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Research Article

Strength and Micromechanism Analysis of Microbial Solidified Sand with Carbon Fiber

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Microbially induced calcite precipitation (MICP) is an effective and ecofriendly technology that utilizes the microbes-induced mineralization to improve foundation soils of the transportation infrastructure. The carbon fiber can be used along with the MICP in order to reduce the brittleness of microbial solidified soil. This paper investigated the strength of carbon fiber-reinforced sand with different mass fractions through a series of unconfined compression tests. The effect of fiber content on the solidification of carbon fiber-reinforced sand was quantitatively analyzed using calcium carbonate content test and penetration test. The microsolidification mechanism was investigated by micrographs from the optical and scanning electron microscope (SEM). The test results showed that unconfined compressive strength generally increased first and then decreased with the increase of the fiber content. The optimal fiber content in the silica and calcareous sand was 0.2% and 0.1%, respectively. The bulging deformation of the fiber-reinforced sand sample was gradually developed along with the fiber breakage during loading.

1. Introduction

In the transportation infrastructure practices, some unfavorable foundation soils that cannot meet the engineering requirements will be encountered and should be improved to meet the requirements of a strong and reliable transportation foundation [1]. The common foundation improvement methods utilize large-scale mechanical or chemical consolidation to reinforce the soil, such as the dynamic consolidation treatment and chemical grouting. These methods were typically energy-intensive and caused environmental pollutions; for example, the chemical slurry is toxic except for silicon [2]. In recent years, microbially induced calcite precipitation (MICP) technology was developed as a soil improvement reinforcement technology [3]. MICP was an effective bioconsolidation technology and received much attention due to its great benefits for engineering construction [4–8]. This technology utilizes microbial secretion of urease to promote the hydrolysis of urea to form carbonate ions and calcium ions to form calcium carbonate, thereby cementing the sand particles to improve the physical and mechanical properties of the soil [6, 9, 10]. ý Figure 1 shows the reaction chemical formula and schematic diagram of MICP [11, 12]. Compared with traditional soil treatment methods, this technology has the advantages of abundant resources, clear mechanism, small environmental pollution, and excellent performance [2, 13–15].

Whiffin [16] proposed the use of MICP to consolidate loose particles of sand. DeJong et al. [17] observed that MICP technology can improve the mechanical properties of sand in laboratory tests. Paassen et al. [18] demonstrated that this technique can enhance the bearing capacity and stiffness of soils in large-scale in situ tests. Park et al. [19], Li et al. [20], and Xiao et al. [21] investigated the effect of polyvinyl alcohol (PVA) fiber, polypropylene (PP) fiber, and basalt fiber on the strength of microbial solidified sand. The current research studies show that MICP technology can effectively improve the strength, stiffness, and liquefaction resistance of sand [22]. However, the properties of sand ductility and toughness after the use of MICP are poor. The microbial solidified sand was a typical brittle material and its strength can reduce drastically after failure, which may cause problems for the long-term performance and safety. Therefore, strengthening the toughness of the microbial

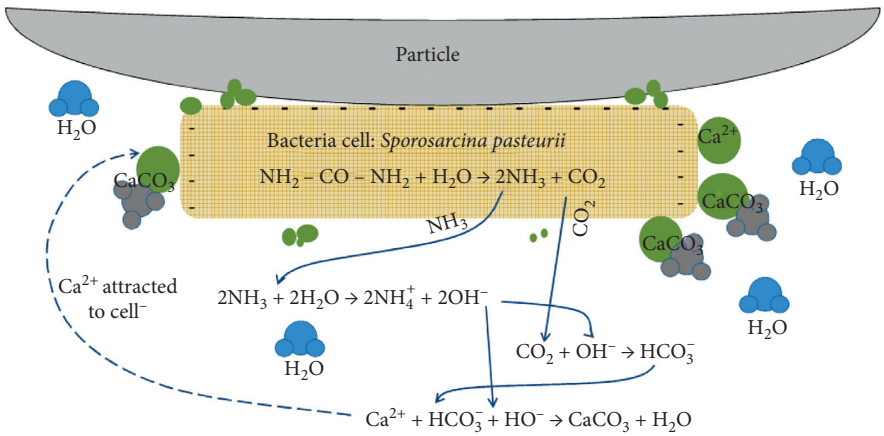


Figure 1: Schematic procedure of microbial-induced calcite precipitation (MICP).

solidified soil has important value in the research of MICP technology.

Recent studies have shown that the addition of short fiber filaments to the microbial solidified sand can effectively enhance the strength of the soil and improve the toughness. The brittle failure was prevented because the solidified sand would not lose strength immediately after the damage [23, 24]. Most of the previous research mainly used polypropylene fiber as the reinforcement for the microbial solidified sand. The literature on the carbon fiber-reinforced sand was limited and further research was necessary. Carbon fiber has the advantages of low density, high axial tensile strength and modulus, no creep, good fatigue resistance, high temperature resistance, insolubility in organic solvents, acids and alkalis, and outstanding corrosion resistance [25]. Young's modulus of carbon fiber was more than three times that of traditional glass fiber and was two times that of the Kevlar fiber [26]. Therefore, this study conducted multiscale coupling tests and mechanism analysis to investigate the influence of carbon fiber content on the mechanical properties of microbial solidified sand.

