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Combined Effects Of Coir Fiber And MICP On The Mechanical Properties Of Loose Fine Sand

Joga Suryaprakash Reddy[1*], K. Mallikarjuna Rao[2]
[1*]Research Scholar, Dept of Civil Engineering, S.V.U. College of Engineering, S.V. University, Tirupati - 517502. E-mail: joga.spreddy@gmail.com
[2]Professor, Dept of Civil Engineering, S.V.U. College of Engineering, S.V. University, Tirupati - 517502. E-mail: kmr_svuce@yahoo.com
Corresponding author: Joga Suryaprakash Reddy[1]
[1*]Research Scholar, Dept of Civil Engineering, S.V.U. College of Engineering, S.V. University, Tirupati - 517502. E-mail: joga.spreddy@gmail.com

Abstract
In recent years, there has been a notable surge in interest surrounding the technique known as microbial-induced calcium carbonate precipitation (MICP), which is being recognized as a promising and eco-friendly method for improving soil conditions. A laboratory experiment was conducted to investigate the influence of incorporating randomly distributed non-continuous Coir fibers on the stress-strain characteristics of soil treated with Microbial-induced Calcium carbonate Precipitation catalysed by bacteria. In geotechnical engineering, the direct shear test is a widely utilized laboratory procedure to assess the shear strength characteristics of soil or sand materials. The specimens were prepared in a highly unconsolidated form, with a relative density ranging from 14% to 18%. The preparation involved using flexible moulds that allowed for complete contact. Five various aspect ratio's (45, 90, 136, 182, and 227) and fiber contents (0.1, 0.2, 0.3, 0.4, and 0.5% by weight of sand) were employed in the preparation process. The Direct Shear Tests performed on both fiber-reinforced fine sand and bio-cemented fiber-reinforced fine sand. The findings indicated that the inclusion of fibers led to enhancements in ductility and failure strain. The stress-strain curves demonstrate that the presence of fiber inclusions induces a transition in the failure behavior of bio-cemented soil from brittle to ductile modes. The shear modulus exhibits an initial decrease followed by a subsequent increase, reaching its maximum value at an optimal aspect ratio of 182.

Keywords: *Fiber-reinforced sand, Microbial-induced Calcium carbonate Precipitation (MICP), Fiber Content, stress-strain curves, Aspect Ratio.*

Abbreviations:
MICP: *Microbial-induced Calcium carbonate Precipitation*
AR: *Aspect Ratio*
EDAX: *Energy-Dispersive X-ray Spectroscopy*
SEM: *Scanning Electron Microscopy*
FC: *Fiber content*
BC: *Bio-cemented*
$CaCO_3$: *Calcium Carbonate*
DST: *Direct Shear Test*
G: *Shear Modulus*

1. INTRODUCTION

The currently popular soil stabilizing methods frequently have some negative environmental effects. For instance, it seems that the production of cement, which is widely used for construction and to improve ground conditions, is one of the primary causes of carbon release and global warming from the combustion of fossil fuels [1]. The predominant grouting injection fluid utilized for chemical soil stabilization is toxic and poses significant risks to both human health and the environment [2]. It is necessary to switch to more sustainable and ecologically friendly soil improvement methods from the ones currently in use. Due to this, bio-mediated soil stabilization approach

alters the engineering properties of soil like stiffness and permeability via biological processes. Extensive research has been conducted on the bio-mediated soil improvement technique known as MICP (1-15). When compared with standard cementation procedures, which can be harmful to the environment [3], MICP provides an alternative that is more environmentally friendly. The implementation of the Mechanically Induced Compaction Process has potential to enhance the engineering properties of sandy soil. This includes an icrease in compressive strength and a reduction in permeability. However, it is important to acknowledge that there are limitations associated with this approach. MICP-treated soil may undergo brittle failure, by adding fibers to MICP-treated soil can prevent its brittle failure [16-17]. Soil shear strength and ductility can be improved by using randomly distributed discontinuous fibers [18-19]. The addition of fiber significantly increased the sand's shear strength, as discovered by [20]. The angle of internal friction and cohesiveness both exhibited enhancement as the FC increased, indicating an improvement in the shear strength of the mixtures. The incorporation of fibers into soil has been observed to enhance its ductility by minimizing the post-peak weakness. The study conducted by [21] aimed to investigate the impact of incorporating different quantities of PVA fiber on the alteration of engineering parameters in Ottawa silica sand treated with MICP. Unconfined compressive testing and triaxial drainage compressive tests were also conducted on fiber-reinforced Ottawa silica by [22] Adding fibers to MICP-treated soil in order to boost its engineering qualities has only been the subject of a small number of research so far. This prompted us to delve deeply into the characteristics of fine sand that had been treated with MICP and fibers.
The main objective of this work is to investigate the impact of randomly scattered discontinuous fiber on the stress-strain behavior of soil under MICP conditions, with particular emphasis on ductility. The research methodology employed direct shear experiments on fine sand treated with MICP. The experiments were carried out using different fiber percentages, namely 0%, 0.15%, 0.2%, 0.3%, 0.4%, and 0.5%, as well as variable AR's of *45, 90, 136, 182, and 227*. The microstructure analysis of the BC fiber-reinforced fine sand was conducted using SEM. The chemical composition of samples was assessed using EDAX.

2. MATERIALS AND METHODS

2.1 Sand

Sand is collected from the Swarnamukhi River bank in the vicinity of Chandragiri in Tirupati, Andhra Pradesh. Figure 1 depicts the site where the soil sample was taken. As can be seen in Figure 2, sand has a very uniform particle size distribution. In the unified soil classification system, this soil type is referred to as fine and poorly graded sand (SP). Using the measured values of D_{10} = 0.18, D_{30} = 0.23, and D_{60} = 0.23, the values of the coefficient of uniformity Cu = 1.83 and the coefficient of curvature Cc = 0.89 were calculated. As for sand, its specific gravity was measured to be 2.61. Maximum and minimum e values are 0.97 and 0.69, respectively.

