STUDY ON SHEAR RESPONSE OF BIOPOLYMER-MICP TREATED SAND-STEEL INTERFACES

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ABSTRACT

This paper explores the influence of introducing a natural biopolymer, gum of Prunus scoparia (P. scoparia), to Microbially Induced Calcite Precipitation (MICP) treated soil-steel interfaces. The conventional MICP method, involving low-rate injection of cementation solutions into the soil, faces limitations in terms of cost and practical applicability at a field scale. To address this, the natural biopolymer is incorporated into the MICP process, enabling simultaneous application of the cementation solution and gum without controlled injection rates. Through a series of modified direct shear tests, the study investigates the impact of the biopolymer addition to the cementation solution and its potential to reduce the dependency of shear strength parameters on the cementation solution injection rate in treated sand-steel interfaces. The results demonstrate a significant enhancement in shear strength when the biopolymer is introduced into the MICP-treated soil-steel interfaces, independent of the cementation solution's application rate. This innovative approach holds promise for achieving more efficient soil stabilization compared to the traditional MICP method.

1 INTRODUCTION

Indeed, the performance of various geotechnical structures such as floating piles, retaining walls, reinforced slopes, and embankments relies significantly on the response of the soil-steel interface. Therefore, enhancing the strength characteristics of the soil-steel interface is crucial in numerous geotechnical engineering projects. This importance underscores the potential value of adopting practical and environmentally friendly approaches like Microbially Induced Calcium Carbonate Precipitation (MICP) as an alternative to conventional soil improvement techniques, including cement-based and chemical grouting ground improvement methods.

The microbially induced calcite precipitation (MICP) method offers an eco-friendly approach to strengthen the soil-steel interface. It serves as an alternative to traditional stabilization methods such as cement-based and chemical grouting. The MICP method employs urease enzymes to catalyze urea hydrolysis, accelerating the chemical reaction by up to 1000 times compared to uncatalyzed rates. This results in the precipitation of calcium carbonate ($CaCo_3$) within soil voids and on particle surfaces. Various bacterial species, including Sporosarcina pasteurii, Bacillus megaterium, and Bacillus subtilis, serve as biological catalysts in the bio-cementation process.

The bio-cementation process involves specific chemical reactions illustrated in Figure 1 for a granular soil-steel interface. To initiate the process, urea and a calcium source (calcium chloride) are introduced to the soil medium using a cementation solution. Additionally, bacteria are added to the soil medium through a bacterial solution. The MICP process results in the creation of calcium carbonate, also known as bio-cement, that forms between the soil particles. Earlier research has demonstrated that the formation of bio-cement between the soil particles and steel within the soil-steel interface plays a crucial role in enhancing the shear strength properties at that interface (Bak et al., 2021; Sharma and Satyam, 2021).

Earlier research on the MICP technique indicates that applying cementation solution at rates below 10-40 cm/hr leads to the creation of more uniform and superior-quality bio-cemented soil samples. These samples are characterized by well-developed calcite crystals (Whiffin et al., 2007; Mortensen et al., 2011; Cheng et al., 2013). Consequently, injecting cementation solution into one cubic meter of sandy soil could take between 2.5 to 10 hours, presenting challenges related to equipment and labor costs, as well as the implementation time for practical MICP soil stabilization projects.

This study focuses on evaluating the potential of Zedo gum, a water-absorbent biopolymer (Rahimi and Abbasi, 2012), as an additive to the MICP method. The utilization of Zedo gum in this study is motivated by its exceptional water-absorption capacity, as demonstrated by Rahimi and Abbasi (2012), which enables it to effectively address concerns related to calcium solution applying rates impacting the strength parameters of MICP-cemented soil samples. Zedo gum, harvested from Prunus scoparia Spach in Fars province in Iran, forms biofilm networks when combined with cementation solution simplifing the application process by eliminating the need for precise injection rate monitoring. Therefore, it leads to time savings and can improve efficiency in implementing MICP method for soil stabilization projects. Additionally, Zedo gum exhibits soil-stabilizing properties, as seen in previous studies (DABESTANI et al. 2018; Khalesi et al., 2012). While other natural biopolymers (like, Arabic and Xanthan gum) and synthetic materials (like, polyacrylamides) could be considered, the unique combination of properties offered by Zedo gum and MICP reactions makes it a compelling choice for this study.

The objective is to mitigate the impact of cementation solution application rate and enhance the practicality of the MICP method for interface improvement. To accomplish this goal, a series of modified direct shear tests were conducted on soil-steel interfaces, and the shear strength parameters of the soil-steel interface, namely the friction angle and cohesion, are estimated. These parameters offer valuable insights into the effects of the MICP method on the shear response of the soil-steel interface.

