Arabian Journal of Geosciences (2020) 13:317
https://doi.org/10.1007/s12517-020-05309-7

ORIGINAL PAPER

Influence of different fiber types on properties of biocemented calcareous sand

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Received: 8 August 2019 / Accepted: 31 March 2020

Abstract
Within recent years, microbial induced calcium carbonate precipitation (MICP) technology has been widely applied to ground improvement. The addition of fiber has a great improvement on properties of biocemented sand. This paper studied the influence of three fiber types on properties of biocemented calcareous sand by using MICP technology and discovered the influence mechanism of three fiber types on biocemented calcareous sand. Unconfined compressive strength (UCS) test, tensile strength test, and calcium carbonate content were carried to estimate properties of biocemented calcareous sand. The microstructures of biocemented calcareous sand with fibers and surface of three fiber types were observed under the scanning electron microscope. The test results showed that the ductility, the bridging role, and calcium carbonate content of biocemented calcareous sand with carbon fiber were better, followed by basalt fiber and glass fiber. The UCS, tensile strength, and calcium carbonate content of biocemented calcareous sand increased with the increasing fiber content. The optimum fiber content of biocemented calcareous sand was found to be 1%. Compared with biocemented calcareous sand without fiber, the unconfined compressive strength of biocemented calcareous sand at optimum glass fiber, basalt fiber, and carbon fiber content increased by 458%, 784%, and 1133%, respectively. Meanwhile, the tensile strength of biocemented calcareous sand at optimum basalt fiber, glass fiber, and carbon fiber content increased by 115%, 129%, and 317%, respectively. Therefore, the properties of biocemented calcareous sand with carbon fiber are better than basalt fiber and glass fiber.

Keywords MICP · Sand · Fiber · UCS · Tensile strength · Microstructure

Introduction

The main principle of microbial induced calcium carbonate precipitation (MICP) technology is used to provide nutrients and metal ions for specific microorganisms. Urease is produced by microbial life activity, which breaks down urea to form carbonate ions and ammonia ions. Carbonate ions combine with metal ions to form carbonate precipitation. The carbonate precipitation acts between the soil and makes the loose soil bond into a solid with cementation strength (Cheshomi et al. 2016; Chu et al. 2013; Zhao et al. 2014b). MICP technology is interdisciplinary, simple, efficient, and environmentally friendly, which has a good prospect in civil engineering and material engineering (Sharaky et al. 2018; Bu et al. 2018; Aamir et al. 2018; Liang et al. 2015). Many scholars have made a series of studies on influence of curing effect of MICP technology; they found that the effectiveness of a MICP process were affected by many factors (Muynck et al. 2010; Shahrokhi-Shahraik et al. 2015; Martinez et al. 2012; Mortensen et al. 2011; Cui et al. 2017): the source of calcium ions (Zhang et al. 2014), the concentration of calcium ion and microbial (Qabany and Soga 2013), urease activity of bacteria solution (Qabany et al. 2012), and oxygen availability (Li et al. 2018). Application of MICP technology in engineering field, the main issues to be considered, was the uniformity

Responsible Editor: Zeynal Abiddin Erguler

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Published online: 15 April 2020

and durability of biocemented soil (Farah et al. 2016; DeJong et al. 2010). Cheng and Shahin (2016) proposed a new grouting method for the uniformity problem, but it was limited to the sand column test in laboratory. Meanwhile, Wang et al. (2017) thorough studied the review of ground improvement using MICP technique and found that it was very promising to use the MICP technology to reinforce the ground improvement. Wang et al. (2018) thorough studied the wind erosion resistance and strength of biocemented sand and found that using MICP technique could improve the strength and wind erosion resistance of the sands. Liu et al. (2017) thorough studied the biocementation of calcareous sand using soluble calcium derived from calcareous sand and found that the MICP method had potential to treat calcareous sand. Xiao et al. (2018) through found the dynamic characteristics test of MICP cementing calcareous sand that MICP cementation could significantly improve the anti-liquefaction capacity of calcareous sand.

