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Optimization of EICP Treatment Parameters for Dust Mitigation

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ABSTRACT

A series of laboratory tests were conducted to determine optimal treatment concentrations and deployment strategies for field implementation of enzyme-induced calcium carbonate precipitation (EICP). EICP offers the potential for cost-effective mitigation of fugitive dust in a more sustainable way than conventional dust suppression methods. Unsustainable practices associated with traditional dust suppression methods include spraying high volumes of potable water or salt solutions on the soil. EICP, a nature-inspired technology, creates a durable calcium carbonate ($CaCO_3$) crust on soil surfaces, improving soil resistance to dust formation. A series of 20 tests were conducted to explore the impact of different combinations of EICP treatment solution constituent concentrations (calcium chloride urea, milk powder, and crude urease enzyme) and sequence of application on EICP dust control effectiveness. The Portable In-Situ Soil Wind Erosion Laboratory (PI-SWERL^{TM}), penetrometer tests, and carbonate content measurements were used to assess the effect of constituent concentrations, treatment sequences, and number of treatment cycles on EICP performance. The experimental program employed a quasi-factorial design to obtain the optimal combination of parameters for field treatment, providing practical insight on deployment of EICP for fugitive dust mitigation.

INTRODUCTION

A series of laboratory tests were conducted to determine optimal enzyme induced carbonate precipitation (EICP) treatment concentrations and deployment strategies for fugitive dust mitigation. Dust events are recognized as major contributors to adverse air quality in Arizona, posing significant risks to human health and safety. These risks include respiratory issues and, in some cases, fatal traffic accidents (Joshi et al. 2021; Vergadi 2022; Henry 2023). Dust also serves as a transmission route for plant and animal pathogens (Finn et al. 2021). Enhancing surficial soil strength using carbonate precipitation via approaches like enzyme induced carbonate precipitation (EICP) in dust-prone soils has been suggested as an effective intervention for fugitive dust mitigation (Nemati et al. 2003; Hamdan and Kavazanjian 2016; Almajed 2018; Krajewska 2018; Song et al. 2020; Ahenkorah et al. 2021; Saif et al. 2022).

EICP is a nature-inspired bio-geotechnical/soil bio-cementation technology with several promising geotechnical applications, including the formation of surficial crusts to improve resistance to wind shear, thus mitigating fugitive dust. One approach for EICP involves using crude urease enzyme extracted from jack bean (*Canavalia ensiformis*) to catalyze hydrolysis of urea in an aqueous system (Khodadadi Tirkolaei et al. 2020). This reaction produces carbonate ions (CO_3^-) which, in the presence of calcium ions (typically from calcium chloride, $CaCl_2$), precipitate as calcium carbonate ($CaCO_3$) (Equation 1). Spraying or injecting the treatment solution into the soil improves the soil's physical and mechanical properties (Kavazanjian and Hamdan, 2015; Hamdan and Kavazanjian, 2016; Khodadadi Tirkolaet et al., 2017). Recent studies have shown that the addition of non-fat milk powder promotes $CaCO_3$ precipitation at interparticle contacts, thereby enhancing the strength gain from the precipitated carbonate (Krishnan et al. 2021).

$$CO(NH_2)_{2(s)} + CaCl_{2(s)} + 2H_2O_{(l)} \xrightarrow{Urease\ enzyme} CaCO_{3(s)} + 2NH_4Cl_{(s)} \qquad \text{Eq. 1}$$

A limited number of attempts have been made to scale up EICP for field implementation. Xu et al. (2023) explored the potential application of EICP to reinforce a 0.6-meter bedding layer over clay to improve the bearing capacity of the foundation beneath an underground cable duct. Washed sea sand was mixed with the EICP treatment solution and compacted in three layers, with additional EICP solution sprayed on the top surface after compaction of each layer. This effort resulted in a bedding layer with a dynamic deformation modulus (E_{vd}) of 31.7 to 50.55 MPa. Martin et al. (2024) demonstrated that EICP treatment, delivered via conventional tube-a-manchette pressure grouting, can be employed to create field-scale bio-cemented columns 0.3 to 1.0 meter in diameter with strength up to 500 kPa in just three days. These studies highlight that the application of EICP depends on factors such as the application rate, treatment solution concentration, and the number of application cycles.

