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Preliminary Study of the Effect of EICP and X-EICP Treatment on Wind Erosion and Penetration Resistance of a Clayey Sand

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ABSTRACT

Laboratory tests were conducted using the Portable In-Situ Wind ERosion Laboratory (PI-SWERL™) and a penetrometer to investigate the influence of enzyme-induced carbonate precipitation (EICP) on wind erosion resistance and strength of a clayey sand. Measurements on specimens treated with two different types of EICP were compared to results obtained from the untreated specimen. The PI-SWERL™ device creates a small vortex in a chamber in which the emission from the specimen surface of particles 10 microns or less in diameter (PM_{10}) is measured. In the penetrometer test, a 0.25-inch diameter blunt-end probe was inserted 0.5 inches into the specimens to measure penetration resistance. Specimens were prepared at 90% of maximum dry unit weight and 2% wet of the optimum moisture content as measured in the Harvard miniature compaction test. Treatments included a standard EICP treatment solution and an enhanced solution incorporating xanthan gum (labelled as X-EICP). Both treatments consisted of 1.5 M:1 M urea: calcium chloride mixed with 30 ml/L of crude jack bean urease enzyme solution with an activity of 100 U/m and 4 g/L non-fat milk solids. For the X-EICP treatment, 3 g/L xanthan gum mixed with 3 ml vegetable glycerin was added to the original EICP recipe. The treatments were applied using percolation only and mix and compact followed by percolation. Results indicated that specimens treated with the X-EICP solution exhibited higher wind erosion resistance and strength compared to those treated with the conventional treatment solution. However, the potential for biodegradation of the X-EICP treatment was not considered.

INTRODUCTION

Background

Enzyme-induced carbonate precipitation (EICP) has been investigated by several researchers as a durable means of suppressing soil erosion. EICP has been shown to create a crust on the soil surface that is effective for erosion control. Several studies have been conducted that focus on the effect of EICP on wind erosion resistance (fugitive dust control). Hamdan and Kavazanjian (2016) demonstrated the ability of EICP treatment to supppress wind erosion by conducting wind tunnel tests on various types of fine sandy soil treated by spraying an EICP solution on the soil surface. Xanthan gum-enhanced EICP treatment (X-EICP) is a modified form of EICP treatment wherein xanthan gum is included in the basic EICP treatment solution (Woolley et al. 2023). In laboratory and field trials,Wooley et al. (2023) found that, while EICP and X-EICP treatments were both effective in creating a wind erosion resistant crust, X-EICP offered somewhat greater strength and erosion reistance even though the amount of preciptiated carbonate was reduced. As soil erosion due to water is also a major environmental protection issue, EICP has also been investigated as a means to enhance soil resistance against rainfall-induced soil erosion (Ossai and Bandini, 2021).

X-EICP appears to be particularly effective (compared to EICP) in soil containing fine-grained particles (Jain et al. 2024). In X-EICP, the xanthan gum appears to act as an additional binder that holds the fine-grained soil particles together, hence increasing the erosion resistance and strength of the soil. In soils with significant fines content, where cementation via carbonate precipitation is not optimal, X-EICP may offer a better treatment alternative for soil improvement. However, one potential drawback of X-ECIP is that, while the calcium carbonate is expected to be long lasting (based on natural analogs), the xanthan gum may be biodegradable.

In this study, the impact of EICP and X-EICP treatment on erosion resistance of a clayey sand was evaluated using the Portable In-Situ Wind ERosion Laboratory (PI-SWERL^{TM}) and penetrometer testing. The PI-SWERL^{TM} device measures the wind erosion resistance of soil. The device creates a small vortex in a chamber seated on the soil by means of a rotating blade at the top of the chamber. The chamber is fitted with a sensor that measures the concentration of entrained particles less than 10 microns in diameter (PM_{10}) (Etyemezian et al. 2007) at friction velocities of up to 125 cm/s.