Fiber is widely applied as a reinforced material to improve the properties of undisturbed soil. Chen et al. (2015) thorough studied the influence of polypropylene fiber on strength of Shanghai soft clay and found that adding fibers could observably enhance ductility and strength of the soil. Boz et al. (2018), through the effect of different fiber types on strength of lime-stabilized clay, found that different fiber types had different reinforcing effects on the samples. Liang et al. (2018), through the effect of fiber on the strength of biocemented ISO standard sand of different particle sizes, found that particle size was 0.25 ~ 0.5 mm; the fibers could enhance the strength of the sample. Choi et al. (2016) found through biocemented, fiber reinforced Ottawa silica sand and that the ductility of biocemented sand with fiber could be increased, and UCS and tensile strength could also be improved. Li et al. (2016), thorough studied the effect of fiber contents on the properties of biocemented sand, found that the influence of adding different fiber contents on UCS and tensile strength of biocemented sand were different; it got the best fiber content. All of these previous studies have shown that MICP technology could improve the properties of the sand, but the brittle failure occurred. At the same time, adding fiber could effectively improve properties and ductility of the soil, and adding fiber in the MICP process could increase the properties and ductility of samples. However, there is limited information about the influence of different fiber types on properties of biocemented calcareous sand. Therefore, it is necessary to study the influence of different fiber types on properties of biocemented calcareous sand in the future research. The purpose of the paper was to study the influence of fiber types on properties of biocemented calcareous sand. In addition, the reasons for the otherness were discovered through the different influences of different fiber types on properties of biocemented calcareous sand.

In the study, fiber types were carbon fiber, basalt fiber, and glass fiber; fiber content was 0.0%, 0.4%, 0.8%, 1%, and 1.2% by weight, respectively. MICP technique was used to treat calcareous sand. The UCS, tensile strength, and calcium carbonate content were measured to compare the effects of three fibers on properties of biocemented calcareous sand, and microstructures of biocemented calcareous sand with fiber and surface of three fiber types were observed under the scanning electron microscope. The detailed experimental work and test results are as follows.

Materials and methods

Materials

Calcareous sand from a reef in the South China Sea was used for this study. The initial void ratio was $e = 0.96$ ($e_{max} = 1.14$, $e_{min} = 0.67$). The dry density was 1.408 g/cm^3. Specific gravity of the sand was 2.76. Calcareous sand was cleaned and dried, and then using geotechnical standard sieved for screening. The grading curve of calcareous sand is shown in Fig. 1.

Fiber length used in the test was 8 mm; the fiber types were carbon fiber, basalt fiber, and glass fiber, respectively. The pictures of three fibers are shown in Fig. 2. The basic physical-mechanical parameters are shown in Table 1.

Microorganism

The freeze-dried *Bacillus* sp. (American Type Culture Collection, ATCC 11859) was used in the test. The reasons for using freeze-dried microorganism were to facilitate the storage a lot of microorganism for future test. The freeze-dried *Bacillus* sp. was activated by slant culture in the incubator, and then, single colonies from slant were dissolved in liquid medium and expanded culture at a 30 °C incubator