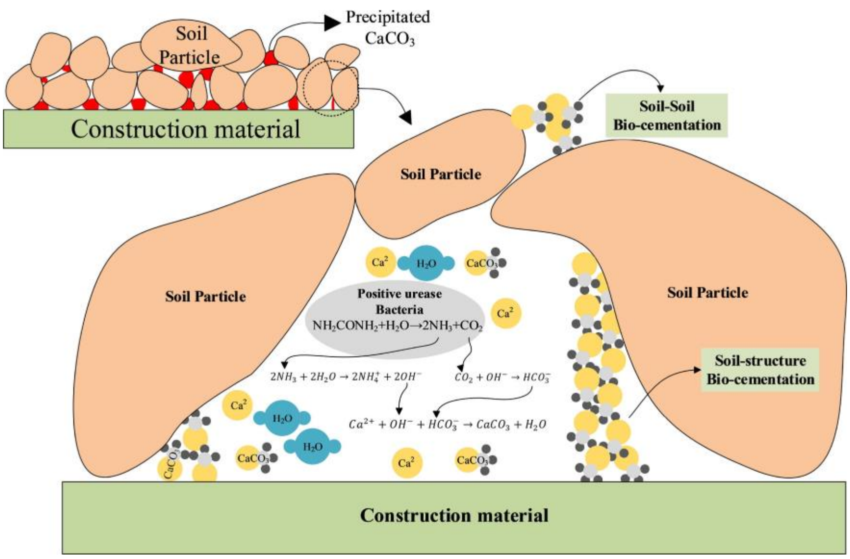


Figure 1: Bio-cementation process in the soil-steel interface (Bak et al., 2021)

2 MATERIAL AND METHODS

This section will initially present the characteristics of the soil and soil-steel interface, followed by a discussion on the preparation of cementation solutions, bacterial solutions, and gum solutions.

2.1 SOIL

In all the tests, a poorly graded sand (SP) was employed. The gradation curve of the soil can be observed in Figure 2. All samples were prepared at a relative density of 30%. Minimum Unit Weight and specific gravity of the soil was 14.2 kN/m^3 and 2.76, respectively.

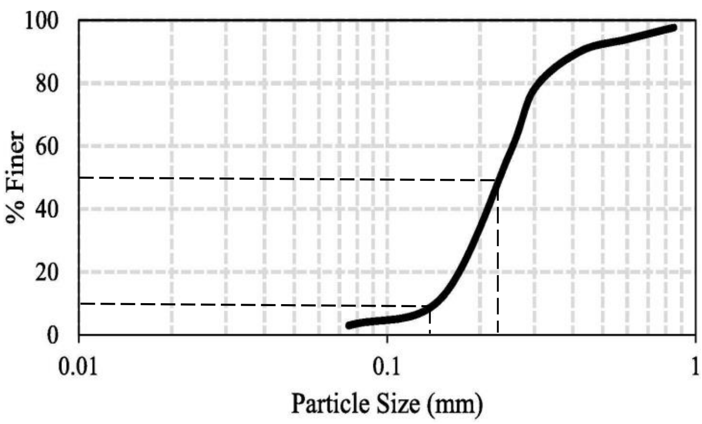


Figure 2: Grain size distribution of the SP sand

2.2 INTERFACE MATERIALS

In this study, a 4 mm thick ST37 steel plate was utilized to examine the interface shear strength. Figure 3 displays the surface profile of the steel plate, which was measured using the Mitutoyo SURFTEST SJ-210 portable surface roughness tester. In Figure 3, The parameter denoting the maximum peak-to-valley distance of the surface profile is referred to as R_{max}. Uesugi and Kishida (1986) introduced the normalized surface roughness (R_n) as a parameter to quantify the roughness of the soil-interface system. It involves normalizing R_{max} against the mean grain size of the interface soil, as represented by the following equation:

$$R_n = {}^{R_{max}}/_{D_{50}} \quad \textbf{(1)}$$

The normalized surface roughness (R_n) has been widely employed by scholars as a reliable measure to assess the roughness of soil-steel interfaces (Mortazavi Bak et al., 2021; Su et al., 2018). Previous studies have shown that practical R_n values often exceed 0.05. A soil-construction material interface is typically considered rough when R_n is greater than 0.1-0.15, depending on particle size and shape.

