

Stabilization of cement-soil utilizing microbially induced carbonate precipitation

Shuang Li^{1a}, Ming Huang^{*1}, Mingjuan Cui¹, Peng Lin², Liudi Xu² and Kai Xu¹

¹College of Civil Engineering, Fuzhou University, Fuzhou 350108, Fujian, China

²Department of Civil and Environmental Engineering, Shantou University, Shantou, 515063 Guangdong, China

(Received December 1, 2022, Revised September 5, 2023, Accepted September 11, 2023)

Abstract. Soft soil ground is a crucial factor limiting the development of the construction of transportation infrastructure in coastal areas. Soft soil is characterized by low strength, low permeability and high compressibility. However, the ordinary treatment method uses Portland cement to solidify the soft soil, which has low early strength and requires a long curing time. Microbially induced carbonate precipitation (MICP) is an emerging method to address geo-environmental problems associated with geotechnical materials. In this study, a method of bio-cementitious mortars consisting of MICP and cement was proposed to stabilize the soft soil. A series of laboratory tests were conducted on MICP-treated and cement-MICP-treated (C-MICP-treated) soft soils to improve mechanical properties. Microscale observations were also undertaken to reveal the underlying mechanism of cement-soil treated by MICP. The results showed that cohesion and internal friction angles of MICP-treated soft soil were greater than those of remolded soft soil. The UCS, elastic modulus and toughness of C-MICP-treated soft soil with high moisture content (50%, 60%, 70%, 80%) were improved compared to traditional cement-soil. A remarkable difference was observed that the MICP process mainly played a role in the early curing stage (i.e., within 14 days) while cement hydration continued during the whole process. Micro-characterization revealed that the calcium carbonate filling the pores enhanced the soft soil.

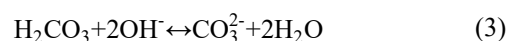
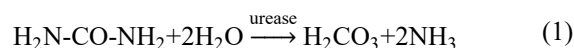
Keywords: cement-soil; mechanical properties; MICP; soft soil foundation

1. Introduction

Soft soils are widely distributed in coastal areas, which have the natural properties of low permeability, low strength, high organic matter and high compressibility, posing a challenge for the development of transportation infrastructure construction (Wang *et al.* 2019, Yao *et al.* 2019, Lang *et al.* 2021). An established way is to utilize the cement to solidify the soft soil. It has been demonstrated that chemical solidification and physical interaction can significantly improve the mechanical and physical properties of soft soil including compressive strength (Anagnostopoulos 2015). However, organic matter has negative influence on the effect of cement solidification. Tremblay *et al.* (2002) studied the effect of 13 kinds of organic matter on the strength of cement-soil, and found that most of them had adverse effects on the solidification of cement. Jonah Abbey (2019) also found the organic matter would affect the performance of organic soil treated by cement. Besides, ordinary cement-soil is also susceptible to plastic shrinkage, low early strength caused by incomplete hydration, and strength loss from water loss (Mosallanejad *et al.* 2017, Yao *et al.* 2017). Moreover, more

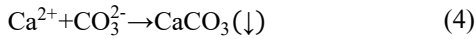
than 4.2Gt of greenhouse gases are emitted into the atmosphere each year from Ordinary Portland Cement (OPC) production, which accounts for around 12% of total manmade carbon dioxide production (Hassan *et al.* 2020), and around 8% of global carbon dioxide emissions (Benhelal *et al.* 2013). Consequently, air pollution causes serious damage to human health and the ecological environment (Bushlaibi and Alshamsi 2002, Gao *et al.* 2013, Ghadir and Ranjbar 2018).

As an alternative, MICP has attracted great attention among researchers (Achal and Kawasaki 2016, Ivanov *et al.* 2019, Omeregic *et al.* 2021, 2021). The urease enzymes are produced by bacteria and then catalyzes the hydrolysis of urea to H₂CO₃ and NH₃. NH₃ hydrolysis to form ammonium ions and hydroxide ions, while H₂CO₃ hydrolyzes into carbonate ions. Bacterial cell wall can adsorb Ca²⁺ due to their negative charge. And then the CO₃²⁻ and Ca²⁺ combine to form CaCO₃, continuously depositing on the bacteria serving as nucleation templates. OH⁻, in turn, raise the pH of the surrounding environment of bacteria, facilitating the precipitation of CaCO₃. The main reaction process of MICP can be expressed as follows