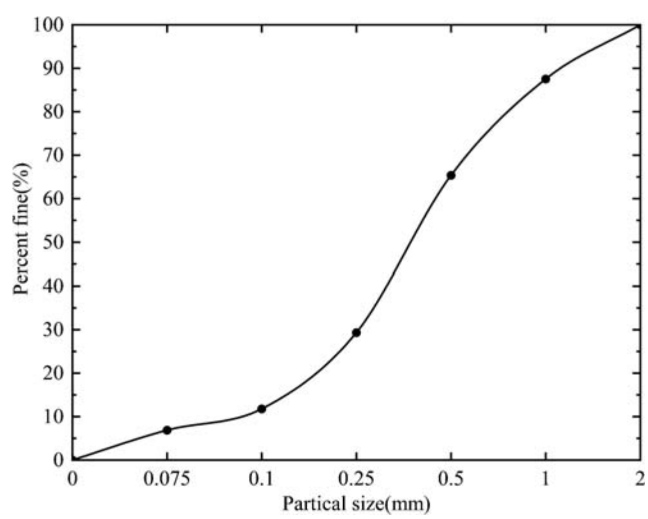


Fig. 1 Grading curve of calcareous sand

(a) Carbon fiber (b) Glass fiber (c) Basalt fiber

Fig. 2 Physical pictures of the three fibers

for 36 h; finally, the bacterial suspension was put in freezer at 4 °C; it must be used within 7 days. The medium for culturing bacteria was made of tryptone (15 g), peptone (5 g), sodium chloride (5 g), urea (20 g), and distilled water (1000 g); the pH value was adjust to 7.3 with sodium hydroxide (1 mol/L). The activity of urease in bacterial suspension was 1.5 mmol/(L min) and the absorbance (OD_{600}) was 1.205 (Zhao et al. 2014a). The cementation solution used in the test was prepared by an equal volume mixture of 1 M urea and 1 M calcium chloride.

Sample preparation

Test device for sample preparation is shown in Fig. 3. The polyvinyl chloride (PVC) tube was used as the test mold and cut evenly in half; the rubber film used in the triaxial test was put into the mold; two separate molds were tightened with the stainless steel throat. Rubber plug with a drain channel was provided at the bottom and upper of the mold. Finally, the assembled sample mold was fixed on the iron support, and the silicone tube was connected with the peristaltic pump.

This paper studied the influence of three fiber types on properties of biocemented calcareous sand. Fiber length was 8 mm, and the fiber content was 0%, 0.4%, 0.8%, 1%, and 1.2%, respectively. The unconfined compressive strength, tensile strength, and calcium carbonate content were measured. The test results are shown in Table 2.

In order to prepare for the samples of biocemented calcareous sand, calcareous sand was firstly placed into the mold. Three types of dry fibers were added into dry calcareous sand and mixed by hands until the fibers were uniformly distributed. After mixing, the mixture was placed into the 50 mm in diameter by 100 mm height PVC tube in 10 layers with each layer compacted to be 10 mm height. The reason to use 10 layers was to insure the uniform fiber distribution in the specimens (Park 2011).

Specimen preparation process was presented in the following: (1) 100 mL (pore volume of 1.2 times) of bacterial suspension was pumped into the specimen from the top at a rate of 5 mL/min and drained out from the bottom, let stand 20 min. (2) After the completing exudation of the bacterial suspension, then 100 mL of cementation solution was pumped into the specimen from the bottom at a rate of 10 mL/min and drained out from the top, let stand 2 h; the aim was to make the mixture and solution fully react; then, the bottom drain was opened. (3) Three times of above steps were repeated; it was set to a curing cycle. The curing cycle was repeated 14 times and the mold was removed after drying.

Tests and methods

Out of the 2 groups of specimens at each fiber type and fiber content, 1 group of sample was prepared for unconfined compressive strength tests and the other group for tensile strength tests. After the strength test, samples damaged were collected and prepared for the measure of calcium carbonate content. The method for determination of calcium carbonate content was ASTM D4373 (2014). The method for UCS test was ASTM D2166 (2013). The method for tensile strength test was ASTM C496 (2011).

Table 1 Physical-mechanical parameters of fiber

Fiber types	Density (g/cm^3)	Diameter (μm)	Tensile strength (MPa)	Elasticity modulus (GPa)	Tensile fracture rate (%)
Basalt fiber	2.65	10	3500	100	2
Glass fiber	2.71	14	1700	7.0 ~ 8.0	2.0 ~ 3.5
Carbon fiber	1.76	7	3800	230	1

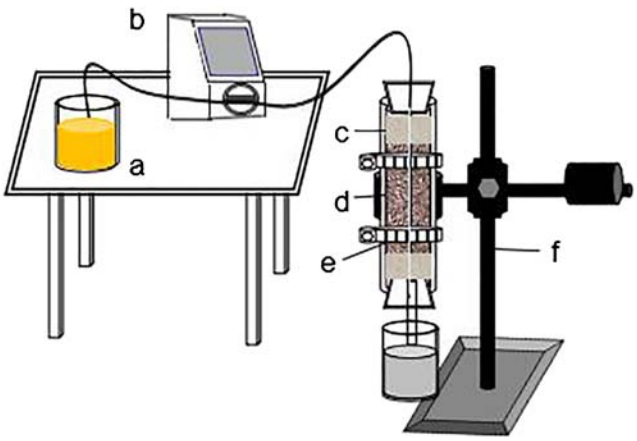


Fig. 3 Testing device (**a** bacterial suspension/cementation solution; **b** peristaltic pump; **c** isolating layer; **d** sand column; **e** PVC split mold; **f** metal rod)