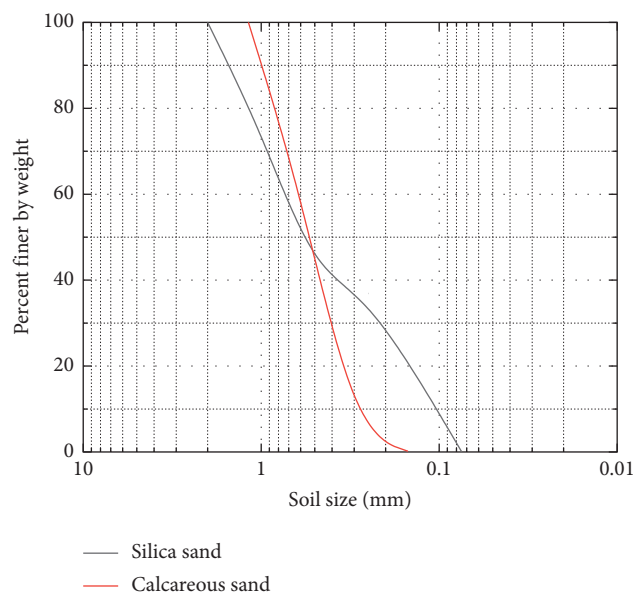


Figure 2: Grain size distributions of silica and calcareous sand.

2. Experimental Program

2.1. Test Materials. The silica and calcareous sands used in this study were obtained from the Xiamen Province, China. Figure 2 presents the particle size distributions of the sand, which was classified as poorly graded sand according to the Unified Soil Classification System (ASTM2006). The short carbon fiber with a length of 10 mm was used in the test. The mechanical properties of the carbon fiber are provided by the merchant of GW COMPOS and are shown in Table 1.

2.2. Test Bacteria. The bacterium used in this test was *Sporosarcina pasteurii* and was provided by DSM, The Netherlands, under the designation of DSM33. Table 2 showed the liquid medium ingredients. The prepared liquid medium is sterilized by using a high temperature sterilizer at 121°C for 20 minutes. After adding bacteria under aseptic conditions, the bacteria are cultured in a constant temperature shaking incubator at 30°C and 200 rpm for 12–48 hours [27]. Table 3 shows the average urease activity of bacteria according to the method proposed by Whiffin [16].

2.3. Sample Preparation. The nutrient solution of this test was composed of 0.5 mol/L $CaCl_2$ and 0.5 mol/L urea [28]. Different water content or soil particle composition can affect soil strength [29]. In order to ensure the uniformity and consistency of the sample, a method of adding the bacterial liquid and the nutrient solution multiple times was adopted. The sample was added to the bacterial liquid in three rounds. Six nutrient solutions were added after each addition of the bacterial liquid. The nutrient solution was added for 5 hours each time.

The prepared sample has a size of 80 mm in height and 39.1 mm in diameter. The weight of the sample was 170 g for silica sand and 125 g for calcareous sand. The sand was uniformly mixed with fibers of mass fractions of 0.0%, 0.1%, 0.2%, 0.3%, and 0.4%, respectively. Deionized water was

Table 1: Basic physical and mechanical properties of carbon fiber.

Type	Tensile strength (MPa)	Tensile modulus (GPa)	Linear density (g/1000 m)	Volume density (g/cm^3)	Elongation (%)	Diameter (μm)	Carbon content (%)
Bundle monofilament	3530	230	198	1.76	1.5	7	93

Table 2: Liquid medium ingredients.

Component	Concentration
NaOH (g/L)	2
$(NH_4)_2SO_4$ (g/L)	10
Yeast (g/L)	20

added to the sand to attach an initial moisture content of 5%. The wet sand then was mixed with dry carbon fibers using SM950 mixer. The water in the sand avoided the accumulation of fibers and behaved as a lubricant and dispersion [30]. The sand-fiber mixture was divided equally into 10 parts; each part was evenly added to the PVC mold to achieve a uniform density [19, 31]. Three parallel samples were prepared for each fiber content to check the repeatability of test results. Figure 3 shows the test device for the sample preparation. Figures 4 and 5 show the microbial solidified samples in the private mold for the silica sand and calcareous sand, respectively.

3. Results and Discussion

3.1. Unconfined Compressive Strength Test. The microbial solidified sand was created by microbial-induced calcium carbonate, which filled the pores between the sand particles and cemented sand particles. The loose sand particles were bonded together to improve the unconfined compressive strength of the sand. The unconfined compressive strength is an important property to evaluate the solidation effect of microbial solidified sand. A series of unconfined compressive tests were conducted in accordance with ASTM D2166 to measure the unconfined compressive strength (q_u). A liquid crystal automatic pressure testing machine (YAW-S300) with a loading rate of 1.0 mm/min was used to load the sample until failure. The recorded peak compressive strength was treated as the unconfined compressive strength of the sample.