Woolley (2023), in field tests at landfill sites in Arizona, reported that EICP shows promise as a method for fugitive dust mitigation. Achieving cost-effective dust mitigation at a large scale requires optimizing the key factors influencing EICP effectiveness. The objectives of this study were to explore the impact of different combinations of treatment solution concentrations, treatment application sequences, application rates, and number of treatment cycles, on crust strength and performance (wind shear resistance and suppression of particulate matter) against wind erosion.

MATERIALS AND METHODS

Soil. The soil samples used in this study were collected from dust-prone fallow agricultural land in Pinal County, Arizona. Index properties and particle size distribution of the soil are reported in Table 1. The fines component of the soil has a liquid limit of 27% and is non-plastic (as measured per ASTM D4318-05). The soil is classified as SM-SC, silty and clayey sand according to the Unified Soil Classification System (USCS). The soil displays minimal cohesion in a disturbed state, leading to susceptibility to wind erosion. The naturally occurring carbonate content of this soil, determined using an Eijkelkamp Calcimeter ranged from 4.02% to 4.45%. The soil has a pH value of 8 – 9 as measured per ASTM D4972.

Table 1. Soil Properties

D_{60}	0.4
D_{30}	0.13
D_{10}	0.05
% < #200 Sieve	15.56
Cu	8
Cc	0.85
Gravel %	11.5
Sand %	63.7
Silt %	15.53
Clay %	0.03
LL	27%
PI	NP
USCS Classification	SM-SC

Sample Preparation and EICP Treatment Solutions. Soil samples were prepared in metal pans 23 cm in diameter and 2.5 cm deep. Approximately 1.7-1.8 kg of air-dried soil was lightly compacted into each pan to a dry density of approximately 1.75 g/cm^3 and leveled off to create a smooth surface with minimal surface roughness prior to treatment application and/or assessment.

The EICP treatment solutions consisted of varied concentrations of urea, hydrated calcium chloride ($CaCL_2$), crude urease enzyme (extracted from jack bean), and non-fat milk powder. A crude urease enzyme solution with an activity of 10000 U/L was used in this study. The urease extraction followed the procedure described by Khodadadi Tirkolei et al. (2020).

Experimental Design/set-up. To achieve experimental objectives, an experimental design involving a range of treatment combinations was set up as detailed in Table 2. The experimental matrix was aimed at exploring the effects of urea and $CaCl_2$ concentrations and application rates across single and double treatment cycles to assess the resulting impacts on dust mitigation. For reasons of efficiency and economy, a single application of the treatment solution is preferred. However, experience suggested that spreading the same volume of treatment solution over multiple applications might be more effective. Therefore, the experimental matrix included single and double applications. Treatment requiring three applications was considered too burdensome for what is intended to be a one-and-done dust mitigation technique.

Three separate test scenarios were implemented. In the first scenario, three different single-application treatments (designated *A, B,* and *C*) were applied at an application rate of 2.4 L/m^2. In this scenario, treatment solution concentrations were varied from 1 M urea / 0.67 M $CaCL_2$ (Treatment A) to 1 M urea / 0.83 M $CaCL_2$ (Treatment B) to 1.5 M urea / 1.2 M $CaCL_2$ (Treatment C). The second scenario involved two applications of the treatment solution with varied application rates and combinations of urea and $CaCl_2$ concentrations, using the same concentrations for each application. These scenarios were designated as X-Y-Z, where X refers to the treatment concentration ratio and Y and Z refer to the application rates. For example, for treatment *A-1.2-1.2*, solution concentrations are the same as single treatment 'A' (1 M urea 0.67 M $CaCl_2$) and the application rate was 1.2 L/m² for both cycles. The third scenario used the treatment solution A concentrations for the first cycle followed by either solutions B or C for the second cycle with slightly lower application rates for the second cycle than used in Scenario 2 solutions. These treatments were designated A-Y-X-Z, where X refers to treatment concentrations for the second application (either B or C) and Y and Z are the respective application rates. Table 2 lists the various scenarios used in this study.