Figure 1: Location of Sand Sample Collected

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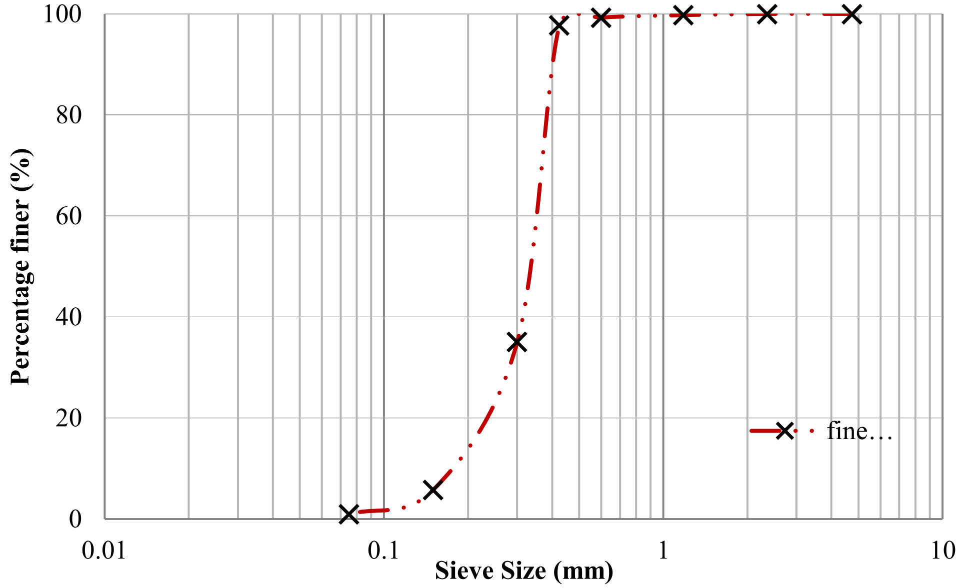

Figure 2: Grain Size Distribution Curve of tested sand

2.2 Coir Fiber:

The effectiveness of soil reinforcement fibers is strongly influenced by several fiber parameters, including fiber length, fiber ratio, and natural fibers [23]. Coir fiber used in the present study is obtained from the local market in the form of bundles shown in Figure 3(a). Figure 3(b) shows the threads were manually separated from the bundles and cut into required lengths. The FC's (0.1, 0.2, 0.3, 0.4, and 0.5% by weight of sand) and ARs (45, 90, 136, 182, and 227), average diameter of fiber 0.11cm.

(a)

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(b)

Figure 3: (a) Coir Fiber bundle; (b) Coir Fiber with different AR

2.3 Bacteria and Cementation Solution:

The bacterium Sporosarcina pasteurii (MTCC-1761), previously identified as Bacillus pasteurii, was selected for this experiment because of its significant capacity for producing the urease enzyme. The particular bacterial strain was acquired from the Gene Bank located at CSIR-Institute of Microbial Technology in Chandigarh. The bacteria were cultured on a medium consisting of nutrient broth with a concentration of 13 g/L and a pH range of 7.5–8.5). The culture tubes were thereafter subjected to incubation for a duration of 24 to 36 hours at a temperature of 30 degrees Celsius, with agitation at a speed of 200 revolutions per minute. When the bacterial culture reached an optical density of 600 nm (OD-600) of 1.2. The Cementation solution media was prepared by combining components as follows: Urea [$CO (NH_2)_2$] (7.5 g), $CaCl_2$ (13.33 g), and distilled water, resulting in a solution volume of 1 L. The experimental medium utilised was nutritional broth with equivalent molarity of cementation solution (Urea & $CaCl_2$) have been succinctly outlined in Table 1.

Table 1: Treatment Components of BC

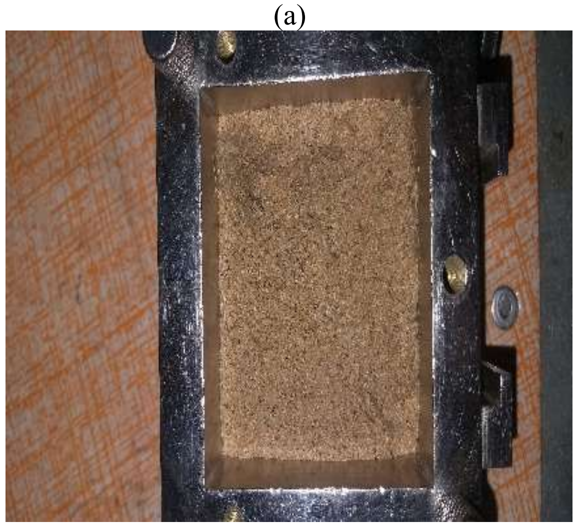
Solution	Constituents
Nutrient Broth	13g/L
Bacteria Medium	Sporosarcina pasteurii (1-1.2 OD)
Cementation solution	Urea 7.5g/L Calcium chloride 13.88g/L
Molarity	3M

2.4 Sample Preparation

2.4.1 Coir fiber-Reinforced Fine Sand:

The specimens were prepared with a relative density range of 14-18% in a very loose form. The fibers are cut into different AR's and FC's (45, 90, 136, 182, and 227) (0.1, 0.2, 0.3, 0.4, and 0.5 by weight of sand) respectively. The fibers were mixed with sand by hand to achieve a uniform mix as shown in Figure 4a. Care should be taken while mixing fiber into sand to reduce floating tendency of fiber. The mixture is then transferred to a direct shear box as shown in Figure 4b. Care should be taken while transferring to reduce the segregation of fibers. The samples are then tested on direct shear equipment as shown in Figure 4c.

(a)



(b)

(c)

Figure 4: Sample Preparation for Testing; (a) Sand-Coir fiber Mixture; (b) Direct shear box with sand-fiber mixture; (c) Samples testing using DST equipment

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2.4.2 Bio-Cemented Coir Fiber- Reinforced Fine Sand:

A known quantity of sand was poured to achieve a target relative density range of 14 to 18%. Coir fibers of different aspect ratios (45, 90, 136, 182, and 227) were cut and then mixed with sand in varying percentages (0.1%, 0.2%, 0.3%, 0.4%, and 0.5%) by weight. This process is depicted in Figure 5a. Depending on the degree of saturation, the bacterial solution was added to the sample (Figure 5b), which was then mixed evenly (Figure 5c). Coir fibers of different aspect ratios were combined with sand in a container along with bacteria at various ratios, taking care to minimize floating and fiber segregation. A mold made from 6 cm × 6 cm × 2.5 cm thermocol (Figure 5d) had inner walls lined with a plastic cover and filled in three layers.

