne A, Sikorski P (2021) A sample cell for the study of enzyme-induced carbonate precipitation at the grain-scale and its implications for biocementation. *Scientific Reports* 11(1):1-11, DOI: 10.1038/s41598-021-92235-7

Zhang M, Guo H, El-Korchi T, Zhang G, Tao M (2013) Experimental feasibility study of geopolymer as the next-generation soil stabilizer. *Construction and Building Materials* 47:1468-1478, DOI: 10.1016/j.conbuildmat.2013.06.017