EICP

The baseline EICP treatment solution used in this research as developed by Almajed et al. (2019) consists of 1.0 M urea ($CO(NH_2)_2$), 0.67 M calcium chloride ($CaCl_2$), 3 g/l urease enzyme with an activity of ≈ 3500 U/g extracted from jack beans, and 4 g/l non-fat milk solids in an aqueous solution. Combining these constituents results in carbonate precipitation. While non-fat milk solids do not directly engage in precipitation of the calcium carbonate in the EICP process, they influence the reaction dynamics by modulating enzyme activity, promoting the growth of larger mineral crystals, and focusing precipitation at the inter-particle contact, thereby enhancing the overall effectiveness and characteristics of soil stabilization (Almajed et al. 2019).

X-EICP incorporates xanthan gum mixed with vegetable glycerin to form a hydrogel, which is then added to the standard EICP recipe. While not participating in the precipitation reaction, this mixture appears to function as a fluidizer for the treatment solution as well as a supplemental binder. The treated soil retains the solution longer than treatments without xanthan gum, prolonging the presence of the reaction matrix and extending the EICP reaction time, which may potentially increase precipitation efficiency. The hydrogel also localizes the EICP reaction matrix by limiting solution penetration into the soil (Hamdan et al. 2016). Furthermore, xanthan gum is known for its binding properties and it adheres to the soil particles, acting like a weak glue. This lets the hydrogel in the X-EICP act as a supplemental binder to the precipitated carbonate.

MATERIALS AND METHODS

The test soil was clayey sand with a plasticity index of 9% designated SC in the Unified Soil Classification System as it had 12% - 15% (by weight) passing the number 200 sieve. The maximum dry unit weight and the optimum moisture content of the untreated and treated test soil measured using a Harvard miniature compaction device with a 20 lb spring were 20 kN/m^3 and 13% for the untreated soil, 18 kN/m^3 and 14% for the EICP-treated specimen, and 19 kN/m^3 and 14% for the X-EICP treated specimen, respectively (Jain et al. 2024). The compaction curves are provided in Figure 1.