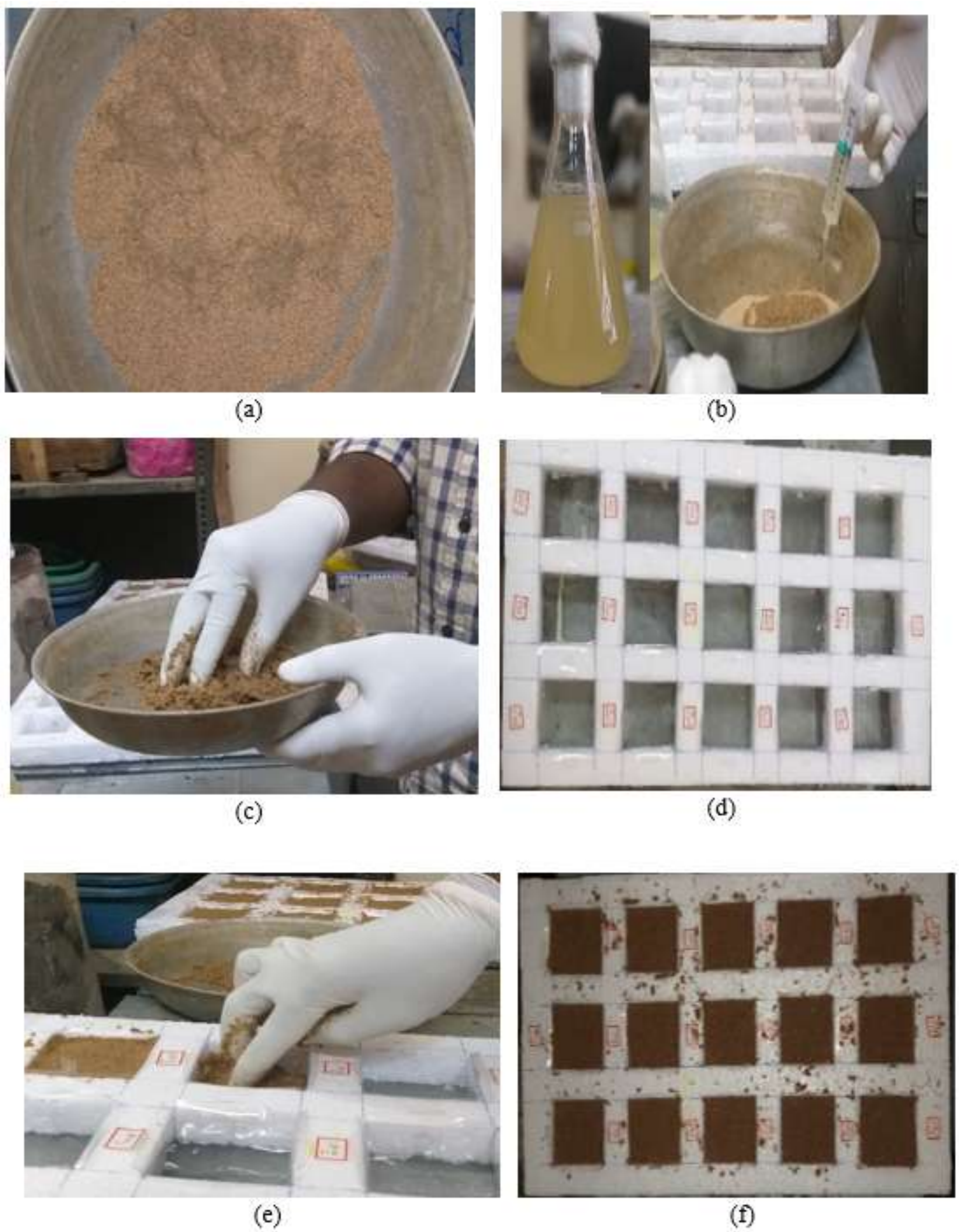


Figure 5: Sample Preparation for Testing; (a) Sand-Coir fiber Mixture; (b) Adding Bacteria Solution to Soil-Fiber Mix; (c) Mixing Sample for Uniformity; (d) Mould; (e) Placing Samples in mould; (f) Curing of Samples

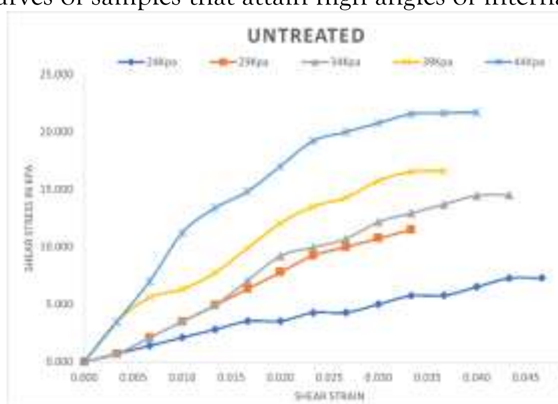
The sand-fiber-bacteria mixture was placed into the mold in three layers to ensure uniformity (Figure 5e). To facilitate bacterial attachment, the prepared samples were incubated for 4 to 6 hours to ensure consistent and uniform attachment of bacteria to the particles. Then, the bio-cementation solution of the desired molarity was injected drop by drop at 12-hour intervals for one week, without disturbing the samples (Figure 5f). After curing, the samples were removed from the mold, dried, and tested using Direct Shear Equipment.

The study involved conducting Direct Shear Tests on fine sand, reinforced sand, and Microbially Induced Calcite Precipitation (MICP) treated reinforced sand. The tests were executed under various normal stresses at a loading rate of 0.95 mm/min, employing a Direct Shear Apparatus with molds measuring 6×6×3 cm. A total of 25 reinforced samples, 25 MICP-reinforced samples, one virgin sample, and one MICP-treated fine sand sample underwent testing over 7 days. Subsequently, the samples underwent Scanning Electron Microscopy (SEM) analysis to scrutinize the formation of $CaCO_3$ and pore fillings within the soil microstructure.