Figure 6 shows the unconfined compressive strength of the sampleý with different fiber contents. The unconfined compressive strength of the silica sand sample was only 0.23 MPa at the fiber content of 0%. High unconfined compressive strength was achieved with the addition of the carbon fiber. The strength was increased to 0.39, 0.42, 0.37, and 0.35 MPa for the silica sand sample at the fiber content of 0.1%, 0.2%, 0.3%, and 0.4%, respectively. The maximum strength for the silica sand sample (i.e., at the fiber content of 0.2%) was 183% higher than the strength of the fiber-free sample. The change of unconfined compressive strength of the calcareous sand sample showed similar trend. The unconfined compressive strength of the calcareous sand sample was 1.41 MPa at the fiber content of 0%. The strength was increased to 1.97, 1.93, 1.75, and 1.69 MPa for the calcareous sand sample at the fiber content of 0.1%, 0.2%, 0.3%, and 0.4%, respectively. The maximum strength for the calcareous sand sample (i.e., at the fiber content of 0.1%) was 139% higher than the strength of the fiber-free sample.

Figure 7 shows the bulging failure that happened in the unconfined compressive strength test. Large bulging deformation was observed in the middle section of the sample. The microbial solidified sample with the addition of carbon fiber showed excellent toughness and ductility after reaching peak compressive strength. Three-dimensional network of ribbed structure was formed within the sample due to the addition of the fiber, which prevented the development of the surface failure and the void between particles. The carbon fiber carried the major tensile force during the bulging deformation with the advantage of its excellent tensile properties. The microbial solidified sample with fiber behaved as little brittle property after the sample reaches the ultimate compressive strength.

In general, the unconfined compressive strength of the sample showed a tendency of increasing first and then decreasing with the increase of the fiber content. The fiber was not fully distributed within the sample and the reinforcement effect was limited at low fiber content. However, the fiber was entangled into bundles during the preparation of the sample if the fiber content was too high [32]. It was difficult for the microorganisms to form an effective calcium carbonate connection between the fiber and the sand. Therefore, the unconfined compressive strength of the sample decreased with the increase of the fiber content. An optimal fiber content should be determined for project applications to achieve a good reinforcement effect.

3.2. Calcium Carbonate Content and Permeability Coefficient. It was generally believed that the calcium carbonate produced during the process of microbial solidification of sand will fill the pores between the sand particles and form effective cementation to improve the strength of the sand [33]. The calcium carbonate content was one of the important indicators to evaluate the properties of microbial solidification sand [34, 35]. The calcium carbonate content was defined as the mass of the produced calcite divided by that of the untreated specimen. The mass of the produced calcite for the silica and calcareous sands was measured using an acid washing technique and weighing method, respectively [21]. Figure 8 shows the average content of $CaCO_3$ for the sample with different fiber contents. The silica sand sample without fiber had the lowest calcium carbonate content of 11.30%, while silica sand sample at the optimal fiber content (i.e., 0.2%) showed the highest calcium carbonate content of

Table 3: OD600 and enzyme activity per unit concentration.

Type	OD_{600}	Enzyme activity per unit concentration (mm urea hydrolysed/min)
Silica sand	2.20	4.75
Calcareous sand	1.90	4.30

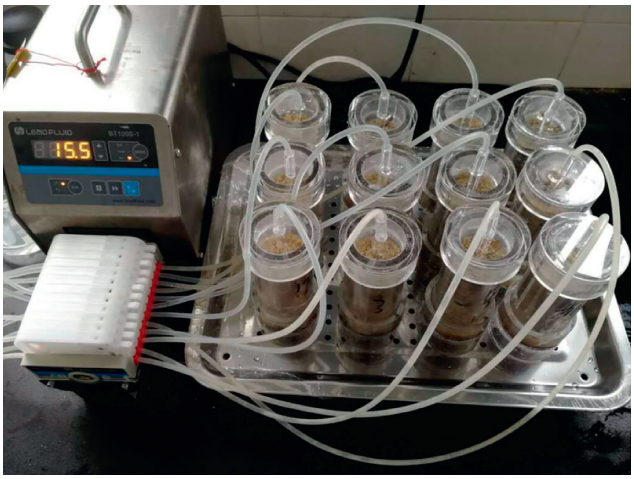


Figure 3: Schematic drawing of the batch reactor.

Figure 4: Microbial solidified sample of silica sand in private mold.

Figure 5: Microbial solidified sample of calcareous sand in private mold.

