

Biocomposite treatment for sand: enhancing shear strength and reducing carbon emissions

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ABSTRACT: Conventional grouting techniques for ground improvement frequently generate excessive carbon emissions and raise serious concerns about environmental sustainability. As an eco-friendly bio-grouting technique, microbially induced calcium carbonate precipitation (MICP) can efficiently reinforce soil; however, its effectiveness requires further optimization. In response, hydrogel, a polymer material capable of forming a three-dimensional network gelling structure through cross-linking, not only reinforces soil but also holds potential to synergize with MICP for biocomposite treatment. This study investigates the synergy between two hydrogels (pectin and guar gum) and MICP by injecting varying concentrations (0.05%, 0.1%, and 0.2%) of hydrogels for biocomposite treatment of sand. Unconsolidated undrained triaxial tests were conducted to evaluate the shear strength of biocomposite-treated specimens, scanning electron microscope tests were employed to examine their microstructure, and carbon emissions were analyzed. The main findings are: (1) Biocomposite-treated specimens exhibit significantly higher shear strength compared to MICP-treated specimens. With increasing hydrogel additions, the peak strength of specimens treated with pectin increases, whereas it declines in specimens treated with guar gum. (2) Microstructural analysis reveals the formation of hydrogel-calcite biocomposite bonding between the sand particles, tightly connecting adjacent particles, which is key to the biocomposite treatment. (3) Carbon emissions analysis indicates that biocomposite treatment achieves better carbon efficiency than MICP alone. Given its enhanced sustainability and significantly improved shear strength over MICP treatment, biocomposite treatment provides valuable insights for developing more effective and sustainable ground improvement methods.

KEYWORDS: Microbially induced calcium carbonate precipitation; hydrogel; shear strength; synergistic effect.

1 INTRODUCTION

Conventional grouting method for ground improvement are associated with significant energy consumptions, substantial carbon emissions, and potential environmental pollution (Madloul et al., 2011; Bing et al., 2023). These issues highlight the urgent need for more sustainable and eco-friendly ground improvement methods (Mitchell and Santamarina, 2005). As an eco-friendly bio-grouting techniques, microbially induced calcium carbonate precipitation (MICP) has gained attentions as sustainable alternatives (DeJong et al., 2010). Utilizing urea hydrolysis of urease bacteria, MICP produces calcium carbonate precipitation (CaCO_3) within soil, effectively enhancing its permeability (Chen et al., 2023), shear strength (Zhao et al., 2025), compressive strength (Liufu et al., 2023), liquefaction resistance (Shan et al., 2025), erosion resistance (Yang Xiao et al., 2022), and small strain dynamic properties (Shan et al., 2022). However, large-scale applications of MICP have shown diminishing returns. After multiple cycles of MICP treatment, carbon emissions increases, whereas the mechanical improvements of the soil become increasingly marginal.

In this regard, as a type of biopolymers with the ability of forming a stable three-dimensional network gelling structure (Maitra and Shukla, 2014), hydrogel has been proven its effectiveness in soil improvement (Reza and C., 2013; Chang et al., 2015). Moreover, as some hydrogels are derived from plant or bacterial sources (such as the pectin and guar gum used in this study), their production processes are associated with low carbon emissions. Synergy of soil using hydrogel and MICP offers a highly efficient and low-carbon pathway for further soil improvement (Dubey et al., 2022; Xiao et al., 2025). Therefore, this study injected 0.05%, 0.1%, and 0.2% of pectin and guar gum, respectively, to synergize with MICP for biocomposite treatment of sand column specimens. Specifically, in order to exclude significant effects of water content on the mechanical contribution of hydrogel, unconsolidated undrained (UU) triaxial tests were conducted to evaluate the shear strength of the specimens. Scanning electron microscope (SEM) tests

were employed to examine their microstructure, and carbon emissions were analyzed. By revealing the feasibility of biocomposite treatment, this work provides valuable insights for developing more effective and sustainable ground improvement methods.

2 MATERIALS AND METHODS

2.1 Materials

In this study, the test sand used was ISO standard sand (Fujian, China). Its distribution of grain size is shown in Figure 1, and its detailed physical properties are provided in Table 1. The two hydrogels of pectin (CAS: 9000-69-5) and guar gum (CAS: 9000-30-0) are presented in Figure 2. Pectin is a soluble polysaccharide found in fruits (Thakur et al., 1997), while guar gum is a galactomannan polysaccharide extracted from guar beans (Thombare et al., 2016).