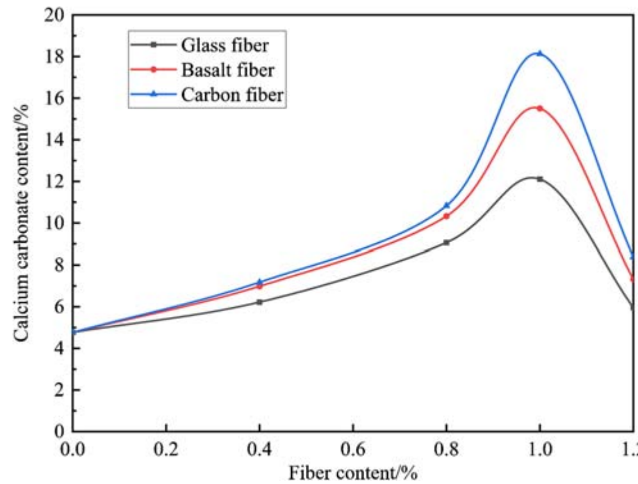


Fig. 4 Effect of fiber content on calcium carbonate content

The specimen size for unconfined compressive strength test was 50 mm diameter by 100 mm height; the loading rate adopted in the test was 1 mm/s. The sample size for tensile strength test was 50 mm diameter by 50 mm height; the loading rate adopted in the test was 0.5 mm/s.

Results and discussions

Calcium carbonate content

Figure 4 shows with the same fiber length, the calcium carbonate content of biocemented calcareous sand with three fiber types increases firstly then decreases with the increasing fiber content and calcium carbonate content in the fiber content with 1% is the maximum. However, under the same fiber content, different fiber types of biocemented calcareous sand have different effects on increasing the accumulation of calcium carbonate. Compared with biocemented calcareous sand without fiber, when the fiber content is 1%, the calcium carbonate content of biocemented calcareous sand with carbon fiber is the highest, followed by basalt fiber and glass fiber. The reason for this phenomenon is that the fibers are used to bridge the pores between the sand particles to enhance the MICP process (Choi et al. 2016). As the fiber content increases, the bridging of fibers is more obvious, so the calcium carbonate content is greater.

Shear strength

Figure 5 shows the stress-strain curves of all samples. It is shown that the stress-strain curves acquired from UCS of biocemented calcareous sand with different fiber types and fiber content are presented in three sections: (1) The samples

Table 2 Testing results

Fiber types	Fiber content (%)	Average calcium carbonate content (%)	UCS(kPa)	Tensile strength (kPa)
Without fiber	0	4.768	590	291
Basalt fiber	0.4	6.986	833	143
	0.8	10.322	3422	241
	1	15.504	4232	335
	1.2	7.327	998	421
Glass fiber	0.4	6.222	721	152
	0.8	9.059	1936	187
	1	12.104	2702	375
	1.2	5.864	849	455
Carbon fiber	0.4	7.177	1056	615
	0.8	10.823	3724	781
	1	18.127	6685	992
	1.2	8.386	1357	1131