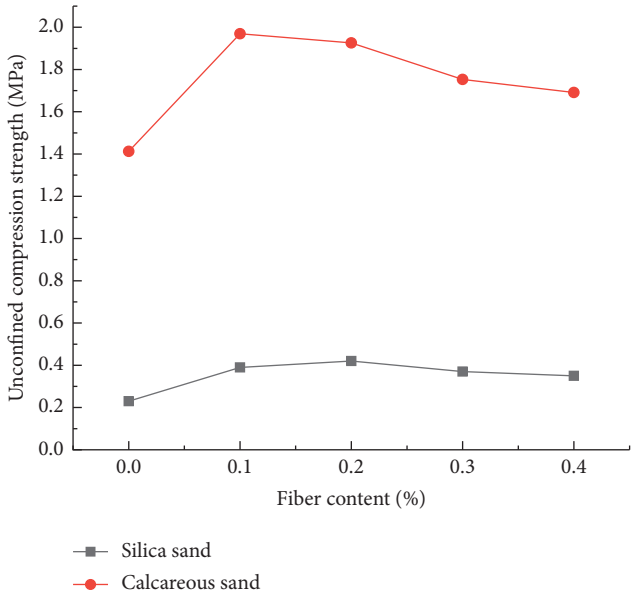


Figure 6: Unconfined compression strength of samples with different fiber contents.

14.58%. In calcareous sand sample, the calcium carbonate content of the sample with the fiber content of 0.0%, 0.1%, 0.2%, 0.3%, and 0.4% was 19.53%, 24.35%, 22.87%, 21.83%, and 21.45%, respectively. The calcium carbonate content of the calcareous sand sample was typically higher than that of the silica sand sample at different fiber contents.

It can be seen that the calcium carbonate content of the fiber-reinforced sand sample was higher than that of the sample without fiber. The change of the calcium carbonate content was increased first and then decreased with the increase of the fiber content, which was consistent with the

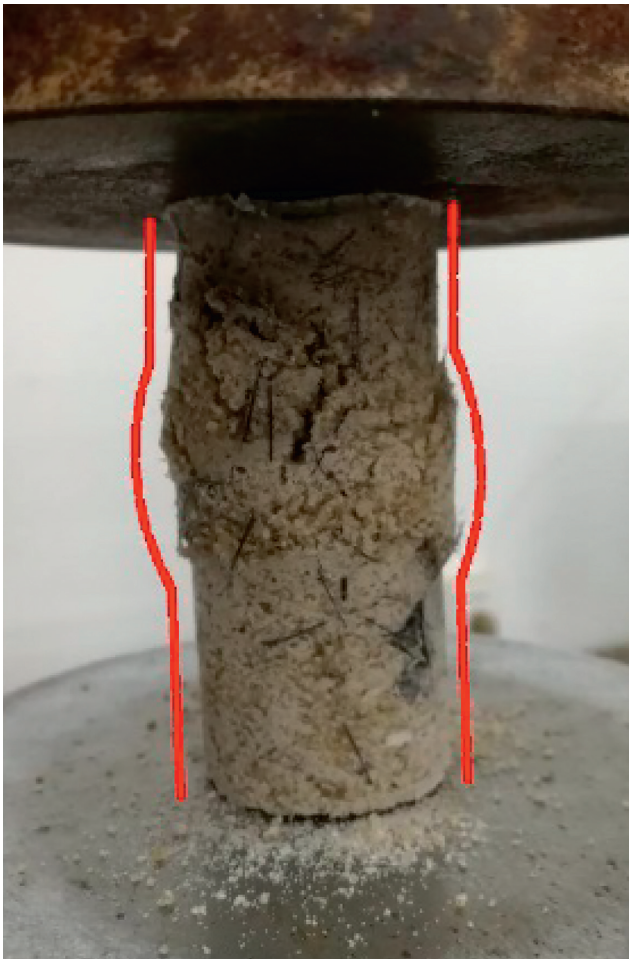


Figure 7: The bulging deformation of the sample reinforced with carbon fiber.

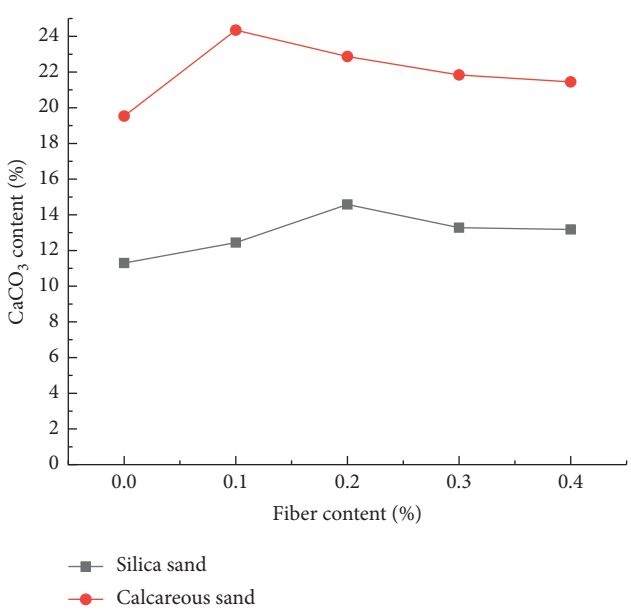


Figure 8: The average content of $CaCO_3$ for the sample with different fiber contents.

trend of the change of the unconfined compressive strength of the sample. This was mainly because the fiber occupied a certain space in the sand sample and increased the growth and colonization area for the microorganism (e.g., the void between sand particles was divided into several small zones and increased the interface area). The area where the microorganism can be planted was larger and more favorable for the formation of calcium carbonate. However, the void in the sand sample was limited. The volume of the space occupied by the fiber increased significantly at higher fiber content. The original growth space of the microorganism was forced to compress, which resulted in a negative effect on the growth of microorganisms. Therefore, the amount of calcium carbonate decreased for the sample with a high fiber content.