In this study, the soil's D_{50} value was 0.21 mm, and the soil-steel interface's R_{max} was 0.05 mm, resulting in R_n > 4, which falls well within the range of rough interface systems.

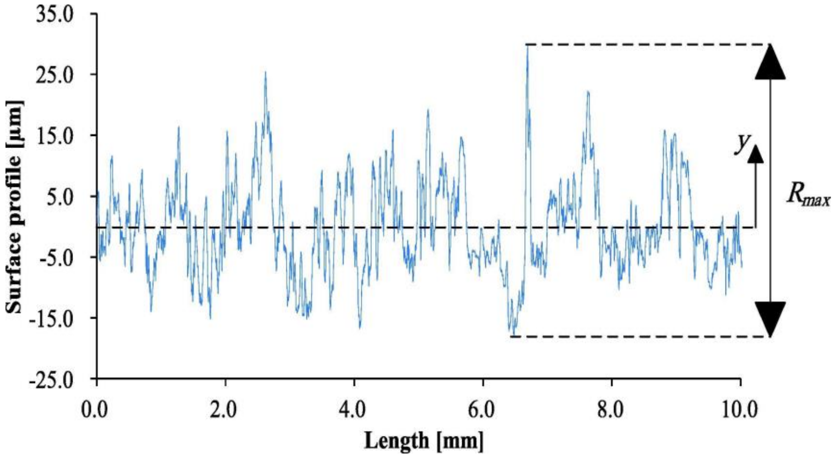


Figure 3: The surface profile of the steel plate sample (Bak et al., 2021)

2.3 PREPARATION OF CEMENTATIN, BACTERIAL, AND GUM SOLUTIONS

In this study, the *S. pasteurii* strain (PTCC 1645) was employed as a suitable urease bacteria for MICP method (Mukherjee et al., 2019; Khaleghi and Rowshanzamir, 2019; Ng et al., 2012; Whiffin, 2004), and the average bacterial population during the stationary phase was 10^9 per ml. The pH was initially set to 7 in an enriched Nutrient Broth (NB) culture medium with urea for MICP, following previous research (Bak et al., 2021). After cultivation, bacteria were collected, washed, and reintroduced into a fresh medium (Wu et al., 2019; Stocks-Fischer et al., 1999; Bak et al., 2021). Equimolar Calcium Solutions with 1 mol/lit concentration of urea and calcium chloride were prepared, following previous studies (Al Qabany et al., 2012; Bak et al., 2021). To prepare the gum solutions, Zedo gum was prepared by grinding, sterilizing, and mixing with water at concentrations of 10mg/ml using a magnetic mixer (60°C, 150 rpm) for two hours.

3 XPERIMENTAL PROGRAM

3.1 MODIFED DIRECT SHEAR TEST

A large-scale direct shear test apparatus, with the sample size of 300 mm×300 mm, was utilized to investigate the soil-steel interface response under the influence of bio-cementation, as depicted in Figure 4. Both standard direct shear tests and modified interface direct shear tests were conducted following ASTM D5321 and ASTM 3080 standards, respectively. In the soil-steel interface tests, a five-legged steel plate (illustrated in Figure 4) was substituted for the soil in the lower part of the box.