Table 2. Experimental Setup for EICP Optimization Testing[1]

Test Scenario	Notation	Urea (M)	$CaCl_2$ (M)	Total Dry Mass (g)	Number of Cycles	Application Rate (L/m^2)
Varied concentrations, single cycle, at a fixed application rate	A	1	0.67	15.8	1	2.4
	B	1	0.83	18.2	1	2.4
	C	1.5	1.2	26.6	1	2.4
Varied concentrations, two cycles with varied application rates per cycle	A-1.2-1.2	1	0.67	15.8	2	1.2
						1.2
	A-1.6-0.8	1	0.67	15.8	2	1.6
						0.8
	B-1.2-1.2	1	0.83	18.2	2	1.2
						1.2
	B-1.6-0.8	1	0.83	18.2	2	1.6
						0.8
	C-1.2-0.8	1.5	1.2	22.1	2	1.2
						0.8
Varied concentrations applied in two cycles with each cycle having varied application rate	A-1.2-B-0.8	1	0.67	14.0	2	1.2
		1	0.83			0.8
	A-1.2-C-0.8	1	0.67	16.8	2	1.2
		1.5	1.2			0.8

Note: 1. All treatment solutions used 4g/L of non-fat dry milk

***Test Procedures*.** Treatment effectiveness was assessed based upon measurements of Peak Friction Velocity (PFV), defined as the velocity at which soil particles are continuously suspended in the air stream, in combination with the maximum concentration of particles less than 10 μm in dimension (PM10), crust strength, and calcium carbonate content. These parameters were assessed using the following procedures.

Peak Friction Velocity (PFV) and Maximum PM10 concentration: The PI-SWERL™ (Portable In-Situ Wind Erosion Laboratory) was used to measure the dust emission potential of test samples. The rotational speed of a motorized annular blade in the top of a chamber placed over the specimen generates increasing levels of wind shear through stepwise increases of the rotational velocity of the blade from 0 to 6000 revolutions per minute (rpm) in 1000 rpm increments. Wind speed (friction velocity) and dust emissions (PM10 concentration) within the chamber are continuously measured. Peak Friction Velocity (PFV) was identified as the wind speed at which particles were continuously entrained and suspended in the chamber (differentiating it from the Threshold Friction Velocity (TFV), which corresponds to the wind velocity for detachment of loose particles). PFV was selected as the governing parameter as it represents terminal particle entrainment, avoiding confusion with initial faux particle mobilization observed at lower rpms due to antecedent loose particles.

Penetration resistance: As an index of surficial soil strength, a 6.4 mm diameter blunt-end probe attached to a loading frame was inserted into the specimens at a constant rate of 1.3 mm/min while the force and displacement are recorded. The peak force required to push the probe into the specimen is designated as the penetration resistance and is strongly correlated to surficial soil strength. In this study, the crust strength was defined as the average of the peak resistance recorded during penetrometer testing at three different locations on the sample surface.

Calcium carbonate content: Determining the calcium carbonate content of the soil using the Calcimeter involves reacting soil specimens with hydrochloric acid (HCl) and measuring the carbon dioxide (CO_2) gas released from the specimen. The released CO_2 gas is collected and measured using a calibrated chamber. The volume of gas is directly proportional to the amount of calcium carbonate in the soil. The result is calculated based on the gas volume and expressed as a percentage of the soil's calcium carbonate content.

Data Analysis. Test data (responses) are normalized using Equation 2 below, prior to creating parallel coordinate plots. Parallel coordinate plots are a graphical method for visualizing multivariate data, where each observation or data point is represented as a line that traverses a series of parallel axes, each corresponding to a specific variable or dimension. This arrangement enables the exploration of relationships, trends, and variations that may not be immediately apparent in raw data.

$$Normalized\ value = \frac{Original\ value - minimum\ value}{maximum\ value - minimum\ value} \quad \text{(Eq. 2)}$$

An optimal treatment is one that exhibits relatively higher normalized response values for PFV (m/s), crust strength (kPa), and $CaCO_3$ content (%), while maintaining a lower value for maximum PM10 concentration (mg/m^3). In this scenario, lower PM10 concentrations indicate greater resistance to wind erosion, as fewer soil particles are detached at the PFV. Higher values of PFV, carbonate content, and penetrometer readings reflect stronger soil resistance to erosion, demonstrating the effectiveness of the applied treatments.