In the process of microbial solidification of sand, calcium carbonate continuously formed in the sand sample and wrapped the surface of the particle or filled the void of the sand sample. The void between the sand particles reduced and the permeability of the sample was gradually decreased. The permeability change was one of the important indicators to evaluate the properties of microbial solidification sand. Figure 9 shows the change of the permeability coefficient of the sample with different fiber contents. The permeability coefficient of the sample first decreased and then increased with the increase of the fiber content. The silica sand sample without fiber had the largest permeability coefficient of 1.14×10^{-50} m/s while the silica sand sample with the optimal fiber content (i.e., 0.2%) showed the smallest permeability coefficient of 6.11×10^{-60} m/s. The permeability coefficient of the calcareous sand sample showed similar a trend. When the fiber content was lower than the optimal value, much calcium carbonate was produced by the bacteria and filled the void of the sand sample. The permeability coefficient was decreased with the increase of the fiber content. If the fiber content exceeded the optimal value, the amount of calcium carbonate produced reduced. The permeability coefficient was improved with the increase of the fiber content.

3.3. Mesoscopic Analysis. Figure 10 shows microscope pictures of silica and calcareous sand using optical microscope. Each type of sand under three conditions (i.e., without microbial solidification, using MICP technology, and using MICP technology with the addition of carbon fiber) was prepared and compared. It can be seen that the surface of the calcareous sand before microbial solidification was rougher than the surface of the silica sand, which can provide a favorable growth colonization area for the bacteria and the calcium carbonate formation. The solidified silica and calcareous sand were mostly coated with calcium carbonate after MCIP. Calcium carbonate coated on the surface of the sand particle occupied the void of the sand sample and reduced the permeability of the sand sample. Meanwhile, the amount of calcium carbonate formed in the calcareous sand was obviously more than that in the silica sand, so the permeability coefficient of the calcareous sand was lower than that of the silica sand. For the case with the addition of carbon fiber, the sample behaved as a three-dimensional

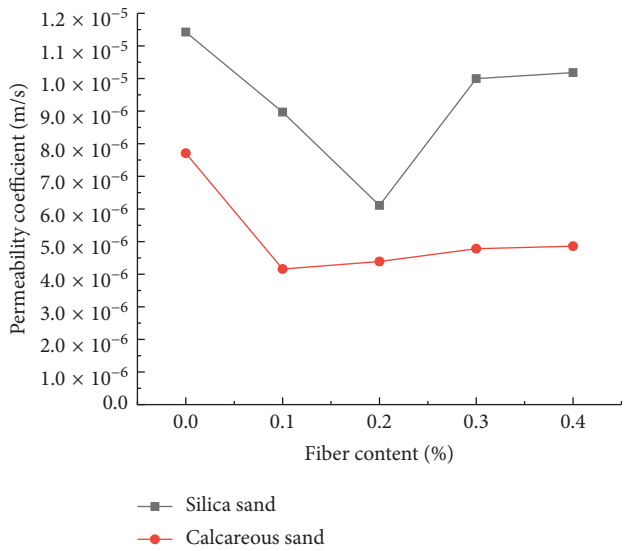


Figure 9: The permeability coefficient of the sample with different fiber contents.