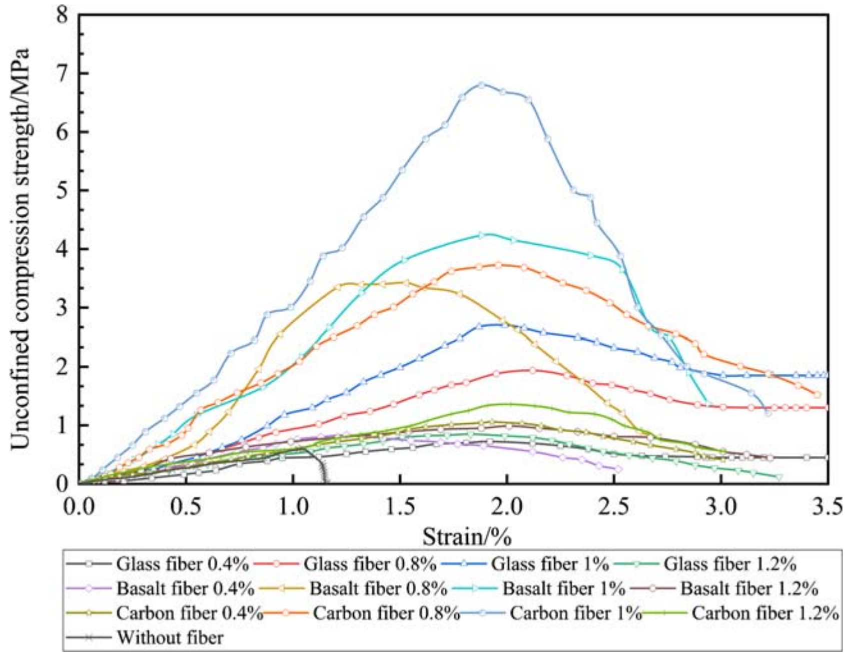


Fig. 5 Stress-strain curves

are gradually compacted; stress increases rapidly with strain. (2) The stress of the samples has been destroyed at maximum value. (3) Stress decreases with the development of strain and finally tends to be stable. The stress-strain curve of the biocemented calcareous sand without fiber has only the first two stages, which is a typical brittle failure. The observation result is consistent with the previous research results (Li et al. 2016; Choi et al. 2016). However, the stress-strain curves of biocemented calcareous sand with fibers all enter the third stage. Therefore, it shows that the addition of fiber can effectively control the deformation and improve ductility of biocemented calcareous sand. It can be also seen that the stress of biocemented calcareous sand with carbon fiber decreases more slowly with strain at the same fiber content. This indicates that ductility of biocemented calcareous sand with carbon fiber is better than that of basalt fiber and glass fiber.

Figure 6a and b shows the effect of fiber content on UCS and tensile strength, respectively. It is shown in Fig. 6a that the UCS of biocemented calcareous sand with three fiber types increases firstly and finally decreases with the increasing in fiber content, and under the samples of same fiber type, the highest unconfined compressive strength is all the biocemented calcareous sand with 1% fiber. Under the same fiber content, three fiber types have different improvement effect on UCS of biocemented calcareous sand. When the content of glass fiber, basalt fiber, and carbon fiber is 1%, UCS of biocemented calcareous sand increases to 2702 kPa, 4232 kPa, and 6685 kPa, respectively. However, when the fiber content is too high (e.g., 1.2%), the interaction between calcareous sand particles and fibers will gradually replace the interaction of between calcareous sand particles and particles; the influence of fibers on UCS of biocemented calcareous

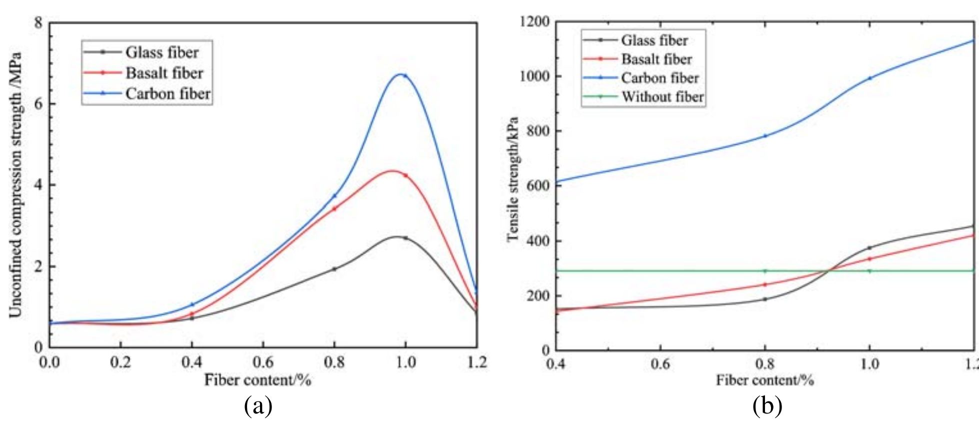


Fig. 6 Effect of different fiber content on strength. **a** Unconfined compressive strength. **b** Tensile strength