RESULTS

Optimal Concentrations of Urea and $CaCl_2$ for Scenario 1. Table 3 presents the values for the total dry mass of the treatment solution, PFV, maximum PM10 concentration, crust strength, and carbonate content (%) across the three different Scenario 1 (single application) treatments. Treatment C demonstrated the highest performance across all four performance indicators. Treatment A demonstrated the lowest performance, with the highest PM10 concentration and lowest crust strength, although PFV was the same and carbonate content was nearly the same as Treatment B. These results make sense in that Treatment C had the highest concentrations of urea and $CaCl_2$ in the treatment solution and Treatment A had a lower $CaCL_2$ concentration than Treatment B. That Treatments A and B have essentially the same carbonate content suggests that the increased strength from Treatment B (compared to Treatment A) may be due to the increased salt content in the treatment solution. Figure 1 illustrates the normalized response values for the treatments listed in Table 3.

Table 3. Effect of Varied Concentration of EICP Treatment

Treatment	Total Dry Mass (g)	PFV (m/s)	Max PM10 Conc. (mg/m³)	Crust Strength (kPa)	Carbonate Content (%)
A: 1 M urea and 0.67 M $CaCl_2$	15.8	15	10.5	98	6.23
B: 1 M urea and 0.83 M $CaCl_2$	18.2	15	2.67	128	6.76
C: 1.5 M urea and 1.2 M $CaCl_2$	26.6	16	0.52	325	8.26

Notes: 1. Results are for one treatment cycle with 2.4 L/m² application rate
2. All treatment solutions used 4 g/L of non-fat dry milk

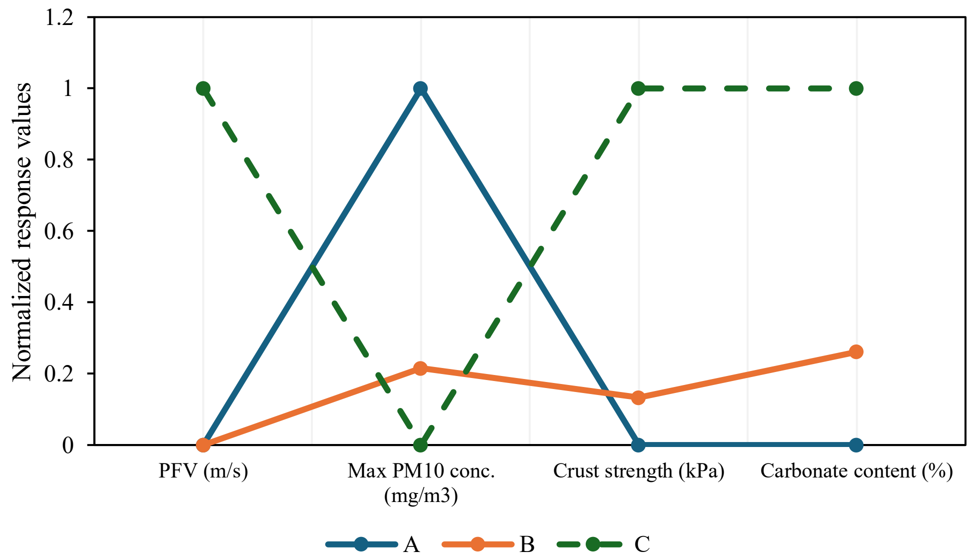

Figure 1. Normalized Response Values of the First Scenario (Single Cycle of Treatment)

Optimal Concentrations and Application Rates for Scenario 2. Table 4 presents the values for total dry mass of the treatment solution, PFV, maximum PM10 concentration, crust strength, and carbonate content across the five Scenario 2 EICP treatments. Treatment C-1.2-0.8, which applied 1.5 M urea and 1.2 M $CaCl_2$ in two cycles with application rates of 1.2 L/m² and 0.8 L/m² per cycle, demonstrated the best overall performance with respect to PFV and PM10, achieving the highest PFV (15 m/s) and the lowest PM10 concentration (0.468 mg/m³), though it has the highest dry mass. In contrast, treatment A-1.6-0.8 recorded the lowest PFV and crust strength and a relatively high PM10 concentration, indicating less effectiveness in resisting wind erosion. Figure 2 illustrates the normalized response values for these treatments, where C-1.2-0.8 consistently outperforms the other treatments, especially in PFV, PM10 concentration, and carbonate content. A-1.2-1.2 performed well with crust strength (580.60 kPa) and carbonate content (6.05%). While it did not surpass C-1.2-0.8 in effectiveness in term of wind erosion resistance, it had approximately 30 % less dry mass.