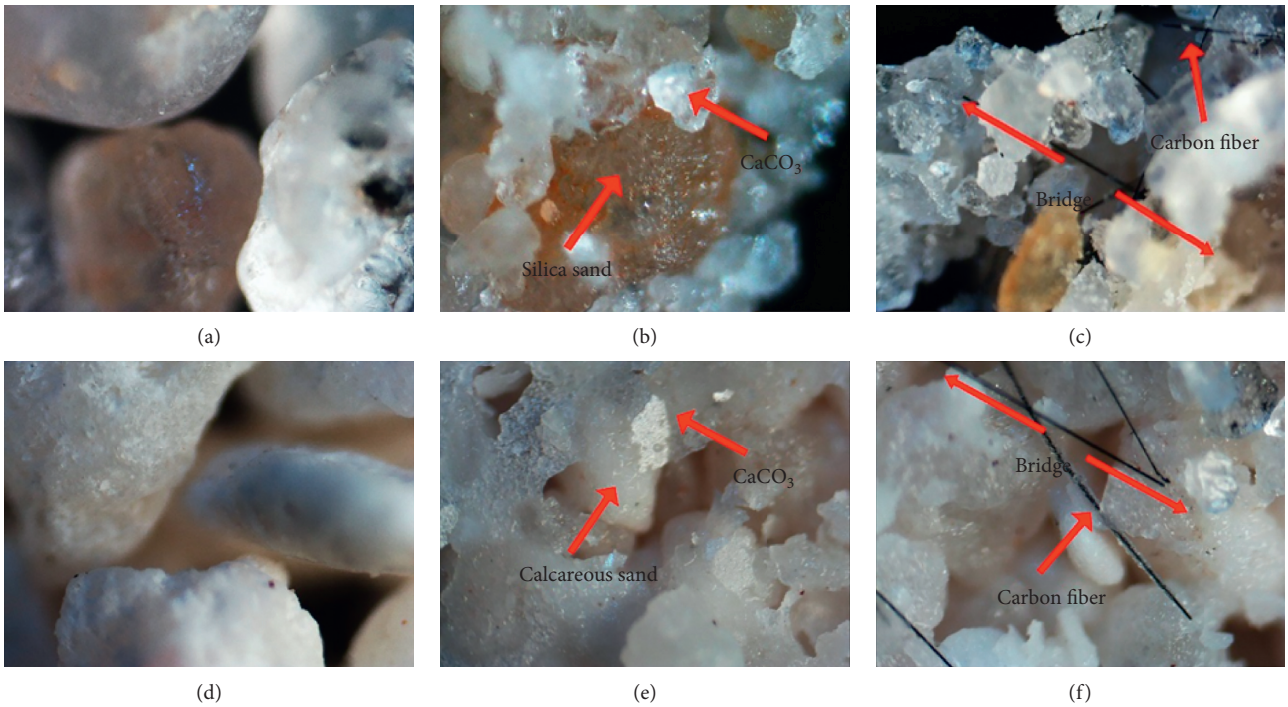


Figure 10: Electron microscope pictures of silica and calcareous sand at different magnification values. (a) Silica sand (100×). (b) After MICP (40×). (c) Reinforced with fiber (40×). (d) Calcareous sand (100×). (e) After MICP (40×). (f) Reinforced with fiber

ribbed structure (as shown in Figure 11). The sand particles and the fiber were bonded together due to the surrounding calcium carbonate, which considerably improved the unconfined compressive strength and the toughness of the sand sample during loading.

3.4. SEM Scanning. The silica and calcareous sand samples at the same fiber content of 2% were selected and analyzed by SEM electron microscopy at different magnifications. The scanning results are shown in Figures 12 and 13. The surface of the calcareous sand was covered with more calcium carbonate. It can be seen that the calcium carbonate in the calcareous sand effectively precipitated and formed a calcium carbonate crystal group, which filled the void between the sand particles and bonded the surrounding sand particles together. This microscale phenomenon was consistent with the observation of the amount of produced calcium carbonate in Figure 8. The amount of calcium carbonate produced in the calcareous sand sample was significantly

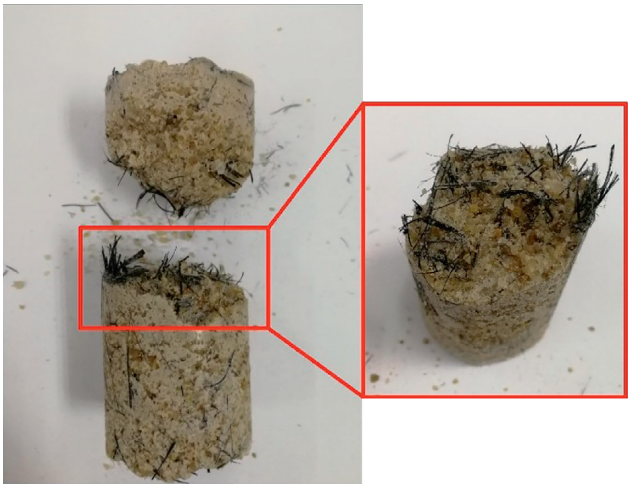
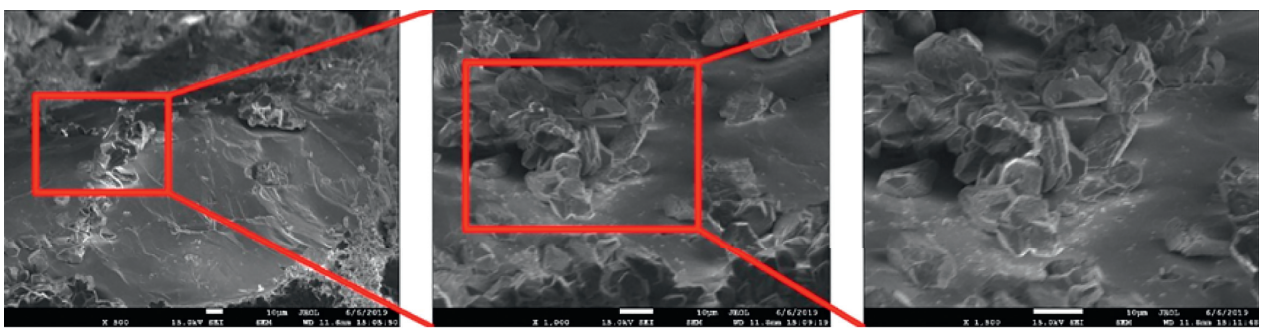
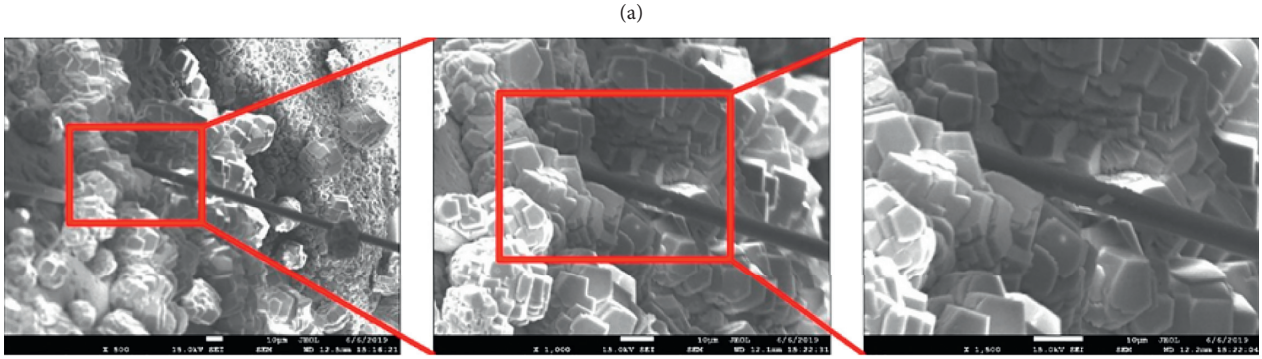