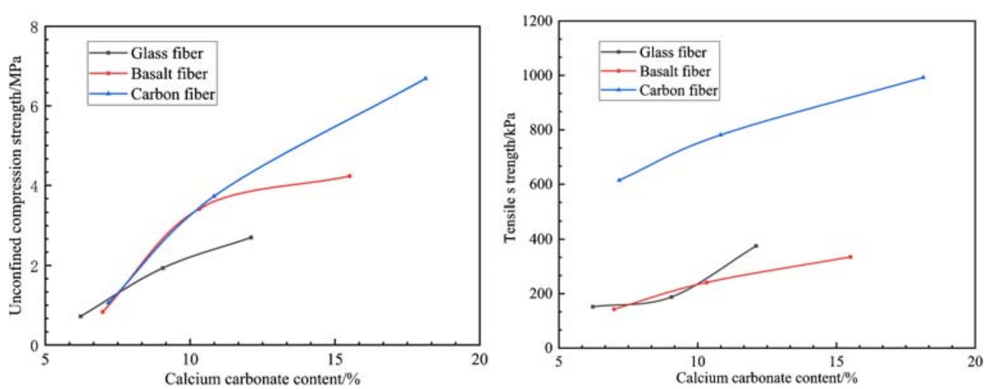
sand will decrease after reaching the peak. It is shown in Fig. 6b that tensile strength of biocemented calcareous sand with the same fiber type gradually increases with the increasing fiber content. When fiber contents are 0.4% and 0.8%, tensile strength of biocemented calcareous sand with basalt fiber and glass fiber decreases. However, tensile strength of biocemented calcareous sand with carbon fiber increases to 614 kPa and 781 kPa, respectively. Compared with biocemented calcareous sand without fiber, when fiber content is 1.2%, tensile strength of biocemented calcareous sand with basalt fiber, glass fiber, and carbon fiber increases to 421 kPa, 455 kPa, 1131 kPa, respectively.

The reasons for these phenomena are that it can be seen from Table 1 the monofilament quality of glass fiber is the maximum, followed by basalt fiber and carbon fiber. Therefore, under the same mass condition, the number of carbon fiber roots is the maximum, followed by basalt fiber and glass fiber. The more the fibers are added, the more the fibers are filled the pores of the calcareous sand particles, and the number of interwoven fibers between the grains is increased, many interwoven fibers form more spatial distribution networks (Jiang et al. 2010), so the fibers can effectively control the lateral deformation and improve the ductility of biocemented calcareous sand. Meanwhile, carbon fiber has the highest elastic modulus and tensile strength, followed by basalt fiber and glass fiber. Therefore, carbon fiber has the best stirrup effect on calcareous sand particles in the process of the sample damage, followed by basalt fiber and glass fiber. In addition, the number of carbon fiber roots is the maximum at the same mass condition; thus, the ductility, the stirrup effect, and calcium carbonate content of biocemented calcareous sand with carbon fiber are better, followed by basalt fiber and glass fiber, so the UCS and tensile strength of biocemented calcareous sand with carbon fiber are higher than basalt fiber and glass fiber.

Figure 7a and b shows the effect of calcium carbonate content on UCS and tensile strength of biocemented calcareous sand, respectively. It is shown that as the calcium carbonate content increases from approximately 5–18%, both the UCS and tensile strength of biocemented calcareous sand with same fiber type increase with the increase of calcium carbonate content. It is shown in Fig. 7a that the UCS of biocemented calcareous sand with carbon fiber increases from 1056 to 6685 kPa with the increase of calcium carbonate content; it increases significantly more than the biocemented calcareous sand with basalt fiber and glass fiber. Similarly, as shown in Fig. 7b, tensile strength of biocemented calcareous sand with carbon fiber increases from 614 to 992 kPa with the increasing calcium carbonate content; the increase of tensile strength of biocemented calcareous sand with basalt fiber and glass fiber is not obvious. It also shows that UCS and tensile strength of biocemented calcareous sand with carbon fiber are improved significantly. This implies that the content of calcium carbonate has great influence on UCS and tensile strength. Calcium carbonate is used as a material to bond loose calcareous sand together; the increase of calcium carbonate content significantly improves properties of biocemented calcareous sand.