Table 4. Effect of Varied Concentration and Application Rates for Scenario 2 Treatments

Treatment	Total Dry Mass (g)	PFV (m/s)	Max PM10 Conc. (mg/m³)	Crust Strength (kPa)	Carbonate Content (%)
A-1.2-1.2	15.8	14.4	1.44	581	6.05
A-1.6-0.8	15.8	11	5.91	85	6.1
B-1.2-1.2	18.2	13.3	7.15	176	6.57
B-1.6-0.8	18.2	11.8	9.86	164	6.5
C-1.2-0.8	22.1	15	0.468	141	5.9

Note: 1. All treatment solutions used 4g/L of non-fat dry milk

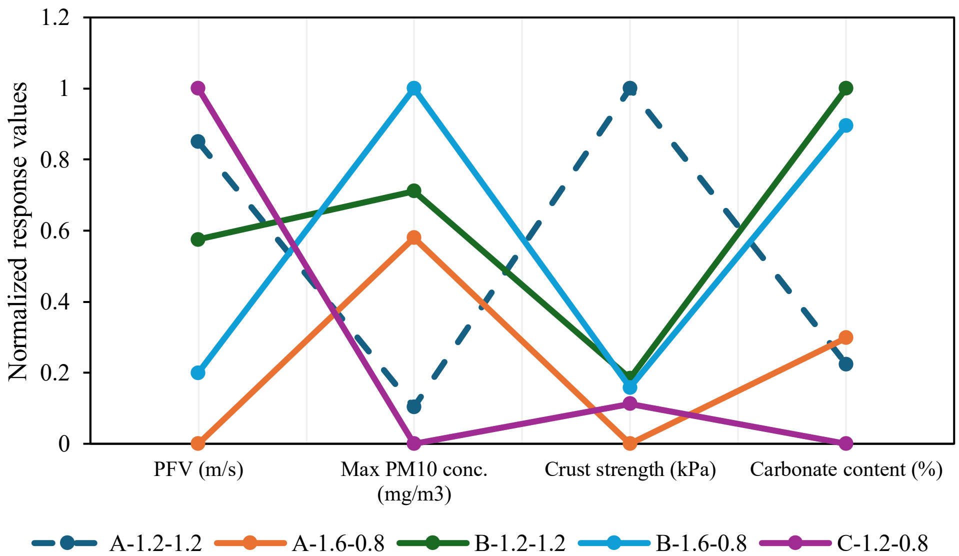

Figure 2. Normalized Response Values of the Second Scenario

Optimal Combination of Concentrations, and Application Rates for Scenario 3. Table 5 presents the response values for dry mass, PFV, maximum PM10 concentration, crust strength, and carbonate content for Scenario 3, which applied different urea and $CaCl_2$ concentrations in the two cycles of treatment. Treatment A-1.2-C-0.8 demonstrated superior performance, achieving the highest PFV (15 m/s), the lowest PM10 concentration (0.803 mg/m³), the greatest crust strength (283.65 kPa), and the highest carbonate content (8.03%). In contrast, with only marginally lower dry mass, A-1.2-B-0.8 exhibited lower PFV (12 m/s), a higher PM10 concentration (2.91 mg/m³), and lower crust strength (218.90 kPa), indicating reduced effectiveness in mitigating wind erosion. Figure 3 illustrates the normalized response values for these treatments, further highlighting the superior performance of A-1.2-C-0.8.