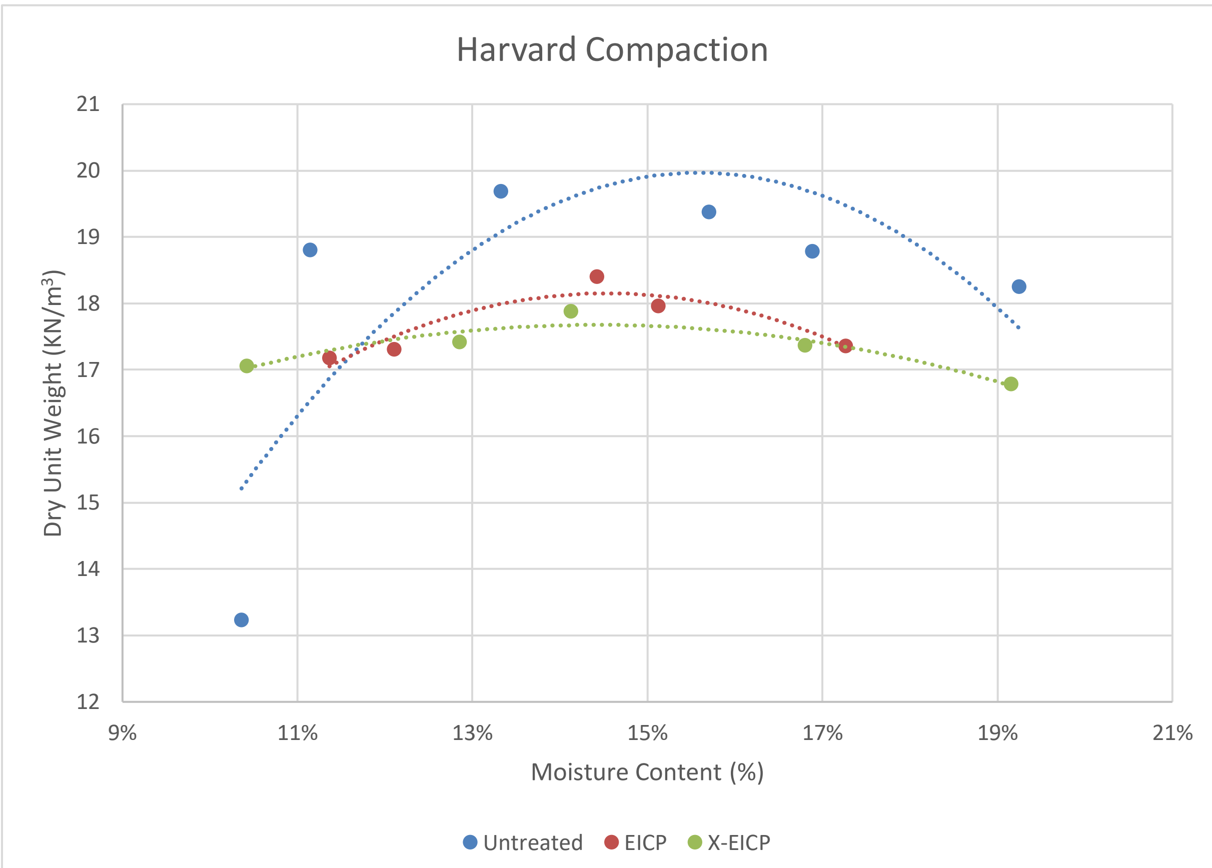

Figure 1. Harvard Compaction Curves for Untreated, EICP, and X-EICP Specimens

Five specimens were prepared for PI-SWERL^{TM} testing in 9-inch diameter, 1.5-inch-deep metal pans. The soil was compacted to 90% of maximum dry unit weight at 2% wet of optimum. For both EICP and X-EICP treatments, the pans were prepared using two different treatment methods: 1) one cycle of percolation; and 2) one cycle of mix and compact followed by one cycle of percolation. One pan was designated for each treatment method, along with one untreated pan. The treatment scheme is illustrated in Figure 2.

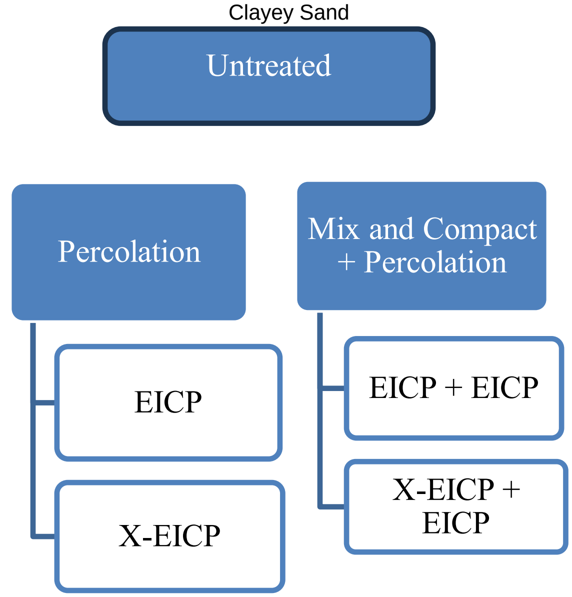

Figure 2. Specimen Preparation

For this study, a 1.5M:1M Urea:$CaCl_2$ mixture was combined with 30 ml/L of crude urease extract (Khodadadi Tirkolei et al. 2020) with an activity of 100 U/m and 4 g/L milk solids for the EICP treatment. For X-EICP treatment, 3 g/L xanthan gum mixed in 3 ml vegetable glycerin was added to the EICP recipe. 96 ml of the treatment solution was applied to the specimen surface at a concentration of 2.4 liters/m^2 for the percolation treatment cycles using a spray bottle at a rate such that the volume of solution was expended in about 40 seconds.

For the mix and compact method, the treatment solution was incorporated into the soil volume in two steps to 2% wet of optimum target moisture content with half the solution applied in each step. The volume of the treatment solution was calculated based on the mass of the untreated dry soil. For the EICP treatment, $CaCl_2$ and urea were mixed first, followed by the urease enzyme and milk solids for a total volume of 340 ml of solution (i.e., 170 ml for each step). For the X-EICP treatment, urea, $CaCl_2$, and the xanthan gum-vegetable glycerin solution were added first, followed by urease and milk solids solution. 300 ml of treatment solution (150 ml each step) was used to prepare the X-EICP specimen (the smaller solution volume due to a lower optimum moisture content). The treated soil was then placed in the pan in three lifts, each compacted with light tamping. For both EICP and X-EICP, an additional 96 ml EICP solution was sprayed on the specimen surface at the rate of 2.4 liters/m^2.