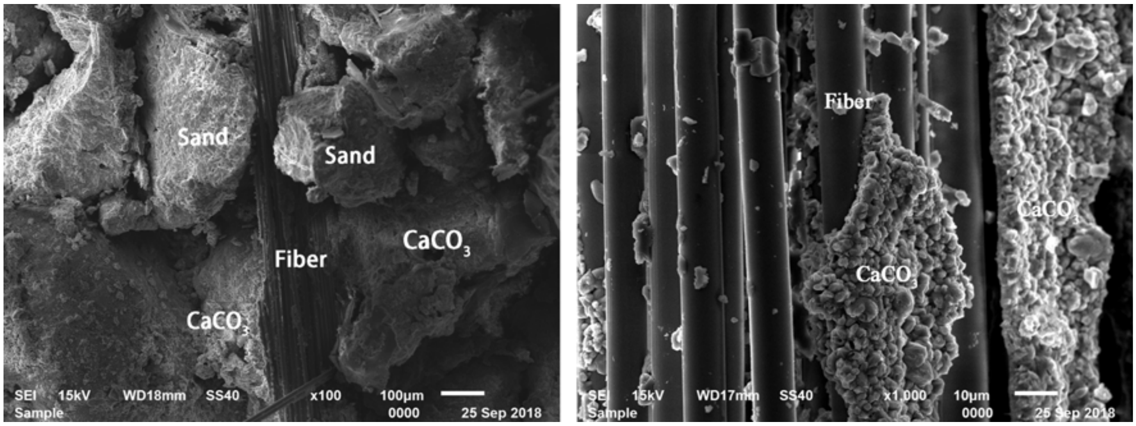
Microstructures

The specimens after strength tests were used for scanning electron microscope (SEM). The fiber specimen image is shown in Fig. 8; it is shown that the fiber fills in the voids and enhances the cementation between the sand grains. It also shows that calcium carbonate attaches to the surface of the fiber. It is suggested that the fiber plays the bridging role in the process of biocemented calcareous sand. The observation is similar to the previous research results (Choi et al. 2016). However, different fiber types have different surface microstructures; it leads to different microbial adsorption capacities on the surface of the fibers. Therefore, the adsorbing amount of calcium carbonate on the fiber surface is different, and the forms of contacting with sand particles are different. Finally, the bridging role of fiber in biocemented calcareous sand is affected; this leads to the different fiber types with different effects on mechanical properties of biocemented calcareous sand.



(a) (b)

Fig. 7 Effect of different calcium carbonate content on strength. **a** Unconfined compressive strength. **b** Tensile strength



(a) Fibers bridge sand grain and help calcium carbonate fill voids (b) Calcium carbonate attaches to the surface of the fibers