Table 5. Effect of Varied Concentrations per Treatment Cycle and Varied Application Rates

Treatment	Total Dry Mass (g)	PFV (m/s)	Max PM10 Conc. (mg/m³)	Crust Strength (kPa)	Carbonate Content (%)
A-1.2-B-0.8	14.0	12	2.91	218.90	6.11
A-1.2-C-0.8	16.8	15	0.803	284	8.03

Note: 1. All treatment solutions used 4 g/L of non-fat dry milk

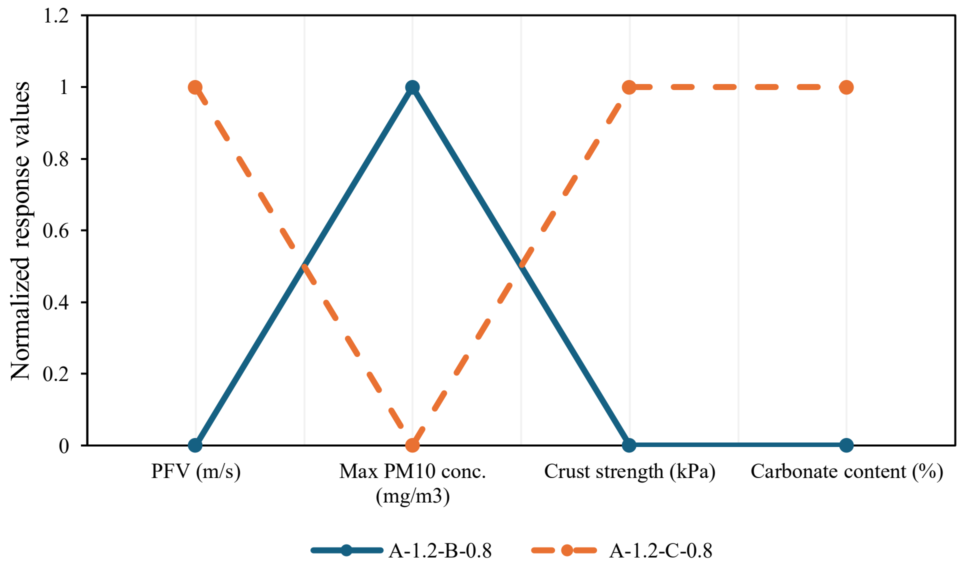

Figure 3. Normalized Response Values of the Third Scenario

CONCLUSION

Three optimization scenarios for EICP fugitive dust mitigation treatment solutions were explored in laboratory testing. The laboratory test program focused on the effects of varying concentrations of $CaCl_2$ and urea in the treatment solution combined with different treatment sequences, application rates, and number of treatment cycles. A range of different treatment solutions provided wind shear resistance of 11 to 16 m/s, crust strength of 85 to 325 kPa, CaCO3 content of 5.9 to 8.26%, and PM10 levels of 0.47 to 7.15 mg/m^3 with dry mass of solids between 14 and 22 g.

For Scenario 1, Treatment C, with a concentration of 1.5 M urea and 1.2 M $CaCl_2$ applied in one cycle at an application rate of 2.4 L/m², demonstrated the highest performance across all treatments in term of wind erosion resistance and the carbonate content percentage. However, it also had the highest solids content (upwards of 50% more than other treatments. Treatment A demonstrated the lowest performance, with the highest PM10 concentration and lowest crust strength, although PFV was the same and carbonate content was nearly the same as Treatment B. Therefore, Treatment A was considered optimal. For. Scenario 2, Treatment A-1.2-1.2 had the lowest dry mass and was second only to Treatment C-1.2-0.8 in PFV and PM10. However, Treatment C-1.2-0.8 has 30% more dry mass than Treatment A-1.2-1.2. Therefore, A-1.2-1.2 was considered optimal. For Scenario 3, both treatments have excellent performance but Treatment A-1.2-B-0.8 had lower solids content, so Treatment A-1.2-B-0.8 was considered optimal. Table 6 summarizes the optimal treatments. Based on the lowest PM10 and highest crust strength and comparable PFV to other alternatives in Table 6, Treatment A-1.2-1.2 may be the recommended treatment scenario for field deployment, although some engineers may prefer Treatment A as it requires only one treatment.

Table 6. Optimal Treatment Combinations and their Respective Response Values

"Best Cases"	Total Dry Mass (g)	PFV (m/s)	Max PM10 Conc. (mg/m^3)	Crust Strength (kPa)	Carbonate Content (%)
A	15.8	15	10.5	98	6.23
A-1.2-1.2	15.8	14.4	1.44	581	6.05
A-1.2-B-0.8	14.0	12	2.91	218.90	6.11

This study provides valuable practical insights into parameters and treatment combinations for EICP treatment to support field deployment of EICP for fugitive dust mitigation.

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