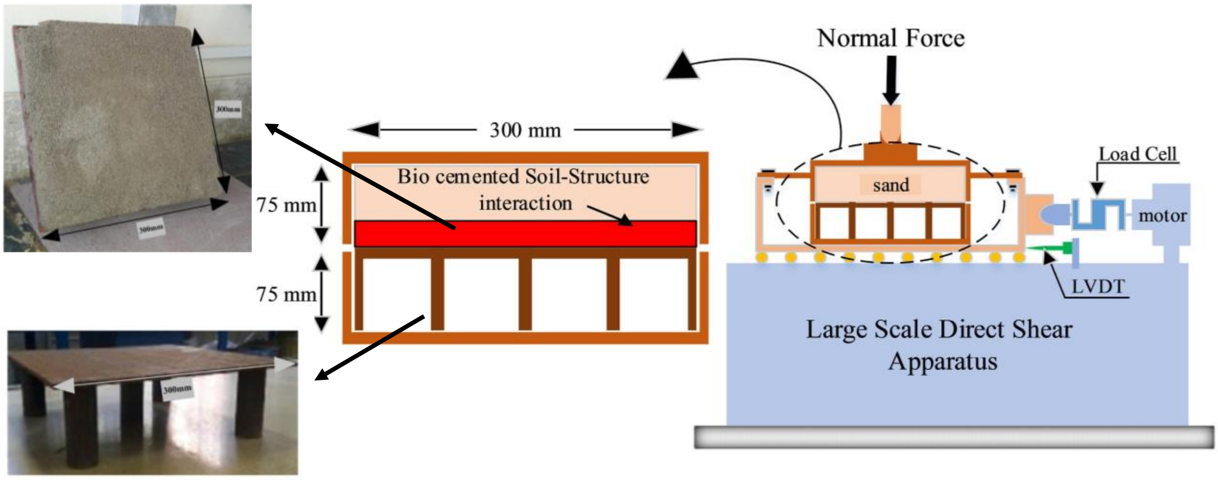


Figure 4: Modifeid direct shear box

3.2 SAMPLE PREPARATION AND TEST PROGRAM

In this study, the soil was placed onto the steel interface, carefully adjusting the desired void ratio and thickness depending on the type of the sample. The next step involved spraying the bacterial solution onto the soil-steel interface sample with a volume equal to the soil void volume (V_v) using hand sprayer. After allowing an hour of rest, a mixture of cementation solution and gum solution was sprayed onto the soil specimen. For samples without gum solution, only cementation solution was sprayed. The spraying volumes were set to V_v for cementation solutions and 0.25 V_v for gum solution, determined according to the experimental plan. After a retention time of 24 hours, another mixture of gum solution and cementation solution was sprayed onto the soil-steel interface systems, with volumes of 0.5 V_v and 0.125 V_v, respectively. The samples were then cured for 14 days before conducting the shear tests. To eliminate the potential impact of suction on the shear strength results, the G-MICP-treated soil-steel interface systems were dried in an oven.

In the current study, 9 different test conditions presented in Table 1 are considered. Table 1 categorizes the samples as U (untreated), M (MICP treated), and BM (biopolymer-MICP treated). The numbers following the letters represent the respective normal stresses applied during the tests. For example, BM100 means a biopolymer-MICP treated sample subjected to a normal stress of 100 kPa. In each test condition, a total of three samples were prepared, and each sample was subjected to a constant normal stress of 50 kPa, 100 kPa, and 150 kPa.

Table 1. Experimental program of the soil-steel interfaces

Set	Experiment	Concentration ratio of urea (mol/litre)	Concentration ratio of $Cacl_2$ (mol/litre)	Spraying rate ($cm^3/h/cm^2$)	Gum Concentration (mg/ml)	Normal Stress (kPa)
A	U50	-	-	-	-	50
	U100	-	-	-	-	100
	U150	-	-	-	-	150
B	M50	1	1	5	-	50
	M100	1	1	5	-	100
	M150	1	1	5	-	150
C	BM50	1	1	10	10	50
	BM100	1	1	10	10	100
	BM150	1	1	10	10	150

3.3 SOIL STRENGTH PARAMETERS

In Mohr-Coulomb shear failure criterion, the interfacial shear strength parameters, denoted by δ and c_m, represent the interfacial friction angle and cohesion, respectively. These parameters have been widely used previously to characterize the shear strength behaviour of soil-construction material interfaces. The following equation defined the relationship between the shear stress and normal stress at the modified direct shear test:

$$\tau_{pm} = c_m + \sigma_{nm} \tan(\delta) \quad \textbf{(2)}$$

where τ_{pm} and σ_{nm} are the peak shear stress and the normal stress (i.e., 50, 100, and 150 kPa) in the direct shear tests or modified direct shear tests.

The interface efficiency factor (IEF) is also defined as the ratio of the peak shear stress of the treated sample to the peak shear stress of the untreated sample at a specific normal stress (Bak et al., 2021). Accordingly, IEF can be calculated by the following formula:

$$IEF = \tau^{t}_{pm} / \tau^{u}_{pm} = (c^{t}_{m} + \sigma_{nm} \tan(\delta^{t})) / (c^{u}_{m} + \sigma_{nm} \tan(\delta^{u})) \quad \textbf{(3)}$$

where superscripts t and u stand for treated and untreated, respectively. Based on Equation 3, a more successful bio-cementation process yields a higher IEF. This parameter is employed in this study to compare the test results in terms of the gain in the interface shear strength due to bio-cementation.

4 RESULTS AND DISCUTION

By utilizing the test results from experiment sets A, B, and C, it is possible to determine the friction angle and cohesion of the untreated samples, MICP treated samples, and biopolymer-treated samples. The subsequent sections will focus on discussing the influence of MICP treatment and the addition of gum on the strength characteristics of the soil-interface. Table 2 summarises the results of the interfacial shear strength parameters of samples.