The prepared specimens were tested for erosion resistance using the PI-SWERL™ device. Treated specimens were allowed to cure for at least 24 hours prior to testing. The test followed a pre-set program, incrementally increasing blade rotation speed by 1000 rpm every two minutes until reaching 6000 rpm. The final speed corresponds to a friction velocity of 100 cm/s. Following erosion resistance testing, three penetration resistance trials were conducted for each specimen using a universal testing machine. A 0.25-inch diameter blunt-end probe was used at a penetration rate of 0.01 in/min to a penetration depth of 0.5 inches. To test for the carbonate content of the treated and untreated specimens, the calcimeter device was used.

RESULTS

Carbonate Content

Calcium carbonate content was evaluated on the untreated and treated specimens using an Eijkelkamp calcimeter (Royal Eijkelkamp B.V.). (B.V., n.d.) The calcium carbonate content found in each specimen is provided in table 1.

Specimen	% $CaCO_3$
Untreated	7.26%
EICP Percolation	9.64%
X-EICP Percolation	8.16%
EICP Compaction+ Percolation	11.39%
X-EICP Compaction + Percolation	8.64%

Table 1. Calcium Carbonate Content of Untreated and Treated Specimens

Wind Erosion Resistance

The PI-SWERL™ tests showed that for the performance of the X-EICP treated specimen was superior to the EICP-treated specimen treated using percolation, as illustrated in Figure 3. Figure 4 shows that the EICP-treated sspecimen performed somewhat better than the X-EICP-treated sample for mix and compact treatment at friction velocities lower than 70 cm/s, while the X-EICP treated specimen performed marginally better than the EICP treated specimen at friction velocities higher than 70 cm/s.