The urease bacteria strain adopted in this study was *S. pasteurii* ATCC 11859. The bacterial solution was prepared by cultivating and augmenting *S. pasteurii* (see details in Shan et al., 2025). The components of MICP treatment solutions are listed in Table 2. The bacterial concentration, expressed as the optical density at 600 nm (OD_{600}), was measured by a spectrophotometer and maintained at 1.5 ± 0.3 . Urease activity was measured by an electrical conductivity meter. The specific urease activity was calculated by dividing the urease activity by OD_{600} and restricted at 4.0 ± 0.5 mM urea hydrolyzed- $\text{min}^{-1} \text{OD}_{600}^{-1}$.

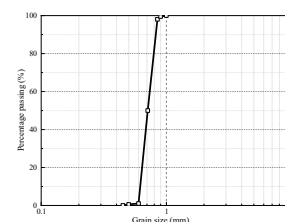


Figure 1. The curve of grain size distribution.

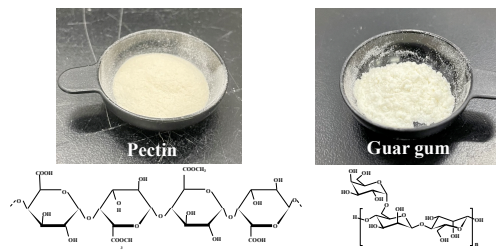


Figure 2. The two hydrogels of pectin and guar gum.

Table 1. The physical parameters of the test sand.

| G_s | D_{50} (mm) | C_u | C_c | e_{max} | e_{min} |
|-------|---------------|-------|-------|-----------|-----------|
| 2.65 | 0.71 | 1.185 | 0.965 | 0.893 | 0.616 |

Table 2. The components of MICP treatment solutions.

| Component | Stimulation | Augmentation | Cementation |
|--------------------|-------------|--------------|-------------|
| TSA | 40 g/L | | |
| Urea | 333 mM | | 500 mM |
| Yeast extract | | 20 g/L | |
| NH ₄ Cl | | 150 mM | |
| NaOH | | 40 mM | |
| CaCl ₂ | | | 500 mM |

2.2 Specimen preparations

The sand column specimens were prepared at a relative density (D_r) of 40% using dry deposition method. The test sand was divided into four equal portions by mass, which were then sequentially poured into a polyvinyl chloride cylinder mold ($D \times H = 38 \text{ mm} \times 76 \text{ mm}$). In this manner, a sand column specimen consisting of four uniform layers was obtained. Then, pectin and guar gum powders were added into the prepared cementing solution (see Table 2) according to the ratio of hydrogel mass to solution volume. Specifically, 0.05%, 0.1%, and 0.2% of hydrogels were gradually added and thoroughly stirred into 40 mL of the cementing solution, respectively. The hydrogel concentrations (0.05%~0.2%) were chosen based on preliminary trials, representing an optimal range balancing a measurable synergistic effect (negligible below 0.05%) and practical groutability (hindered by pore clogging above 0.2%).

Two-phase grouting method was chosen to ensure homogeneous treatment via controlled, uniform solution distribution. Initially, a single injection of bacterial solution was applied from the top of the specimen using a peristaltic pump. After a resting period of 6 hours, twelve injections of cementing solution were made at 12-hour intervals. The specimen was rotated after every two injections, and the solutions were injected from the opposite end. Each injection volume was 40 mL, corresponding to one pore volume of the specimen. After grouting, the specimens were placed in an oven at 50°C for about 72 hours, then rest at room temperature for 7 days.

2.3 UU triaxial tests

The high water content significantly affects the mechanical performance of specimens treated with hydrogel (Chang et al., 2015; Bozyigit, Javadi and Altun, 2021). To exclude significant effects of water content, thus enabling a direct and accurate assessment and comparison of the enhancement effects of different hydrogels, the UU test was adopted and carried out on a GDS triaxial instrument DYNTTS (GDS Instruments LTD., UK). Following ASTM-D2850 (2015) guidelines, the pressure chamber of the triaxial apparatus was sealed after specimen installation, and a 20 kPa confining pressure was applied to protect the specimen. Subsequently, UU triaxial tests under the confining pressure of 100 kPa were conducted on biocomposite-treated specimens. A 15% shear axial strain was

defined as the threshold for shear damage, and the shear rate was set at 0.5%/min.