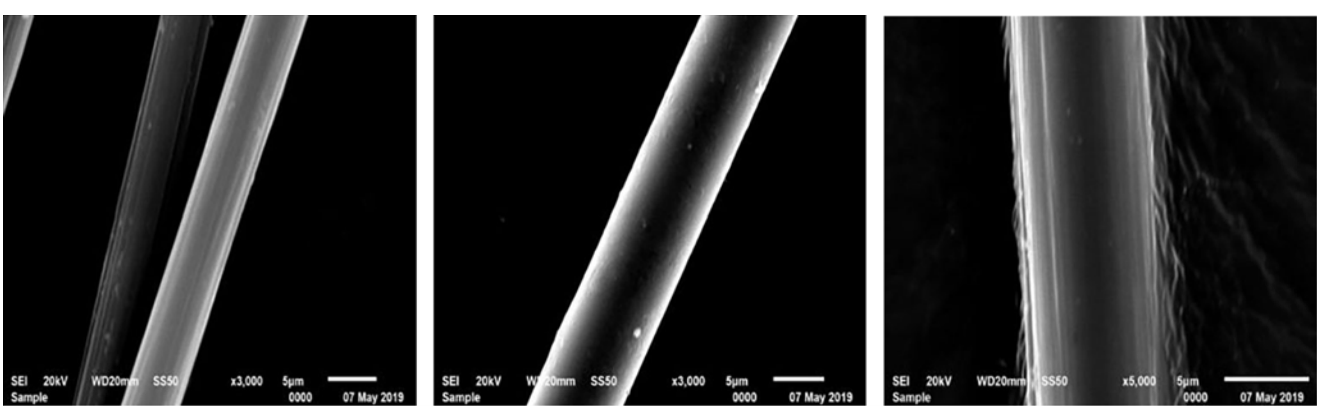
Fig. 8 SEM photos of biocemented calcareous sand with fibers. **a** Fiber bridge sand grain and help calcium carbonate fill voids. **b** Calcium carbonate attaches to the surface of the fibers

Basalt fiber, glass fiber, and carbon fiber were observed by SEM. It is shown in Fig. 9 that the surface of glass fiber and basalt fiber is smooth. However, the surface of carbon fiber is rough and uneven, which presents barb structure. Meanwhile, Table 1 shown that the number of carbon fiber roots is the maximum at the same mass condition, followed by basalt fiber and glass fiber, so carbon fiber has a stronger adsorption capacity for microorganism and bridging role than basalt fiber and glass fiber; thus, calcium carbonate content of biocemented calcareous sand with carbon fiber is the most abundant. Therefore, the improvement effect on properties of biocemented calcareous sand with carbon fiber is the most remarkable.

Conclusions

The influence of different fiber types on properties including UCS, tensile strength, and calcium carbonate content of biocemented calcareous sand was studied. The fiber types were carbon fiber, glass fiber, and basalt fiber, respectively; fiber content was 0.0%, 0.4%, 0.8%, 1.0%, and 1.2%; the microstructures of the biocemented calcareous sand with fiber and the surface of three fiber types were observed under a scanning electron microscope. The conclusions are as followed.

1 Adding fibers could improve ductility of the biocemented calcareous sand. Meanwhile, the ductility of biocemented calcareous sand with carbon fiber was better than that of basalt fiber and glass fiber. Compared with biocemented calcareous sand without fiber, calcium carbonate content of biocemented calcareous sand with glass fiber, basalt fiber, and carbon fiber was increased by 2 times, 3 times, and 4 times, respectively.
2 Under the same fiber length, the UCS and tensile strength of biocemented calcareous sand increased with the increasing fiber content. Optimum fiber content of



(a)Basalt fiber (b) Glass fiber (c) Carbon fibe

Fig. 9 The surface microstructures of the three fiber types biocemented calcareous sand was found to be 1%. Compared with biocemented calcareous sand without fiber, the UCS of biocemented calcareous sand at optimum glass fiber, basalt fiber, and carbon fiber content increased by 458%, 784%, and 1133%, respectively. Meanwhile, the tensile strength of biocemented calcareous sand at optimum basalt fiber, glass fiber, and carbon fiber content increased by 115%, 129%, and 317%, respectively.

3 The scanning electron microscopy photos had shown that calcium carbonate was attached to the surface of fibers. The fibers enhanced the MICP process by bridging the pores in calcareous sand. The surface of carbon fibers was rougher, and the number of carbon fiber roots was the maximum at the same mass condition, followed by basalt fiber and glass fiber, so carbon fiber had a stronger adsorption capacity for microorganism and bridging role than basalt fiber and glass fiber, and thus, calcium carbonate content of biocemented calcareous sand with carbon fiber was the most abundant. Therefore, the improvement effect on mechanical properties of biocemented calcareous sand with carbon fiber was the most remarkable.

Acknowledgments The authors appreciate the National Natural Science Foundation of China, no. 41877267, 41372316, 41472287, and no. 41602314.

Funding information This work is supported by the Priority Research Program of the Chinese Academy of Science, Grant no. XDA13010201.

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