*Corresponding author, Professor
E-mail: huangming05@fzu.edu.cn

^aPh.D. Student
E-mail: cuglishuang@163.com



MICP technique shows a great potential in improving strength (Montoya and DeJong 2015, Cui *et al.* 2021c, Huang *et al.* 2021, Ma *et al.* 2022, Wang *et al.* 2023), stiffness (Thomas O'Donnell and Kavazanjian Jr 2015, Lin *et al.* 2020), permeability (Glover *et al.* 2006, Zamani and Montoya 2017, Kirkland *et al.* 2020, Jiang *et al.* 2021), durability (Jin *et al.* 2020, Sun *et al.* 2021, Gowthaman *et al.* 2022, Imran *et al.* 2022), and homogeneity of CaCO_3 distribution (Cheng *et al.* 2019, Tian *et al.* 2021, Yang *et al.* 2022) of multi-type sand and soil. Besides, the MICP technique has also been utilized to enhance the thermal conductivity of sand (Wang *et al.* 2020, Xiao *et al.* 2021), steel slag (Li *et al.* 2023) and so on. However, few studies focus the improvement of soft soil treated by bio-cemented method. Kannan *et al.* (2020) found that the liquid limit and plastic limit of MICP-treated marine clay soil decreased by 29% and 47%, at same time, the shear strength increased by 148%. The maximum value of UCS of biostimulated soft soil in research of Islam *et al.* (2020) was only 50 kPa in a saturated state. Cheng and Shahin (2015) introduced three different bio-cemented methods to treat the clayed sand. No matter which treatment method was, the UCS of clayed sand always decreased with the increase of clay content. And the values of UCS ranged from 100 kPa to 1400 kPa.

The limit of the study of Cheng and Shahin (2015) was that the material was sand instead of pure clay soil thereby obtaining higher UCS of MICP-treated specimens. Therefore, Gowthaman *et al.* (2021) introduced the scallop shell powder to peat cooperated with MICP to enhance the mechanical strength of peat. However, the maximum value of UCS of MICP-treated peat was only 50 kPa. In brief, the current studies on MICP treatment clay soil could not effectively increase the strength of clay soil, and the mechanical strength rarely meets the requirement for engineering construction. Although, the cement is still widely used to treat the soft soil foundation, although it can bring some environment issues. Therefore, combining the MICP technology with cement for the solidification of soft soils is expected to increase the soil strength while keeping the cement content at a relatively low level, which has been demonstrated in enhancing the strength of granite residual soil (Li *et al.* 2022).

A triaxial test was performed on the MICP-treated soft soil with various concentrations of OD_{600} and CCS as pre-experiment to validate the feasibility of MICP in solidifying the soft soil and obtain the optimal parameters of MICP process for C-MICP-treated soft soil experiment. The main test investigated the effect of bio-cementitious mortars on improving the mechanical performance of soft soil (i.e., C-MICP-treated soft soil). The mechanical properties and strength growth patterns of the C-MICP-treated soft soil were analyzed by varying moisture content (50%-80%) and curing time (7-28 days) compared to OPC soft soil. Additionally, scanning electron microscopy (SEM) was conducted to analyze the microstructure of MICP-treated and C-MICP-treated soft soil.