2.4 CaCO₃ determinations and carbon analysis

The CaCO₃ content of the specimen was determined through dissolution using HCl. The specimen was first rinsed with distilled water, dried, and weighed (denoted as m_0). Subsequently, 1 M HCl was added to dissolve the CaCO₃ precipitation. After repeating filtration and rinsing, the specimen was dried again and weighed (denoted as m). The CaCO₃ content (CC) was calculated using the following equation:

$$CC = \frac{m_0 - m}{m_0} \times 100\% \quad (1)$$

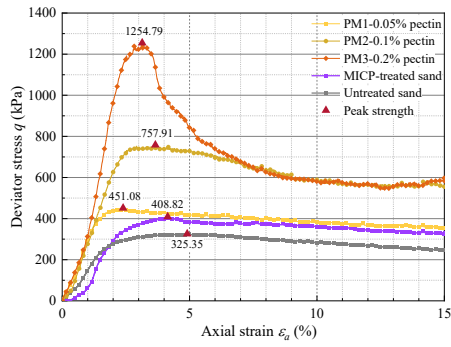
According to relevant life cycle assessment studies, the MICP process generates 3.40 g carbon dioxide equivalent (CO₂e) per gram of CaCO₃ produced (Deng et al., 2021). And the production of one gram of pectin and guar gum emits 9.69 g and 2.52 g CO₂e, respectively (Nadar, Arora and Shastri, 2022; Antonanzas et al., 2023). Therefore, the carbon emissions associated with biocomposite and MICP treatments were estimated based on the mass of CaCO₃ and hydrogel. Moreover, the term of strength-to-carbon efficiency (E_c) is introduced to evaluate the relationship between strength gain and carbon emissions. E_c is defined as the ratio of the peak strength increment (q_{in} , kPa) of treated specimens over untreated sand to the corresponding carbon emissions (CO₂e, g). It is worth noting that referencing carbon emission data from diverse studies introduces inherent uncertainty regarding system boundaries; however, the calculated results sufficiently reflect the trends in E_c associated with hydrogel addition.

3 RESULTS

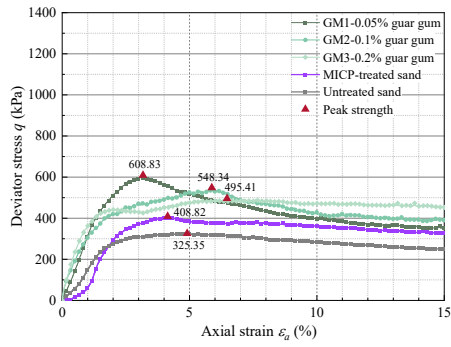
3.1.1 UU triaxial test results

The results of UU triaxial tests are provided in Table 3. Figure 3 presents the stress-strain relationship of the biocomposite-treated specimens, as well as MICP-treated and untreated sand for comparison. As shown in the figure, the biocomposite-treated specimens achieve higher shear strength than MICP-treated sand, indicating that the addition of hydrogel further enhances the improvement effect of MICP.

In comparison with the two hydrogels, pectin exhibits better synergy with MICP. The strength of the specimens treated with pectin (PM) increases as the hydrogel amount increases, while that of the specimens treated with guar gum (GM) decreases. At 0.2% pectin addition, the PM specimens achieve the highest peak strength, and the GM specimens achieve it at 0.05% guar gum addition. Conversely, the CaCO₃ content decreased with increasing hydrogel addition. This indicates that for biocomposite-treated specimens, CaCO₃ content is not the sole determinant of strength. The mechanical enhancement provided by the hydrogel outweighs its inhibitory effects on CaCO₃ precipitation and cementation. Furthermore, the peak strength of the PM specimens is higher than of the GM specimens at each hydrogel addition. These results indicate that pectin is more compatible with MICP than guar gum. But with the both hydrogel addition, biocomposite treatment can achieve the better improvement than MICP treatment.



(a) Pectin



(b) Guar gum

Figure 3. Stress-strain relationship of the biocomposite-treated specimens.