Figure 11: Three-dimensional ribbed structure of the sample with carbon fiber.



500 × magnification 1000 × magnification 1500 × magnification

(a)



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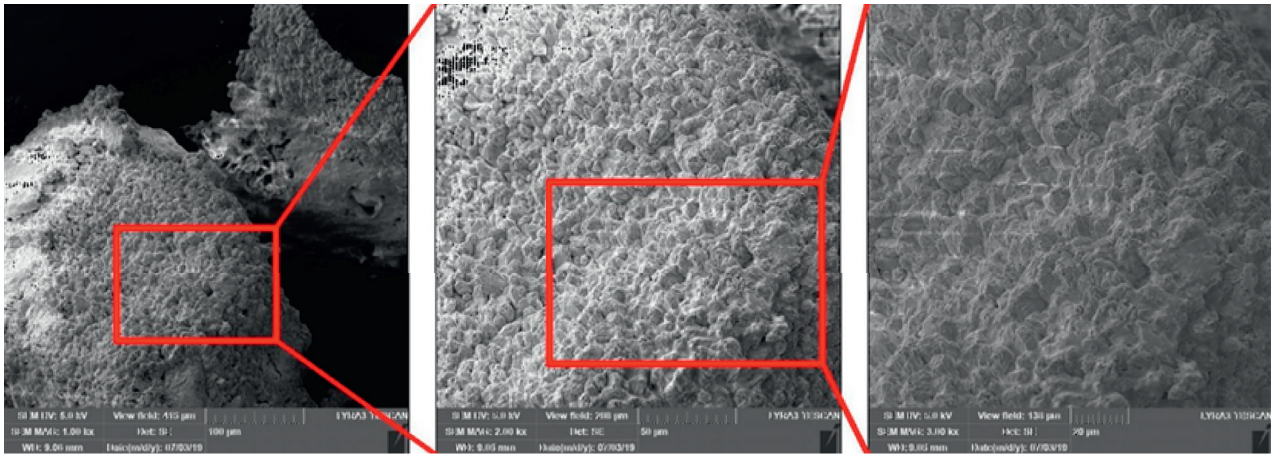
(b)

Figure 12: SEM images of silica sand. (a) Without fiber. (b) With fiber.

higher than that in the silica sand sample. The calcium carbonate filled the void of the sand particles and caused particles to be cemented together, which increased the cohesive strength of the sand sample [36, 37]. The calcium carbonate induced by the microorganisms not only wrapped the surface of the sand particles, but also concentrated in the area which sand particles or the fiber and the particle contacted with.

This is mainly because the fiber provides additional growth and colonization areas for the microorganisms in the sand sample. Microorganisms grow on the surface of the fiber and induced calcium carbonate, which indicated that a certain fiber content was beneficial to the precipitation of the microbial-induced calcium carbonate. The fiber was interwoven in different directions between the calcium carbonate and the sand particle in the sand sample. A three-