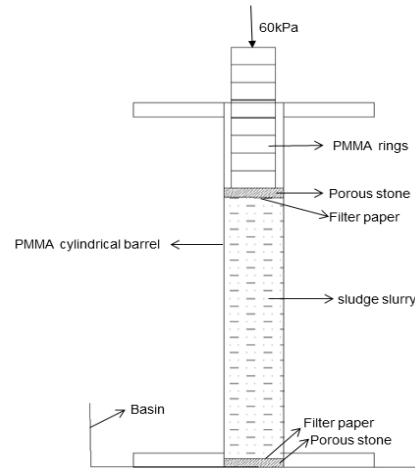


Fig. 1 Remolded soft soil preparation

2. Materials and methods

2.1 Materials

Sporosarcina pasteurii, a type of urease-producing bacteria, was used in this study. The sterilized growth medium included 20g/l yeast extract, 15 g/l NH_4Cl , and 0.1 mM NiCl_2 , at pH=9.25. The bacterial culture was then inoculated into a conical flask and cultured in a shaker at 30°C at 150 rpm for 24 hours. The cementation solution was 1.0 M calcium chloride and 1.0 M urea (Whiffin *et al.* 2007). The concentration of the bacteria was determined by measuring the optical density via an ultraviolet spectrophotometer at a wavelength of 600 nm. After culturing for about 36 hours, the bacteria were harvested, and the OD_{600} value was 1.2, with urease activity of 11 U/ml. The properties of soft soil were as follows: nature moisture content 54%, porosity ratio 1.483, liquid limit 60.2%, plastic limit 33.5%, organic matter content 5.6% and it was oven-dried at 60°C for 48 h before the experiment. The spilt modules with 39.1 mm diameter and 80 mm height were used to prepare the samples.

2.2 Testing program and sample preparation

2.2.1 Preparation of remolded soft soil sample

The procedure of preparing the remolded soft soil is modified according to the study of Fan *et al.* (2020). The soft soil was first mashed with a rubber mallet, and then the soil slurry with a moisture content of 200% was produced by mixing the soft soil with a predetermined quantity of deionized water. After fully immersing for 7 days, the soil slurry passed through a 2 mm sieve to remove the shell and gravel. Next, the soil slurry was stirred in a mixer for 20 min to obtain homogeneous soil slurry. Afterward, the soil slurry was slowly poured into a cylindrical barrel (height 60 cm and inner diameter 9 cm) made of polymethyl methacrylate (PMMA) along the barrel wall. Notably, a porous stone was placed on the bottom of the barrel with a piece of filter paper placed on the top. The height of the sludge slurry was 50 cm, and a porous stone with filter

Table 1 Sample arrangement for the experiment of MICP-treated soft soil

	No.	OD_{600}	Cementation solution concentration (mol/L)	Moisture content (%)	Curing time (days)	Confining pressure (kPa)
Control Group	1	0	Deionized water	50	3, 7, 14, 28	
Test Group	2	0.3	0.5	50	7, 14, 28	
Test Group	3	0.3	1.0	50	3, 7, 14, 28	
Test Group	4	0.3	1.5	50	7, 14, 28	
Test Group	5	0.3	2.0	50	7, 14, 28	
Test Group	6	0.6	0.5	50	7, 14, 28	
Test Group	7	0.6	1.0	50	3, 7, 14, 28	100, 200, 300
Test Group	8	0.6	1.5	50	7, 14, 28	
Test Group	9	0.6	2.0	50	7, 14, 28	
Test Group	10	0.9	0.5	50	7, 14, 28	
Test Group	11	0.9	1.0	50	3, 7, 14, 28	
Test Group	12	0.9	1.5	50	7, 14, 28	
Test Group	13	0.9	2.0	50	7, 14, 28	

Table 2 Sample arrangement for the experiment of C-MICP-treated soft soil

	No.	Water content(%)	Cement mixing ratio(%)	Water-cement ratio	Treatment method
Test Group	I	50	10	0.5	MICP
Test Group	II	60	10	0.5	MICP
Test Group	III	70	10	0.5	MICP
Test Group	IV	80	10	0.5	MICP
Control Group	V	50	10	0.5	Deionized water
Control Group	VI	60	10	0.5	Deionized water
Control Group	VII	70	10	0.5	Deionized water
Control Group	VIII	80	10	0.5	Deionized water

paper, which was on the bottom of the porous stone, was also placed on the top surface of the sludge slurry. Next, six rings made of PMMA and weights were placed on the porous stone one by one to obtain the total pressure of 60 kPa (Fig. 1). The standard samples (height 80 mm and diameter 39.1 mm) were prepared after the sludge slurry was consolidated for 3 months.

2.2.2 Application of bio-cementitious mortar treatment in soft soil

The soft soil that passed through a 2 mm sieve was divided into two parts, which were used to prepare the MICP-treated soft soil samples and C-MICP-treated soft soil samples according to Tables 1 and 2, respectively. Notably, the deionized water was used to replace the bacteria solution and cementation solution.