Table 3. UU triaxial test results of the biocomposite-treated specimens.

| Hydrogel | Specimen | Addition (%) | Peak strength (kPa) | CaCO ₃ content (%) |
|----------|--------------|--------------|---------------------|-------------------------------|
| Pectin | PM1 | 0.05 | 451.08 | 9.37 |
| | PM2 | 0.1 | 757.91 | 8.60 |
| | PM3 | 0.2 | 1254.79 | 7.17 |
| Guar gum | GM1 | 0.05 | 608.83 | 10.10 |
| | GM2 | 0.1 | 548.34 | 8.48 |
| | GM3 | 0.2 | 495.41 | 8.03 |
| Control | MICP-treated | 0 | 408.82 | 8.64 |
| | Untreated | 0 | 325.35 | 0 |

3.1.2 Carbon emission analysis

Figure 4 illustrates the relationship between strength increment and carbon emissions for the biocomposite-treated and MICP-treated specimens. The value of E_c is represented by the diameter of the data points (balls) in the figure, a larger ball indicates higher strength gain efficiency relative to carbon emissions. As shown in the figure, the comparison between biocomposite-treated and MICP-treated specimens (M-1) indicates that the biocomposite treatment achieves higher E_c than MICP treatment. In comparison with the biocomposite-treated specimens incorporating guar gum, those incorporating pectin exhibit higher E_c at the same addition levels. Moreover, the E_c of pectin-treated specimens increases with the pectin content, reaching a peak at 0.2% addition, while the E_c of guar gum-treated specimens decreases as the guar gum content increases.

These results suggest that biocomposite treatment is more efficient than MICP treatment alone in enhancing shear strength while causing less carbon emission. Furthermore, pectin addition demonstrates superior strength-to-carbon efficiency compared to guar gum. Among two hydrogels and addition levels tested, the biocomposite treatment with 0.2% pectin achieves the highest strength-to-carbon efficiency.

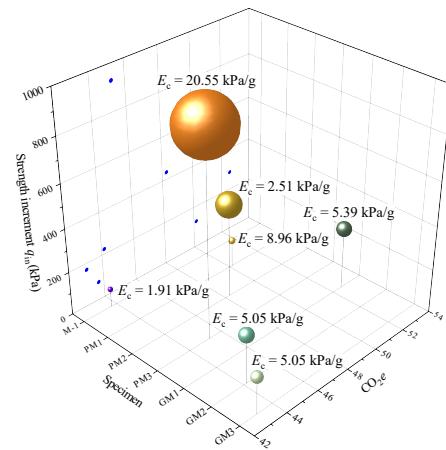
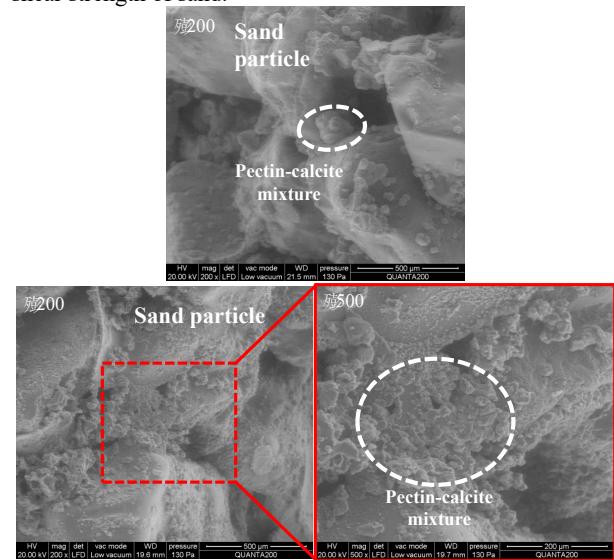


Figure 4. Result of strength-to-carbon efficiency.

3.1.3 Microstructure analysis

Figure 5 shows the microstructures of biocomposite-treated specimens. As shown in Figure 5(a), some irregularly shaped aggregates are deposited in the voids between sand particles of the PM1 specimen, exhibiting both angular features and colloidal stretching characteristics. Angular features indicate the presence of calcite, a crystalline form of CaCO₃, while the colloidal, stretched morphology is characteristic of pectin. The mixture of pectin and calcite deposits between sand particles and bridges adjacent grains, serving as interparticle connects. As the pectin amount increases, the amount of pectin-calcite mixture in the PM3 specimen visibly rises, forming more interparticle contacts. The characteristics of calcite become harder to observe, which can be attributed to the increasing pectin amount and decreasing CaCO₃ content. Similar to the PM specimens, as shown in Figure 5(b), guar gum and calcite also combine together and form a mixture in the GM1 specimen. With increasing guar gum content, the amount of guar gum visibly increases in the GM3 specimen, while calcite becomes more difficult to observe due to being more extensively encapsulated by the guar gum.