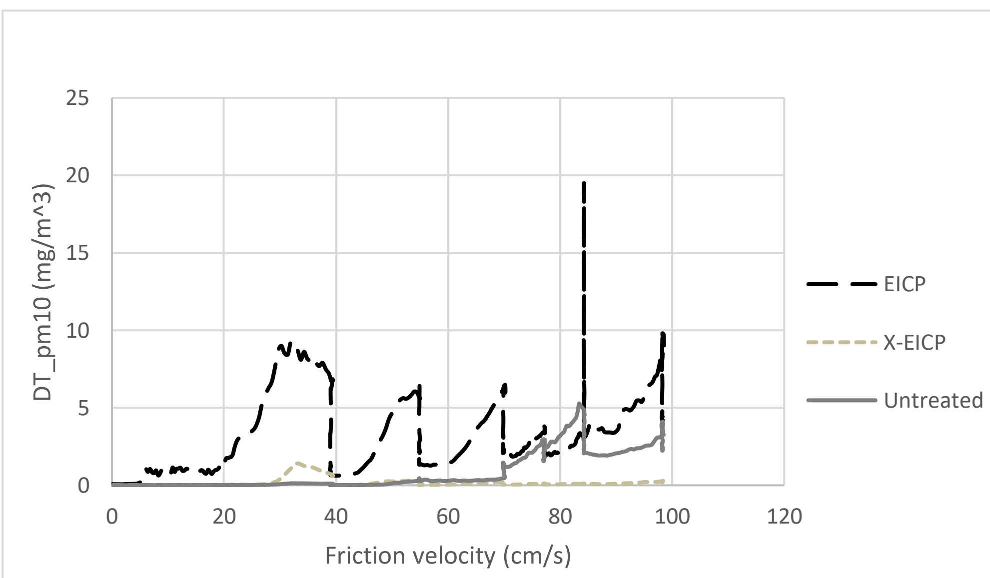

Figure 3. Erosion Resistance for Percolation Technique

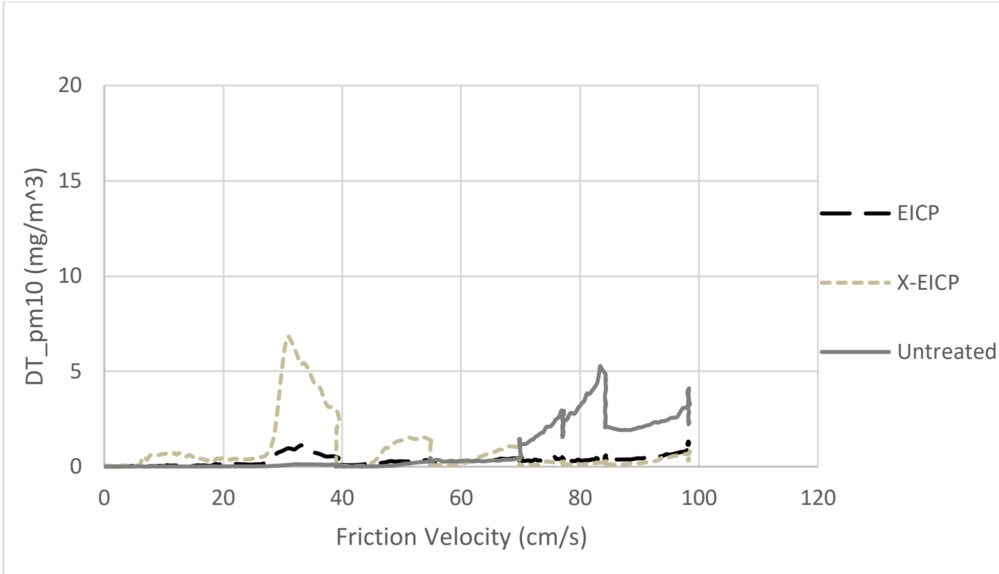

Figure 4. Erosion Resistance for Mix and Compact with Percolation Technique

Penetration Resistance

Figure 5 compares the average penetration resistance of the specimens prepared using percolation only for both EICP and X-EICP treatment with the penetration resistance of the untreated specimen. Figure 6 presents the same comparison for the mix and compact plus percolation specimens. The X-EICP treated specimen showed the highest penetration resistance for both percolation and mix and compact treatment techniques. Figure 7 presents the average penetration resistance for the specimens at one probe diameter displacement (0.25 in).