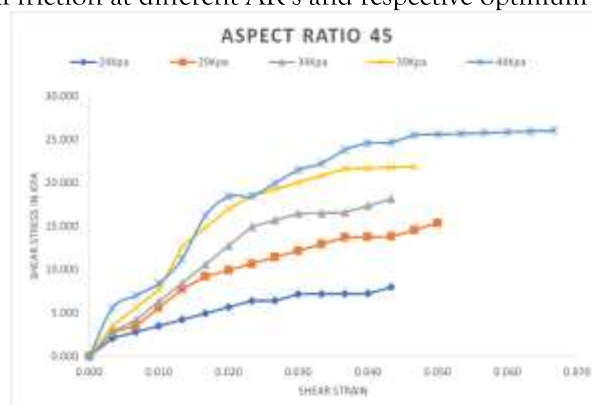
3. RESULTS AND DISCUSSION:

3.1 Deformation Characteristics of Fine Sand Treated with Coir Fiber:

The stress-strain curves are obtained from DST results. DST are conducted according to IS 2720 (part-13) 1986 code of practice while measuring shear deformation and shear load. The results obtained are analysed to get shear stress and shear strain loading. Typical stress-strain curves are developed and presented in Figure 6 (a) to 6(f). The stress-strain curves of samples that attain high angles of internal friction at different AR's and respective optimum FC.



(a)



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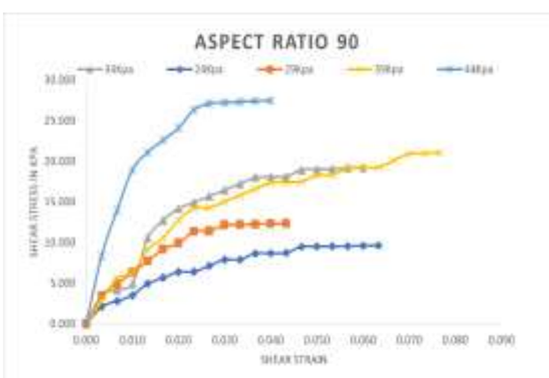

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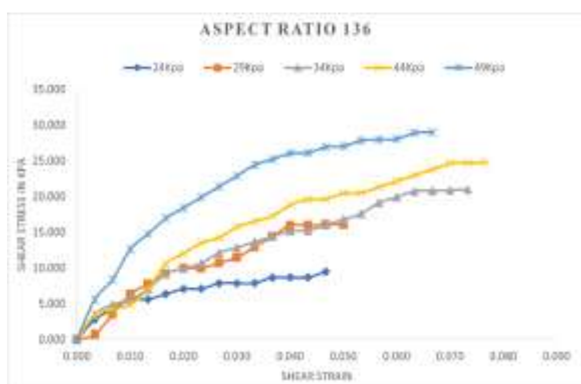
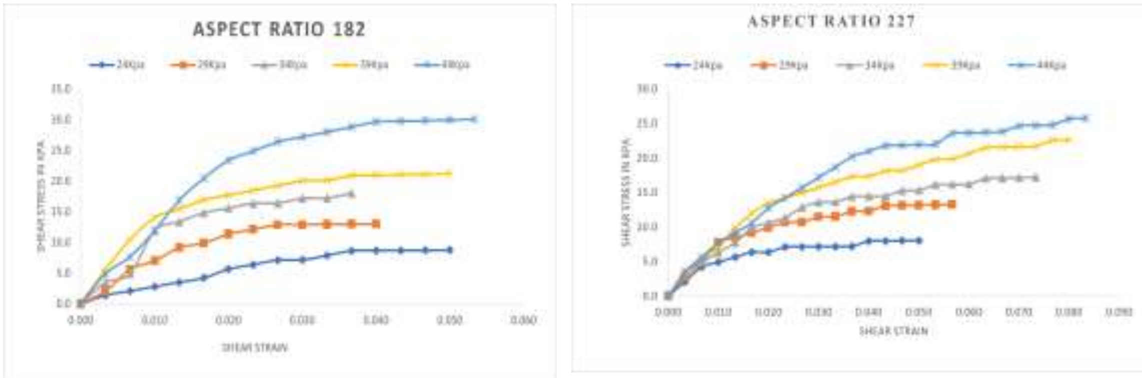


(d)



(e) (f)

Figure 6: Stress-strain curves for (a) Untreated (b) AR-45 (c) AR-90 (d) AR-136 (e) AR-182 (f) AR-227

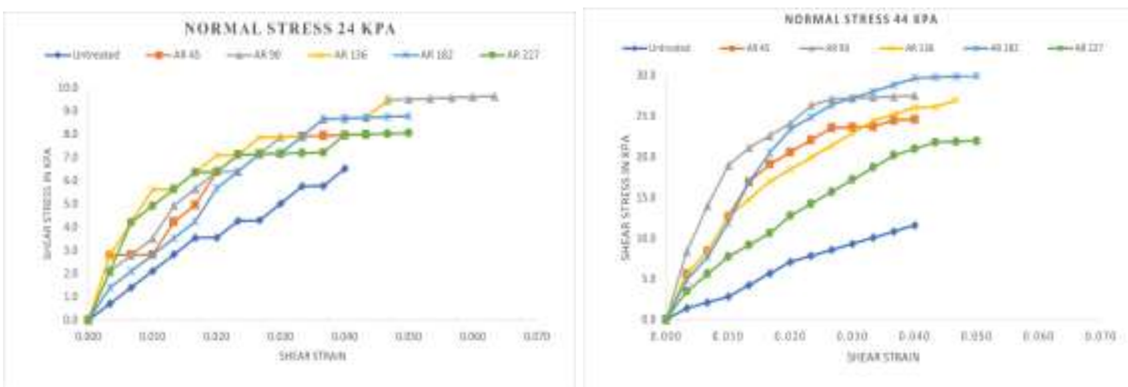


Figure 7: Stress-strain curves for Aspect Ratio 182 corresponding Normal Stress (a) 24 kPa (b) 44 kPa

Based on the findings presented in Figure 7(a) to 7(b), it can be inferred that the impact of coir treatment on fine sand is not discernible until a horizontal strain range of 0.02 to 0.05% is attained, in comparison to the untreated specimen [20]. Furthermore, prior studies conducted by [16,18,24] have demonstrated that the presence of fiber reinforcement does not yield any discernible impact under conditions of low stresses. The shear resistance of fiber-prepared specimens exhibits an upward trend as the horizontal strain increases, in contrast to untreated specimens. Fiber-reinforced sand has greater ductility compared to sand without reinforcement, and demonstrates a reduced decline in shearing resistance after reaching the peak. As the applied normal stress is elevated, the fiber-reinforced sample exhibits a notable rise in resistance to shearing, particularly up to an AR of 182. However, beyond this point, there is no substantial further increase observed. The phenomenon of shear stress augmentation at strain rates exceeding 0.2 to 0.5% strain is seen to be directly correlated with an increase in AR for all normal stress levels. The observed behavior can be attributed to the presence of fibers incorporated within the sand, which tend to experience slippage and deformation at low levels of strain, so initiating the shearing process. Subsequently, under significant strains, all the fibers within the fiber-reinforced sand matrix undergo yielding and stretching, resulting in an observed enhancement of shear strength in comparison to untreated sand. The reinforcing effect is contingent upon both the AR of the fibers and the percentage of fibers present. The effectiveness of fiber reinforcement increases as the AR and fiber percentage approach their respective optimal values. The effectiveness of reinforcing is enhanced when the length of the fiber is greater in comparison to the size of the grain. This is the underlying cause for the observed rise in shear stress when AR's grow.