The SEM results the addition of hydrogel leads to its combination with CaCO₃ generated by MICP, forming biocomposite bonds capable of bridging sand particles. These bonds enhance the stability of the soil skeleton, which is a key mechanism by which biocomposite treatment improves the shear strength of sand.



(a) PM1 (top) and PM3 (bottom)

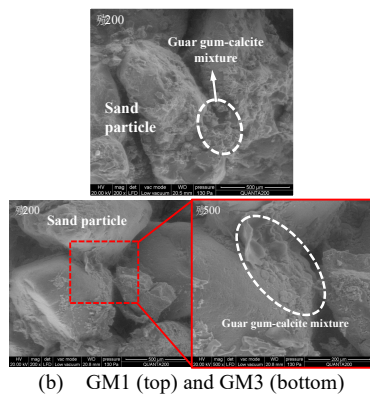


Figure 5. SEM images of the biocomposite-treated specimens

4 CONCLUSIONS

This study focuses on pectin and guar gum, applying biocomposite treatment to sand specimens at different additions in synergy with MICP. UU triaxial tests were conducted to examine the effects of hydrogel type and addition on the shear strength of biocomposite-treated sand, while SEM tests were performed to observe the microstructure. The main findings and conclusions are summarized as follows:

- Biocomposite-treated specimens exhibit significantly higher strength compared to untreated specimens. Under the optimal addition, biocomposite treatment is more effective than MICP alone in enhancing shear strength and strength-to-carbon efficiency (E_c).
- When pectin is in synergy with MICP, the strength of specimens increases with higher pectin additions, whereas the shear strength of the specimens with guar gum decreases. The best efficacy of biocomposite treatment is achieved at 0.2% pectin addition.
- Microstructural results reveal that hydrogel and CaCO_3 combine to form biocomposite bonds between sand particles, which tightly connect adjacent particles and play a crucial role in the biocomposite treatment.

These findings validate the applicability of biocomposite treatment in enhancing the shear strength of sand while maintaining low carbon emissions. This work contributes valuable experimental evidence and provides a theoretical foundation for the development of sustainable and low-carbon soil improvement techniques.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Antonanzas, J., Idowu, O.J., Ray, D.T., Angadi, S., Grover, K., Seavert, C., Summers, H.M. and Quinn, J.C., 2023. Assessment of guar gum production cost and environmental impact in the US Southwest. *Industrial Crops and Products*, 203, p.117116. <https://doi.org/10.1016/j.indcrop.2023.117116>.

Bing, L., Ma, M., Liu, L., Wang, J., Niu, L. and Xi, F., 2023. An investigation of the global uptake of CO_2 by lime from 1930 to 2020. *Earth System Science Data*, 15(6), pp.2431–2444. <https://doi.org/10.5194/essd-15-2431-2023>.

Bozyigit, I., Javadi, A. and Altun, S., 2021. Strength properties of xanthan gum and guar gum treated kaolin at different water contents. *Journal of Rock Mechanics and Geotechnical*

Engineering, 13(5), pp.1160–1172. <https://doi.org/10.1016/j.jrmge.2021.06.007>.

Chang, L., Im, J., Prasadhi, A.K. and Cho, G.-C., 2015. Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials*, 74, pp.65–72. <https://doi.org/10.1016/j.conbuildmat.2014.10.026>.

Chen, Y., Han, Y., Zhang, X., Sarajpoor, S., Zhang, S. and Yao, X., 2023. Experimental study on permeability and strength characteristics of MICP-treated calcareous sand. *Biogeotechnics*, 1(3), p.100034. <https://doi.org/10.1016/j.bgtech.2023.100034>.

DeJong, J.T., Mortensen, B.M., Martinez, B.C. and Nelson, D.C., 2010. Bio-mediated soil improvement. *Ecological Engineering*, 36(2), pp.197–210. <https://doi.org/10.1016/j.ecoleng.2008.12.029>.