The procedures for sample preparation are as follows: (1) The bacteria solution and cementation solution (adding cement for C-MICP-treated sample) was mixed first and then poured into the soft soil for 10 min to achieve uniformity. (2) Then, the mixture was transferred into the split modules. Two detachable plastic lids were used to seal both ends. (3) After 24-48 hours of curing, the stabilized soil specimens were removed from the molds and wrapped using plastic bags, cured in the controlled environment

Table 3 The pH of C-MICP-treated soft soil at different curing time

Water content	pH of C-MICP-treated soft soil			
	0.5 h	2.0 h	12.0 h	24.0 h
50%	9.95	10.25	10.75	10.11
60%	9.84	9.97	10.36	10.03
70%	9.65	9.86	10.14	9.91
80%	9.49	9.52	9.97	9.58

($25\pm 2^\circ\text{C}$ and 95% relative humidity). Additionally, the pH of mixing of C-MICP-treated soft soil was measured at the 0.5h, 2h, 12h and 24h after all materials mixed. The results were listed in Table 3. And the experiment on the effect of pH on the bacteria activity was also carried out, which was displayed in Fig. 2. It can be seen the bacteria activity first increased and then decreased as the pH increased. Notably, the bacterial activity was about 6.5 U/mL when the pH was 11.0, which is about 60% of maximum value (11 U/mL) of bacteria activity when pH was 9.0. The change trend of bacteria activity with the increase of pH was similar to the result of Whiffin (2004). Therefore, the bacteria could maintain higher activity (at least ~ 7.54 U/mL).

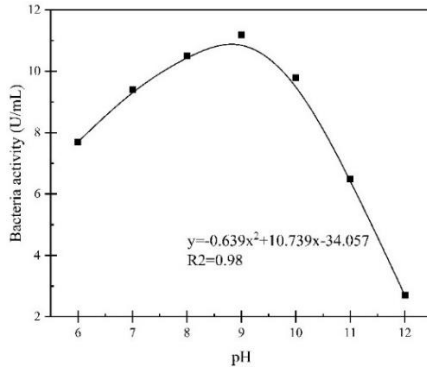


Fig. 2 Variation of bacteria activity on different pH

2.3 Testing methods

The MICP-treated samples were applied to a triaxial compression test (unconsolidated and undrained, UU) with confined pressure of 100, 200, and 300 kPa. The shear rate was 0.08 mm/min (Lo and Wardani 2002, Zhao *et al.* 2019), and the experiment ended when the strain reached 20%. Separately, the uniaxial compression tests of C-MICP-treated soft soil were conducted at a strain rate of 2.5% per hour (Mortensen and DeJong 2011, Montoya and DeJong 2015) until the samples were destroyed.

The internal friction angles φ and cohesion c of MICP-treated samples were calculated from the Mohr circle envelope. For the C-MICP-treated samples, the UCS was obtained through a UC test, and the elastic modulus and toughness were obtained from the stress-strain curves, as shown in Fig. 3. After the UU test and UC test, SEM analysis was conducted on the remolded soil, MICP-treated and C-MICP-treated samples.

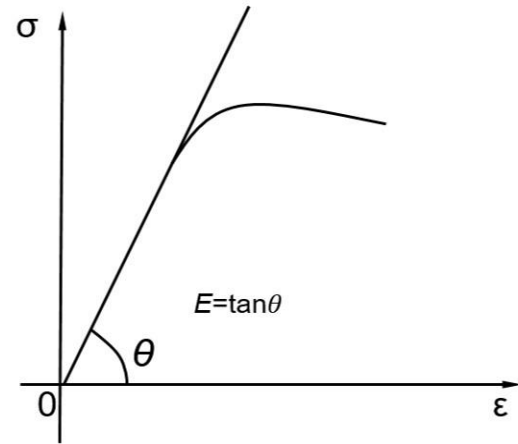
3. Results

3.1 Mechanical indexes improvement of MICP-treated soft soil

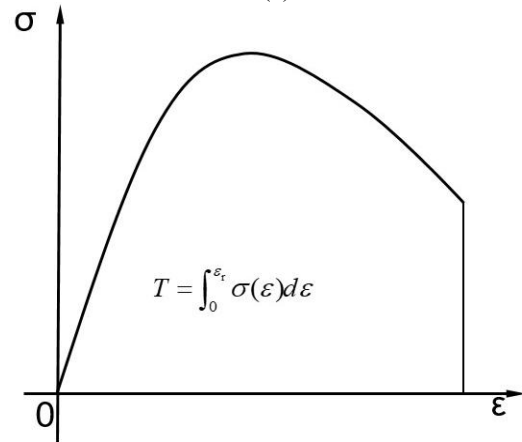
Internal friction angle and cohesion are two basic mechanical indexes of the shear strength of the soil. To assess the variation of parameters of bio-cemented soft soil, the internal friction angle and cohesion (i.e., φ and c) are compared in Fig. 4. For the internal friction angle (Fig. 4(a)-4(c)), it exhibits a similar trend that the φ values increase with the increase of optical density (OD_{600}); however, the φ values increase with the CCS from 0.5 M to 1.0 M and decrease with the CCS from 1.0 M to 2.0 M. It should be noted that when the curing time varies from 7 days to 28 days at given CCS, the φ values increase gradually. The maximum value of φ is 15.3° of 28 days, which is about 1.18 times that of 7 days.