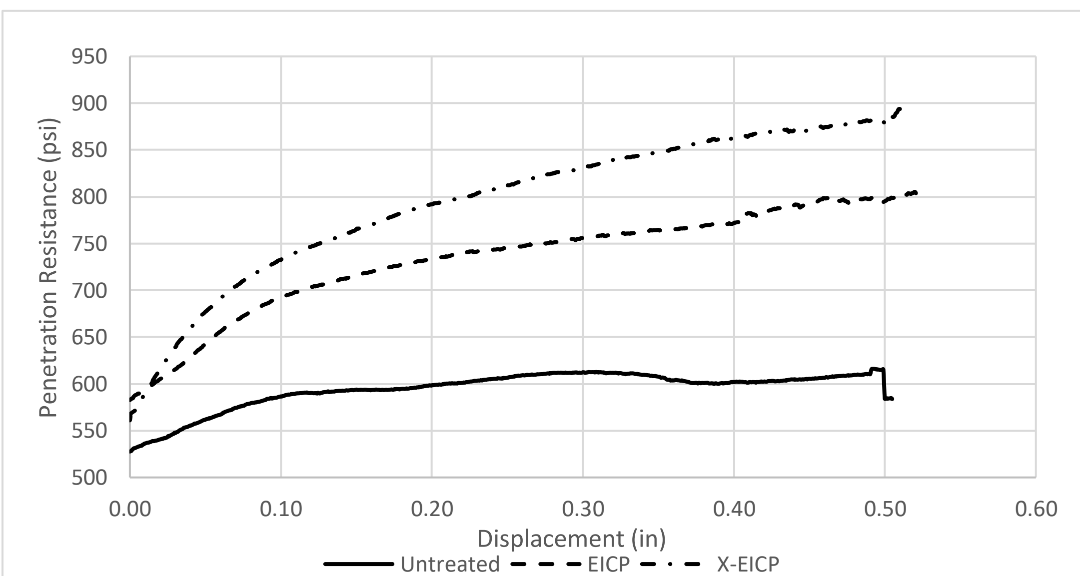

Figure 5. Average Penetration Resistance with Percolation Technique

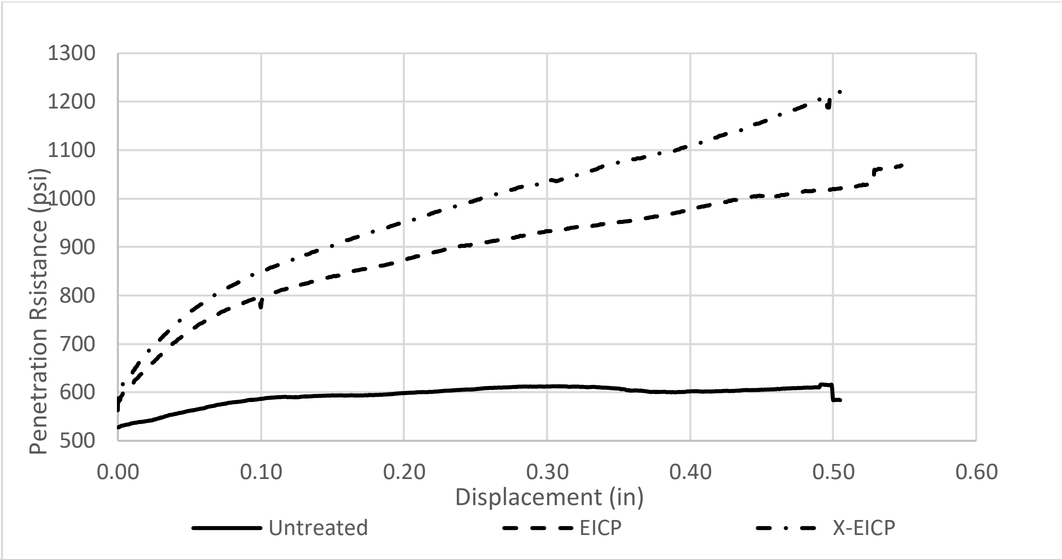

Figure 6. Average Penetration Resistance with Mix and Compact with Percolation Technique