Deng, X., Li, Y., Liu, H., Zhao, Y., Yang, Y., Xu, X., Cheng, X. and Wit, B. de, 2021. Examining Energy Consumption and Carbon Emissions of Microbial Induced Carbonate Precipitation Using the Life Cycle Assessment Method. *Sustainability*, 13(9), p.4856. <https://doi.org/10.3390/su13094856>.

Dubey, A.A., Hooper-Lewis, J., Ravi, K., Dhani, N.K. and Mukherjee, A., 2022. Biopolymer-biocement composite treatment for stabilisation of soil against both current and wave erosion. *Acta Geotechnica*, 17(12), pp.5391–5410. <https://doi.org/10.1007/s11440-022-01536-2>.

Liufu, Z., Yuan, J., Shan, Y., Cui, J., Tong, H. and Zhao, J., 2023. Effect of particle size and gradation on compressive strength of MICP-treated calcareous sand. *Applied Ocean Research*, 140, p.103723. <https://doi.org/10.1016/j.apor.2023.103723>.

Madloul, N.A., Saidur, R., Hossain, M.S. and Rahim, N.A., 2011. A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews*, 15(4), pp.2042–2060. <https://doi.org/10.1016/j.rser.2011.01.005>.

Maitra, J. and Shukla, V.K., 2014. Cross-linking in hydrogels—a review. *American Journal of Polymer Science*, 4(2), pp.25–31. <https://doi.org/10.5923/j.ajps.20140402.01>.

Mitchell, J.K. and Santamarina, J.C., 2005. Biological considerations in geotechnical engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, 131(10), pp.1222–1233. [https://doi.org/10.1061/\(asce\)1090-0241\(2005\)131:10\(1222\)](https://doi.org/10.1061/(asce)1090-0241(2005)131:10(1222)).

Nadar, C.G., Arora, A. and Shastri, Y., 2022. Sustainability Challenges and Opportunities in Pectin Extraction from Fruit Waste. *ACS Engineering Au*. <https://doi.org/10.1021/acseengineeringau.1c00025>.

Reza, K.H. and C., O.B., 2013. Improving Mechanical Properties of Sand Using Biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(8), pp.1402–1406. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000861](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000861).

Shan, Y., Liang, J., Tong, H., Yuan, J. and Zhao, J., 2022. Effect of different fibers on small-strain dynamic properties of microbially induced calcite precipitation–fiber combined reinforced calcareous sand. *Construction and Building Materials*, 322, p.126343. <https://doi.org/10.1016/j.conbuildmat.2022.126343>.

Shan, Y., Liufu, Z., Yuan, J., Li, Y., Tong, H. and Cui, J., 2025. Liquefaction resistance of MICP-treated calcareous sand with different particle size and gradation. *Biogeotechnics*, p.100181. <https://doi.org/10.1016/j.bgtech.2025.100181>.

Thakur, B.R., Singh, R.K., Handa, A.K. and Rao, D.M.A., 1997. Chemistry and uses of pectin — A review. *Critical Reviews in Food Science & Nutrition*. <https://doi.org/10.1080/10408399709527767>.

Thombare, N., Jha, U., Mishra, S. and Siddiqui, M.Z., 2016. Guar gum as a promising starting material for diverse applications: A review. *International Journal of Biological Macromolecules*, 88, pp.361–372. <https://doi.org/10.1016/j.ijbiomac.2016.04.001>.

Xiao, Y., Fu, G., Shi, J., Huang, X., Cui, H. and Liu, H., 2025. Bio-hydrogel and biomineralization in improving water retention ability of sandy soils. *Acta Geotechnica*. [online] <https://doi.org/10.1007/s11440-025-02623-w>.

Yang Xiao, Wei Zhou, Jinqun Shi, Huaming Lu and Zhichao Zhang, 2022. Erosion of Biotreated Field-Scale Slopes under Rainfalls. 36(3), p.04022030. [https://doi.org/doi:10.1061/\(ASCE\)CF.1943-5509.0001732](https://doi.org/doi:10.1061/(ASCE)CF.1943-5509.0001732).

Zhao, J., Tong, H., Yuan, J., Liang, S., Cui, J. and Shan, Y., 2025. Drained behavior of microbially induced calcium carbonate precipitated calcareous sand under true triaxial conditions. *Construction and Building Materials*, 490, p.142546.