The trend of c is similar to that of φ (as shown in Figs. 5(a)-5(c)). As CCS keeps increasing, the c increases first then start to drop, and it increases with the increasing of OD_{600} .

The curing time has a positive effect on c promotion, for instance, the maximum value of c on 28 days is 1.43 times than that of 7 days.



(a)



(b)

Fig. 3 Schematic diagrams for calculating elastic modulus and toughness

The variation of c and φ with respect to curing time and the calcium carbonate content versus curing time were presented in Fig. 6. The c values of bio-cemented soil samples increase with increasing curing time. In contrast, the c values of the remolded soil sample remain constant at about 5.6 kPa (Fig. 6(a)). Additionally, the curve reveals that the c values sharply increase with increasing curing time, especially from 3 days to 7 days, with increment rates of 58.67%, 79.71% and 106.60%, respectively. When curing time varies from 7 days to 28 days, it shows a slow increase in c , indicating that the effect of curing time gradually weakens. As for the internal friction angle, the φ values of bio-cemented soft soil are about 2.4 times, 2.83 times, and 3.06 times, respectively, for $OD_{600}=0.3, 0.6$ and 0.9 compared with those of remolded soil samples at 3 days (Fig. 6(a)). As shown in Fig. 6(b), the maximum value of CCC was only approximately 0.72% when $OD_{600}=0.9$ at 28 days, indicating that MICP was limited in soft soil. Besides, it was found that the increment in CCC at a given OD_{600} gradually declined with increase of curing time, especially, the when the curing time varied from 14 to 28 days, the CCC almost no longer increased. However, it also could be observed that the increment in CCC rapidly increased in 7 days implying that the MICP process only played a role in the early stage of curing.