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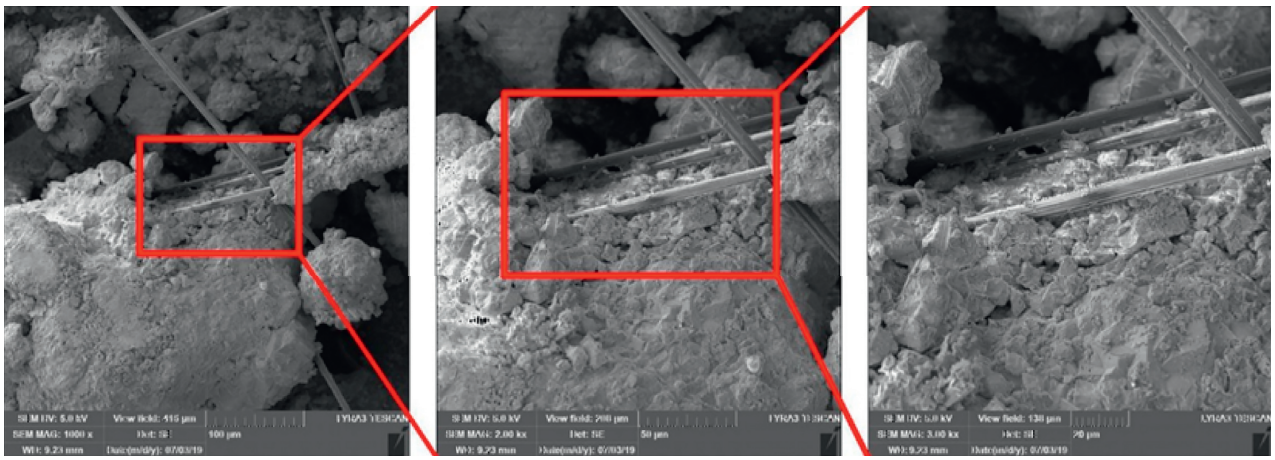
(a)



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(b)

Figure 13: SEM images of calcareous sand. (a) Without fiber. (b) With fiber.

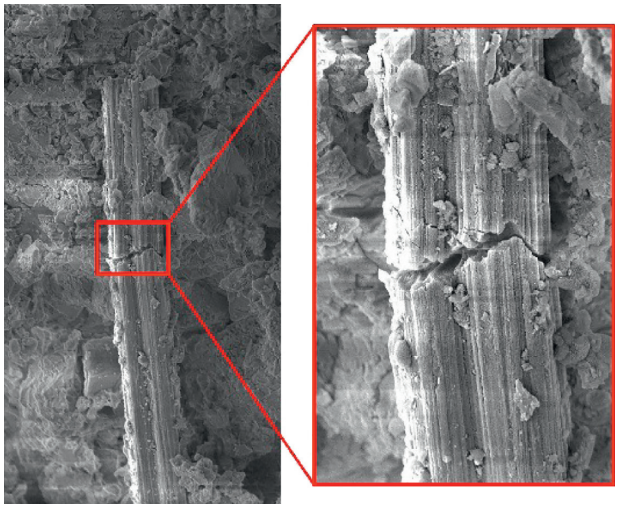

Figure 14: SEM images of fiber breakage.

dimensional network rib structure was developed with the advantage of the fiber, the calcium carbonate, and the sand particle, which effectively restricted the sand particles displacement due to the external loading. Since the calcium carbonate formed on the surface of the fiber had a strong cementation effect, it was advantageous to exert the resistance of the fiber and improve the unconfined compressive strength of the sand sample.

Figure 14 shows the fiber breakage after the unconfined compressive strength test of the sample using SEM electron microscopy. It can be seen that the fiber, the calcium carbonate, and the sand particle bonded together as a whole to carry the external loads. During the loading process, the sample compressed and the weak connection between the calcium carbonate and the sand particle destroyed with the increasing loads. The fracture surface appeared with the relatively large displacement of the sample. The microbial solidified sand without fiber may lose strength instantaneously due to the rapid development of the relative sliding surface (e.g., the brittle failure). However, the microbial solidified sand reinforced with carbon fiber had a strong connection between the fiber, the calcium carbonate, and sand particles. Upon the applied load, the fiber acted as a joint rib. The lateral bulging deformation of the sand sample was gradually developed until failure (as shown in Figure 8). The fiber-reinforced sample lost shear strength until all the fiber in the shear surface broke and it took some time and large deformations. Therefore, the sample showed excellent toughness and ductility after reaching peak compressive strength.

4. Conclusions

This paper investigated the effect of carbon fiber on the mechanical properties of microbial solidified silica and calcareous sand using unconfined compressive strength test, calcium carbonate content test, and permeation test. The SEM electron microscopy was used to scan the microstructure of the microbial solidified sand. The following conclusions were drawn:

(1) The addition of carbon fiber in microbial solidified sand formed a three-dimensional network rib structure in the sand sample. It restricted the development of the failure surface and significantly improved the unconfined compressive strength and toughness of the microbial solidified sand.

(2) The fiber content had a significant effect on the solidification effect of the microbial solidified sand. The unconfined compressive strength of the sample generally increased first and then decreased with the increase of fiber content. The optimal fiber content for silica and calcareous sand was 0.2% and 1%, respectively.

(3) Calcium carbonate content and permeability coefficient were related to the solidification effect of microbial solidified sand. The calcium carbonate content of the fiber-reinforced sand sample was higher than that of the sample without fiber. The sand sample at the optimal fiber content showed the highest calcium carbonate content and the smallest permeability coefficient.

(4) The calcium carbonate induced by the microorganisms not only wrapped the surface of the sand particles, but also concentrated in the area which sand particles or the fiber and the particle contacted with. The bulging deformation of the sand sample was gradually developed along with the fiber breakage.

Data Availability

Some or all data, models, or codes generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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