3.2 Influence of Fiber Content on Shear Modulus:

The Shear Modulus is commonly used in field of earthquake geotechnical engineering for the purpose of identifying elastic solutions to soil-related problems. The Shear Modulus has been evaluated from results of DST using stress-strain curves. Shear modules are calculated for fine sand at different normal stresses and AR's of Coir fiber. The optimum fiber percentage at different ARs is summarized in Table 2.

Table 2: Shear Modulus for Various AR's

Normal stress in (kPa)	Aspect Ratio's (AR)					
	Untreated	**45**	**90**	**136**	**182**	**227**
24	156.01	184.3	217.77	220.2	226	210
29	184.7	284.75	290	307.02	325.52	322
34	220.85	320.13	336	380	418.79	390
39	223.21	369.39	386	452.19	482.46	470
45	226.4	390.63	417.6	435.27	542	510.56

3.3 Influence of AR on Shear Modulus:

Figure 8 illustrates effect of the AR on Shear Modulus. It shows varying differences in peak stress, half of the peak stress and one-third of the peak stress. In present study 0.3% FC, which is optimum for all ARs is considered. Based on the findings presented in Figure 8, it is evident that there exists a positive correlation between the AR and Shear Modulus. Specifically, when the AR increases, Shear Modulus demonstrates an upward trend until reaching an optimal AR of 182. Subsequently, a minimal reduction in the Shear Modulus was observed.

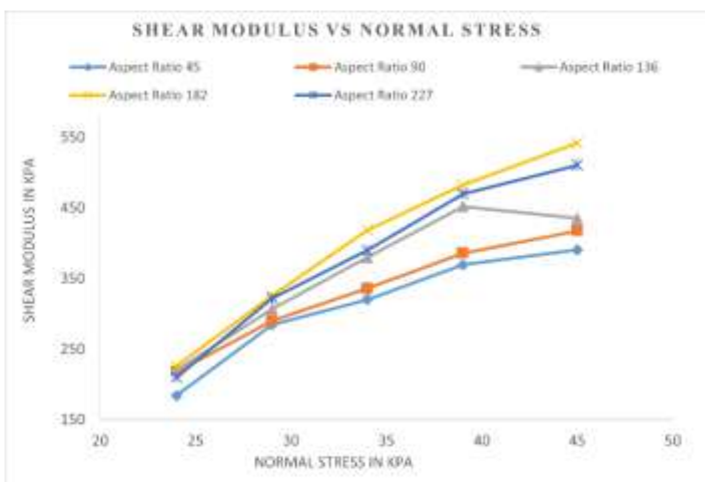


Figure 8: G vs. Normal stress

3.4 Influence of % Fiber on G on Optimum AR:

From Figure 9, it is clear that influence of Shear Modulus with respective % fiber. It shows varying differences in peak stress with % fiber. In present study, fiber influences the Shear Modulus. The Shear Modulus increases with an increase in % fiber.

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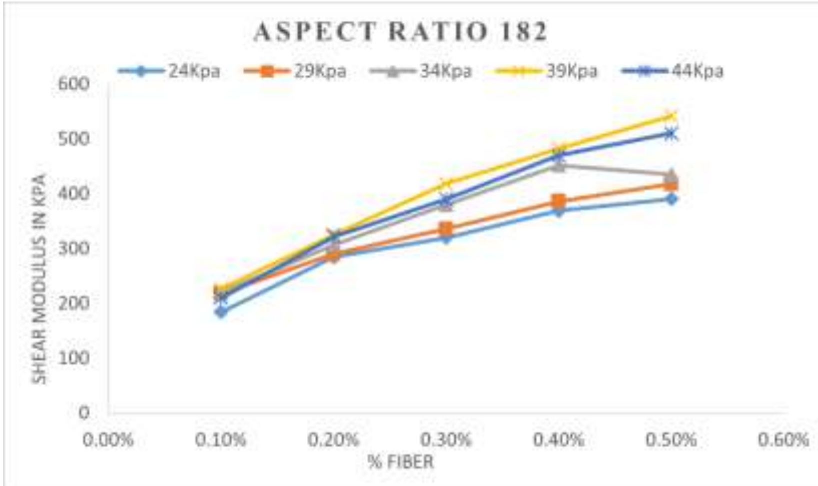
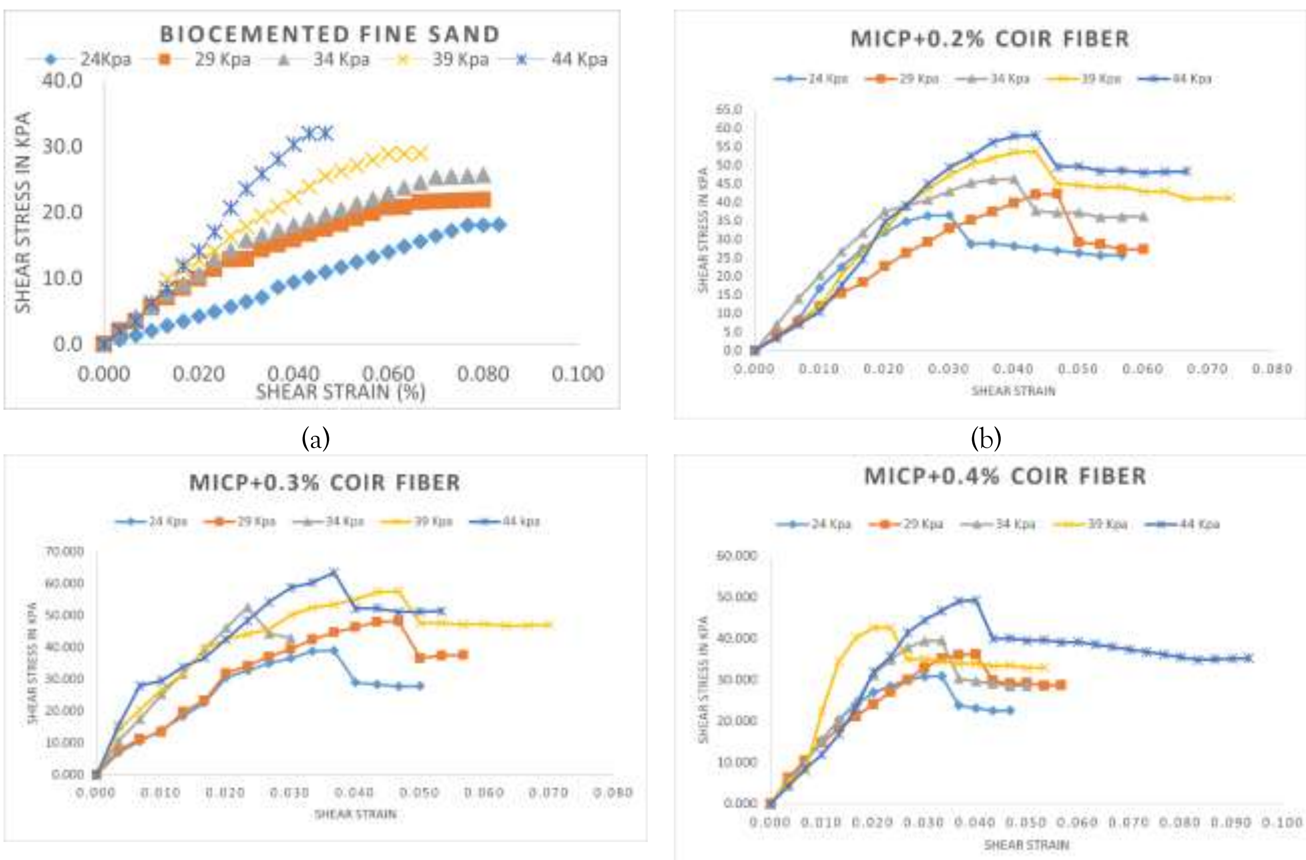