Table 2. Interfacial shear strength parameters of samples

Sample	Interfacial friction angle (°)	Cohesion (kPa)
untreated soil-steel interface	24.8	0
MICP treated soil-steel interface	42.3	112.5
Biopolymer-MICP treated soil-steel interface	42.6	120.6

4.1 FRICITON ANGLE

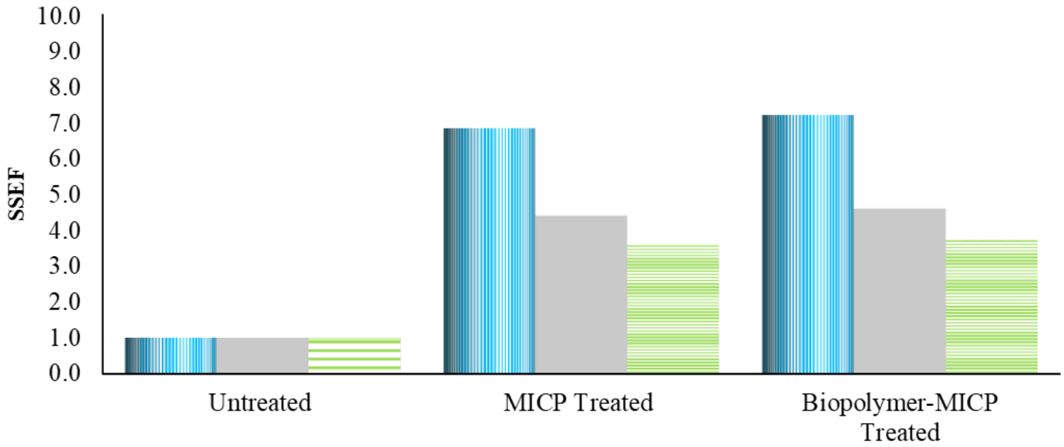
Analysing the test results based on the Mohr-Coulomb shear failure criterion and using Equation 2 reveals that the friction angle of the untreated soil-steel interface was measured at 24.8°. However, after the MICP treatment, the peak friction angle increased to 42.3°, and with the biopolymer-MICP treatment, it further increased to 42.6°. This indicates that the addition of a very low concentration gum solution allows for a twofold increase in spraying rate, while still achieving a higher friction angle compared to the MICP treated samples.

4.2 COHESION

Upon analysing the test results as described in the previous section, it was found that the cohesion values for the MICP treated samples and biopolymer-MICP treated samples were 112.5 kPa and 120.6 kPa, respectively. These findings were consistent with the results of the friction angle, indicating that the addition of a very low concentration of Zedo solution can reduce the influence of spraying rate on the shear strength parameters.

4.3 INTERFACE ENHANCEMENT FACTOR

In this section, the results of the friction angles and cohesions are utilised to further investigate the interface shear strength of samples under different normal stresses in terms of interface enhancement factor using Equation 3. As shown in Figure 5, biopolymer-MICP treated samples exhibit higher interface enhancement factors (IEF) at various stress levels, which aligns with the findings from previous sections. Additionally, Figure 5 demonstrates that the treatment's effect is more pronounced at lower stress levels, consistent with previous studies (Bak et al., 2021).



	Untreated	MICP Treated	Biopolymer-MICP Treated
50 kPa	1.0	6.8	7.2
100 kPa	1.0	4.4	4.6
150 kPa	1.0	3.6	3.7

Figure 5: IEF of the samples at different stress levels

5 CONCLUSIONS AND RECOMMENDATIONS

The impact of adding gum to the MICP treated soil-steel interfaces has been explored. To this end, a series of modified direct shear tests were conducted, and the results were analysed based on the Mohr-Coulomb shear failure criterion. The findings indicated that the biopolymer-MICP treated samples exhibited higher friction angle and cohesion compared to the MICP treated samples, even with lower spraying rates. Moreover, by incorporating very low concentration gum solutions and doubling the spraying rate, the interface enhancement factor (IEF) increased from 6.8 to 7.2, rendering the MICP method more practical and promising for engineering applications.

The results of this study indicated that the incorporation of gum into the bio-cementation process reduces the sensitivity of the shear strength parameters to the spraying rate variations at the interfaces. Using higher spraying rates is more feasible for field applications of the MICP method, enhancing practicality.

While this study demonstrated the efficacy of biopolymer-MICP treatment, further investigations are needed to thoroughly examine the type of the crystals precipitated between the soil particles, durability and CO_2 emission reductions of this method in comparison to conventional methods, and influence of environmental conditions, soil type, and other relevant parameters to gain a comprehensive understanding of the process.

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