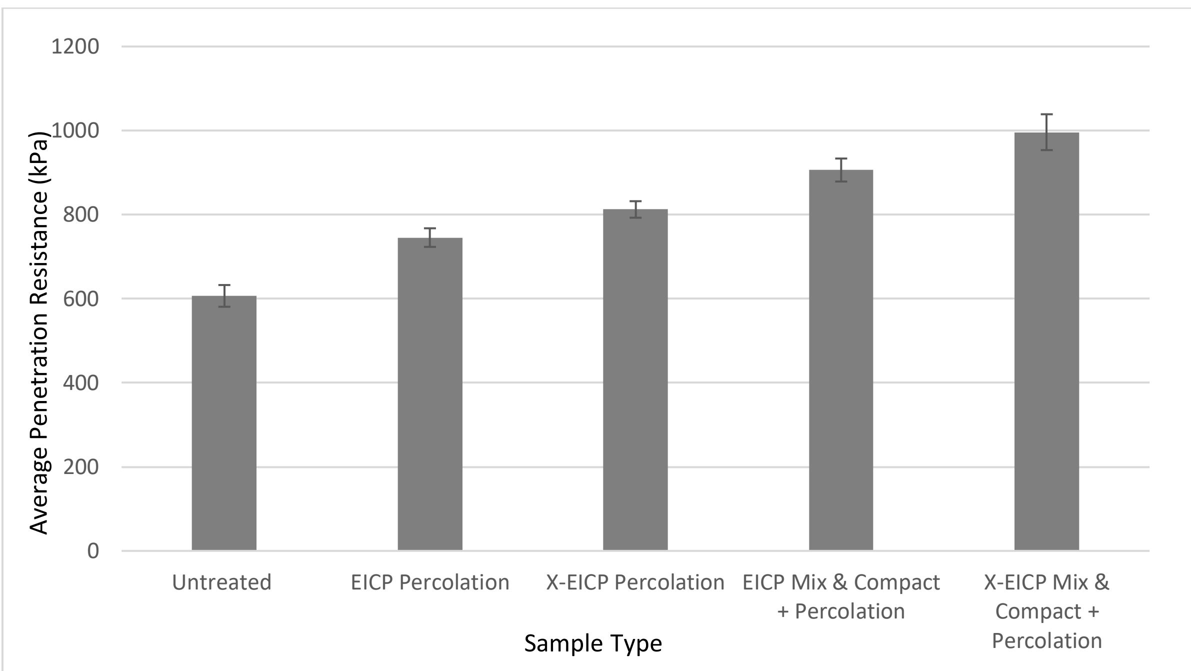

Figure 7. Average Penetration Resistance of Specimens at One Probe Diameter Displacement (0.25 in)

INTERPRETATION

Carbonate Content

The calcium carbonate content was the lowest in the untreated specimen and highest in specimen prepared with the EICP mix and compact with percolation technique. Less calcium carbonate was precipitated in the specimens prepared using X-EICP solution for both percolation and mix and compact with percolation compared to the specimens prepared using the EICP treatment.

Further testing is needed to understand why the addition of xanthan gum and the vegetable glycerin paste in the X-EICP recipe resulted in lower calcium carbonate precipitation.

Wind Erosion Resistance

For the percolation method, visual observations suggest that, because of the low permeability due to the soil's fines content, the calcium carbonate precipitated from the EICP treatment remains on the compacted soil surface, detached from the soil particles. This detachment leads to a weaker crust, resulting in lower erosion resistance than the untreated sample. In contrast, the xanthan gum-vegetable glycerin solution in the X-EICP treatment adhered more effectively to the compacted soil surface, providing the highest erosion resistance among all three specimens.

Unlike the percolation method, the results showed better adhesion, and hence erosion resistance, for the mix and compact specimen treated with EICP solution. We infer that the carbonate at the surface of the mix and compact specimens provided nucleation points leading to the better adhesion. Lower carbonate precipitation in X-EICP treated specimen could be attributed to its lower wind erosion resistance compared to the EICP treated specimen.

Penetration Resistance

The higher penetration resistance of the X-EICP treated specimens in both the percolation and mix and compact techniques can be attributed to xanthan gum binding finer-grained particles together,. However, this result contrasts with the observation of greater wind erosion resistance of EICP mix and compact specimen. One possible explanation is that the specimens exhibit greater compressive strength because more force is required to penetrate the detached EICP layer on top of both EICP and X-EICP mix and compact specimens. However, this same detached layer may be weaker with respect to wind erosion due to the lack of attachment. In addition, reduced carbonate precipitation in the X-EICP mix-and-compact specimen may have contributed to their lower wind erosion resistance compared to the EICP mix-and-compact specimens.

Further testing, including scanning electron microspore imaging, needs to be done to evaluate the morphology of the specimens and to understand the contributions of calcium carbonate and xanthan gum to penetration resistance of the specimens.

SUMMARY AND CONCLUSION

Four different pans treated with either EICP or X-EICP solutions using either the percolation method or a combination of mix and compact and percolation, along with one untreated pan as a control, were subject to testing for wind erosion resistance and penetration resistance to evaluate treatment effectiveness. The prepared specimens were also tested for their calcium carbonate content. The penetration resistance tests showed consistent trends, with X-EICP-treated specimen outperforming EICP treated specimen prepared using both the percolation only and mix and compact with percolation techniques. However, the PI-SWERL™ tests for wind erosion resistance presented somewhat contradictory results. Specimens prepared using EICP and percolation only exhibited the lowest wind erosion resistance. However, for the specimens prepared using mix and compact followed by percolation, the EICP treated specimen outperformed the X-EICP-treated specimen. Specimens prepared using EICP technique had higher carbonate precipitation compared to the X-EICP Technique. These tests serve as an initial comparison of the two treatment methods. The results highlight the need for further testing and analysis to better understand the unexpected results.

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