Figure 9: G Vs %Fiber

3.5 Stress-Strain Behaviour of BC Fiber Reinforced Fine Sand

The stress-strain curves depicted in the figures below have been derived from the DST. The examination of the stress-strain relationship is of great importance in evaluating mechanical consequences of altered soils by [16,19]. By scrutinizing stress-strain curves (Figures 10), a deeper understanding impact of fiber reinforcement on behavior of sand treated with MICP can be attained.



(a) (b) (c) (d)

Figure 10: Stress-strain curve for (a) Bio-cemented Fine Sand (b) MICP+0.2% Coir fiber (c) MICP and 0.3% Coir fiber (d) MICP and 0.4% Coir fiber

As shown in Figure 10 (a), MICP treatment substantially increased the stiffness of fine sand due to calcium carbonate precipitation. This is consistent with previous research results. [1,10]. Figures 10 (b) to 10 (d) depicts the Direct Shear, Stress-Strain curves of MICP-treated samples with different FC's and optimum AR's. Between the stress-strain graphs, three stages can be identified. The stress-strain relationship exhibited a gradual concave manner during the initial phase, indicating the compacting of voids and fractures within the samples. There was a linear relationship between stress and strain during the second phase, which led the stress to increase quickly until it reached its maximum. The strain quickly dropped after reaching its peak stress in the third phase. Several investigations have also found that when the calcium carbonate cementation breaks, the stiffness of BC soil decreases. [25-28]. It can be observed that the ductility and failure strain can be improved by adding fiber reinforcement to BC sand. From Figures (10 (b) to 10 (d)), it can be observed that the ductility and failure strain can be improved by adding fiber reinforcement to MICP sand. In addition, fiber with MICP shows an increase in the ultimate shear strength of the specimens up to 0.3% Fiber substantially when compared with the fine sand with MICP without Fiber. The MICP fiber-reinforced sand can retain shear stress with continued deformation even at considerable strains (4% and beyond), demonstrating that these materials are exceptionally ductile.

3.6 Influence of BC and BC fiber-reinforced fine sand on G:

The elastic solution to the soil problems in the field of earthquake geotechnical engineering, the G is extensively used for analysis and design. Shear Modulus values are calculated for both fine sand treated with MICP and also treated with coir fiber at their respective optimums and are summarized in Table 3.

Table 3: G at various normal stresses for BC and BC fiber-reinforced fine sand

% Fiber	G corresponding to Normal Stress in kPa				
	24 kPa	29 kPa	34 kPa	39 kPa	44 kPa
Bio Cemented	218.2	273.6	301.9	39.6	624.4
Bio Cemented + 0.2% Fiber	1217	905.3	1157	1239.6	1340
Bio Cemented + 0.3% Fiber	1062	1030	2255	1233.1	1730
Bio Cemented + 0.4% Fiber	926.7	904.2	1185	1828.4	1230

From Table 3 it can be observed, that Shear Modulus are increased not only with normal stress but also by MICP with fiber reinforcement. There is a significant increase of Shear Modulus in MICP treated with Coir fiber when compared with the fiber reinforcement in fine sand.

3.7 Shear Modulus corresponding to Normal Stress:

The Shear Modulus values obtained from stress-strain curves for fine sand, fiber-reinforced fine sand, BC fine sand, and BC fiber-reinforced fine sand were summarized in Table 4.

Table 4: Summarized Shear Modulus

Composition	Shear Modulus corresponding to Normal Stress in kPa				
	24 kPa	29 kPa	34 kPa	39 kPa	44 kPa
Fine Sand	156.01	184.7	220.85	223.21	226.4
Fiber-reinforced Fine sand (optimum 0.3% and AR 182)	226	325.52	418.79	482.46	542
BC Fine sand	218.2	273.6	301.9	390.6	624.4

BC fiber-reinforced Fine sand (optimum 0.3% and AR 182)	1062	1030	2255	1233.1	1730

The Fiber-reinforced fine sand G increases by 1.45, 1.76, 1.89, 2.16, and 2.4 corresponding normal stress 24 kPa, 29 kPa, 34 kPa, 39 kPa, and 44 kPa respectively when compared with the untreated fine sand. The BC Fiber-reinforced fine sand G increases by 4.87, 3.76, 7.47, 3.15, and 2.77 corresponding to normal stress 24 kPa, 29 kPa, 34 kPa, 39 kPa, and 44 kPa respectively when compared with the BC fine sand. The BC fine sand G increases by 1.4, 1.48, 1.37, 1.75, and 2.76 corresponding to normal stress 24 kPa, 29 kPa, 34 kPa, 39 kPa, and 44 kPa respectively when compared with the untreated fine sand. When compared to fiber-reinforced sand, the Shear Modulus of BC fiber-reinforced fine sand improves by 4.7, 3.16, 5.38, 2.56, and 3.19 for normal stresses of 24 kPa, 29 kPa, 34 kPa, 39 kPa, and 44 kPa, respectively.

3.8 Scanning Electron Microscopy (SEM):

The process of $CaCO_3$ formation was investigated using SEM. EDAX was employed to analyze the chemical composition of the samples. Figure 11 clearly shows the sand and Jute fiber without MICP treatment. It is obvious that the surface is free from crystallization and that no other mineral exists within the sample. There is no bonding between the sand-to-sand particle and the jute fiber-sand particle. From the EDAX results clear that carbon 32.23%, oxygen 46.2%, Aluminium 6.29%, and Silica 15.28% are the main minerals in the sand. Figure 12 it is obvious that there is $CaCO_3$ precipitation at the location of contact between the fiber and sand particles. The gap between sand-sand particle and sand-coir fiber filling with $CaCO_3$ precipitation. Similar findings were also noted in earlier investigations [16, 21]. According to EDAX analysis, the $CaCO_3$ percentage compositions of each element are carbon 14.69%, oxygen 36.26%, and calcium 36.41%.

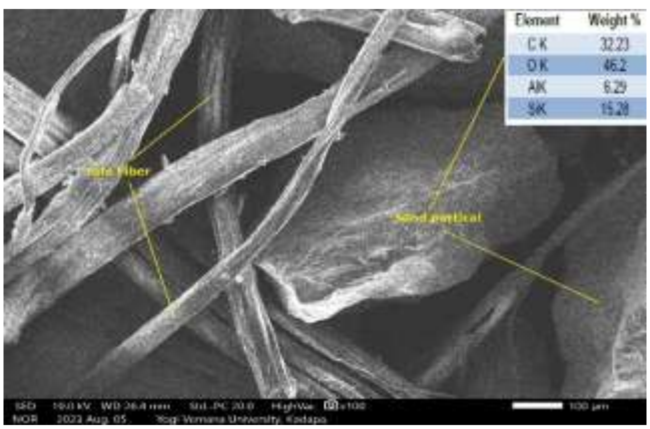


Figure 11: Fiber reinforced Fine sand

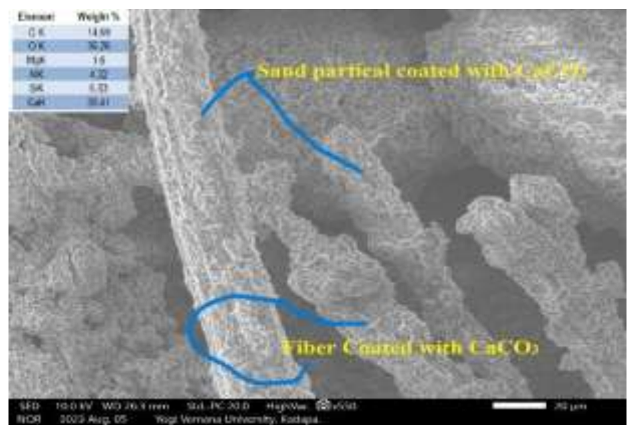


Figure 12: BC Fiber reinforced Fine sand

4. CONCLUSIONS:

This study aimed to investigate the stress-strain behavior and mechanisms of various types of sand specimens through a series of DST's. The specimens included fine sand alone, finer-reinforced fine sand, BC fine sand, and BC fiber-reinforced fine sand. Different FC (ranging from 0.1% to 0.5% by weight of sand) and AR's (ranging from 45 to 227) were used in the preparation of the specimens. The findings of this study led to the following conclusions.

1. The stress-strain analysis reveals that the presence of fiber inclusions induces a transition in the failed behavior of BC soil, shifting it from brittle to ductile modes.
2. The shear modulus exhibits an increasing trend until reaching an ideal AR of 182, after a noticeable decrease.
3. The Fiber-reinforced fine sand shear modulus increases by 1.45, 1.76, 1.89, 2.16, and 2.4 corresponding normal stress 24 kPa, 29 kPa, 34 kPa, 39 kPa, and 44 kPa respectively when compared with the untreated fine sand
4. The BC Fiber-reinforced fine sand shear modulus increases by 4.87, 3.76, 7.47, 3.15, and 2.77 corresponding to normal stress 24 kPa, 29 kPa, 34kPa, 39 kPa, and 44 kPa respectively when compared with the BC fine sand.

5. The inclusion of fiber has been observed to significantly improve the ultimate shear strength of the specimens in comparison to the BC sand. The addition of fiber to BC sand can be observed to mitigate the loss in post-peak strength.
6. Coir fiber has significant effects on the microbial performance, $CaCO_3$ precipitation pattern, and solidification of sand.
7. The precipitation of $CaCO_3$ exhibited a positive correlation with the incorporation of coir fibers, resulting in a notable enhancement of the soil's engineering properties. Scanning Electron Microscopy (SEM) analysis indicated that the introduced coir fibers effectively interacted with $CaCO_3$, creating stable connections within the soil matrix. This interaction appeared to restrict the formation of failure planes in the specimens. Consequently, this process likely contributed to an increase in the strength of the treated specimens in comparison to the control biocemented specimens (without coir fiber).
8. In this study, natural coir fibers were used; however, the effects of chemically treated jute fibers and the roughness of coir fibers (surface roughness) have not been investigated in detail. In order to better understand the effects of fibers on soil stabilization (considering chemical pretreatment of the fiber, fiber roughness, etc.) using the MICP process, further studies are highly recommended.

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Data availability: Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.
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Declarations
Declarations Ethics approval and consent to participate: Not applicable.
Consent for publication: Not applicable.
Competing interests: The authors declare no competing interests

REFERENCES

1. DeJong JT, Mortensen BM, Martinez BC, Nelson DC. 2010. Bio-mediated soil improvement. Ecol Eng 36(2):197–210.
2. Karol, R. H. (2003). Chemical grouting and soil stabilization, revised and expanded. Crc Press.
3. DeJong JT, Mortensen BM, Martinez BC. 2006. Bio-Soils Interdisciplinary Science and Engineering Initiative. Arlingon, VA: National Science Foundation
4. DeJong JT, Soga K, Kavazanjian E, Burns S, van Paassen LA, Al Qabany A, Aydilek A, Bang SS, Burbank M, Caslake LF, et al. 2013. Biogeochemical processes and geotechnical applications: progress, opportunities and challenges. Geotechnique 63(4):287–301.
5. Van Paassen, L. A. (2009). Biogrout, ground improvement by microbial induced carbonate precipitation.
6. van Paassen, L. A., Ghose, R., van der Linden, T. J., van der Star, W. R., & van Loosdrecht, M. C. (2010). Quantifying biomediated ground improvement by ureolysis: large-scale biogrout experiment. Journal of geotechnical and geoenvironmental engineering, 136(12), 1721-1728.
7. Chou, C. W., Seagren, E. A., Aydilek, A. H., & Lai, M. (2011). Biocalcification of sand through ureolysis. Journal of Geotechnical and Geoenvironmental Engineering, 137(12), 1179-1189.
8. Al Qabany, A., Soga, K., & Santamarina, C. (2012). Factors affecting efficiency of microbially induced calcite precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 138(8), 992-1001.
9. Burbank, M., Weaver, T., Lewis, R., Williams, T., Williams, B., & Crawford, R. (2013). Geotechnical tests of sands following bioinduced calcite precipitation catalyzed by indigenous bacteria. Journal of Geotechnical and Geoenvironmental Engineering, 139(6), 928-936.
10. Martinez, B. C., DeJong, J. T., Ginn, T. R., Montoya, B. M., Barkouki, T. H., Hunt, C., & Major, D. (2013). Experimental optimization of microbial-induced carbonate precipitation for soil improvement. Journal of Geotechnical and Geoenvironmental Engineering, 139(4), 587-598.
11. Zhao, Q., Li, L., Li, C., Li, M., Amini, F., & Zhang, H. (2014). Factors affecting improvement of engineering properties of

MICP-treated soil catalyzed by bacteria and urease. Journal of Materials in Civil Engineering, 26(12), 04014094.
12. Sharma, M., Satyam, N., & Reddy, K. R. (2021). Investigation of various gram-positive bacteria for MICP in Narmada Sand, India. International Journal of Geotechnical Engineering, 15(2), 220-234.
13. Wani, K. S., Mir, B. A., & Sheikh, I. R. (2021). Biological processes in the stabilization of weak river sediments: an innovative approach. Innovative Infrastructure Solutions, 6, 1-15
14. Xiao, Y., He, X., Stuedlein, A.W., Chu, J., Matthew Evans, T. and Van Paassen, L.A., 2022. Crystal growth of MICP through microfluidic chip tests. Journal of Geotechnical and Geoenvironmental Engineering, 148(5), p.06022002.
15. Sharma, M. (2024). Potential of Bio-mediated Calcite Precipitation Methods for Heavy Metal Immobilization and Strength Enhancement of Contaminated Soils. Indian Geotechnical Journal, 1-5.
16. Heineck, K. S., Coop, M. R., & Consoli, N. C. (2005). Effect of microreinforcement of soils from very small to large shear strains. Journal of geotechnical and geoenvironmental engineering, 131(8), 1024-1033.
17. Park, S. S. (2011). Unconfined compressive strength and ductility of fiber-reinforced cemented sand. Construction and building materials, 25(2), 1134-1138.
18. Toé Casagrande, M. D., Coop, M. R., & Consoli, N. C. (2006). Behavior of a fiber-reinforced bentonite at large shear displacements. Journal of Geotechnical and Geoenvironmental Engineering, 132(11), 1505-1508.
19. Consoli, N. C., Vendruscolo, M. A., Fonini, A., & Dalla Rosa, F. (2009). Fiber reinforcement effects on sand considering a wide cementation range. Geotextiles and Geomembranes, 27(3), 196-203.
20. Shao, W., Cetin, B., Li, Y., Li, J., & Li, L. (2014). Experimental investigation of mechanical properties of sands reinforced with discrete randomly distributed fiber. Geotechnical and Geological Engineering, 32, 901-910.
21. Choi, S. G., Wang, K., & Chu, J. (2016). Properties of biocemented, fiber reinforced sand. Construction and building materials, 120, 623-629.
22. Li, C., Yao, D., Liu, S., Zhou, T., Bai, S., Gao, Y., & Li, L. (2018). Improvement of geomechanical properties of bio-remediated aeolian sand. Geomicrobiology Journal, 35(2), 132-140.
23. Wei, S., Cui, H., Jiang, Z., Liu, H., He, H., & Fang, N. (2015). Biomineralization processes of calcite induced by bacteria isolated from marine sediments. Brazilian Journal of Microbiology, 46, 455-464.
24. Consoli, N. C., Casagrande, M. D. T., & Coop, M. R. (2007). Performance of a fibre-reinforced sand at large shear strains. Géotechnique, 57(9), 751-756.
25. Liu, S.H.; Wen, K.J.; Armwood, C.; Bu, C.M.; Li, C.; Amini, F.; Li, L. Enhancement of MICP-Treated Sandy Soils against Environmental Deterioration. J. Mater. Civ. Eng. 2019, 31, 13.
26. Lei, X., Lin, S., Meng, Q., Liao, X., & Xu, J. (2020). Influence of different fiber types on properties of biocemented calcareous sand. Arabian Journal of Geosciences, 13, 1-9.
27. Do, J., Montoya, B. M., & Gabr, M. A. (2019). Debonding of microbially induced carbonate precipitation-stabilized sand by shearing and erosion. Geomech. Eng, 17(5), 429-438.
28. Mortensen, B. M., & DeJong, J. T. (2011). Strength and stiffness of MICP treated sand subjected to various stress paths. In Geo-Frontiers 2011: Advances in geotechnical engineering (pp. 4012-4020).