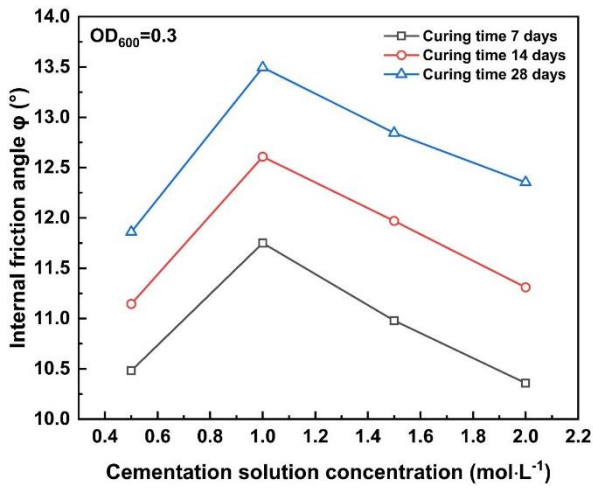
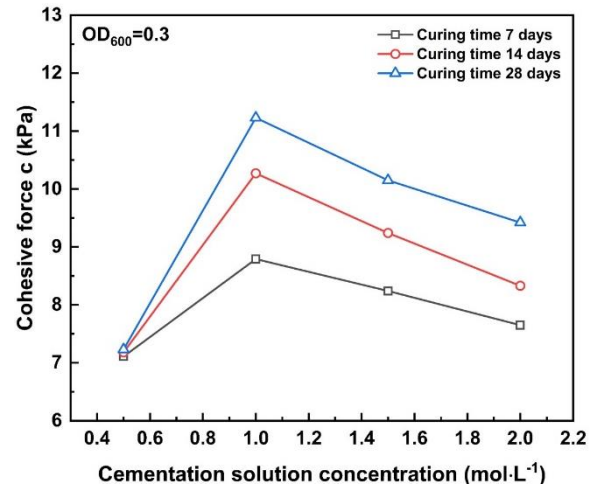
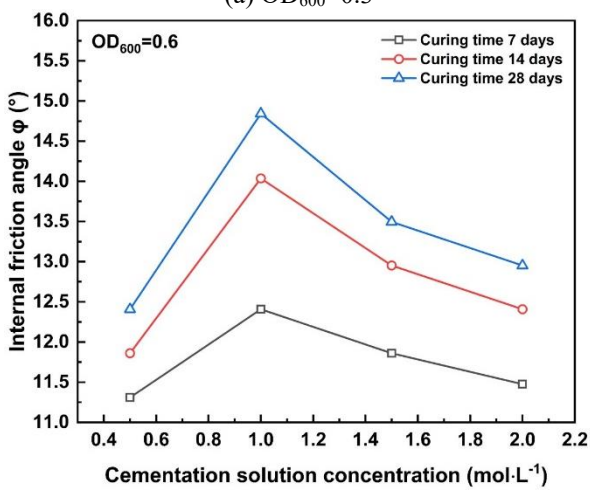
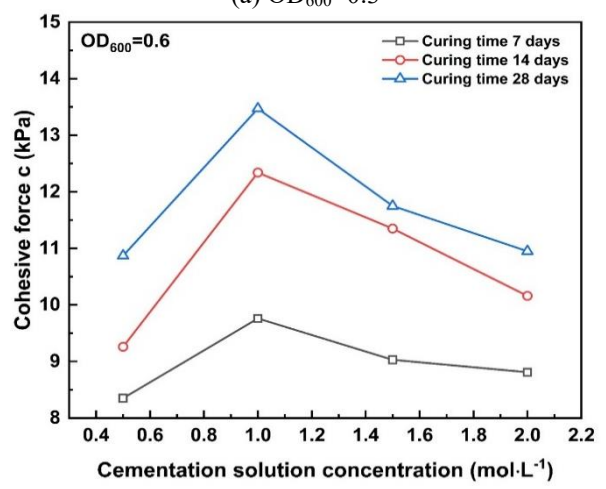
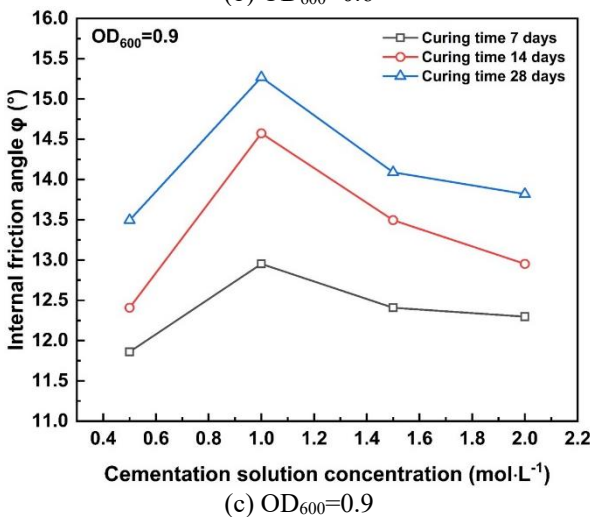

 (a) $OD_{600}=0.3$

 (a) $OD_{600}=0.3$

 (b) $OD_{600}=0.6$

 (b) $OD_{600}=0.6$

 (c) $OD_{600}=0.9$

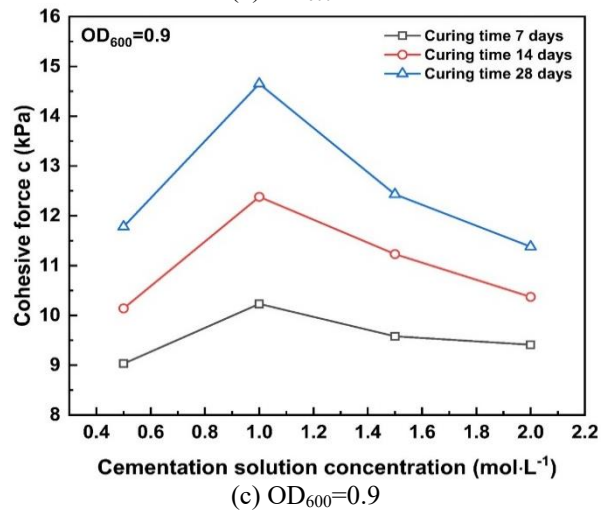
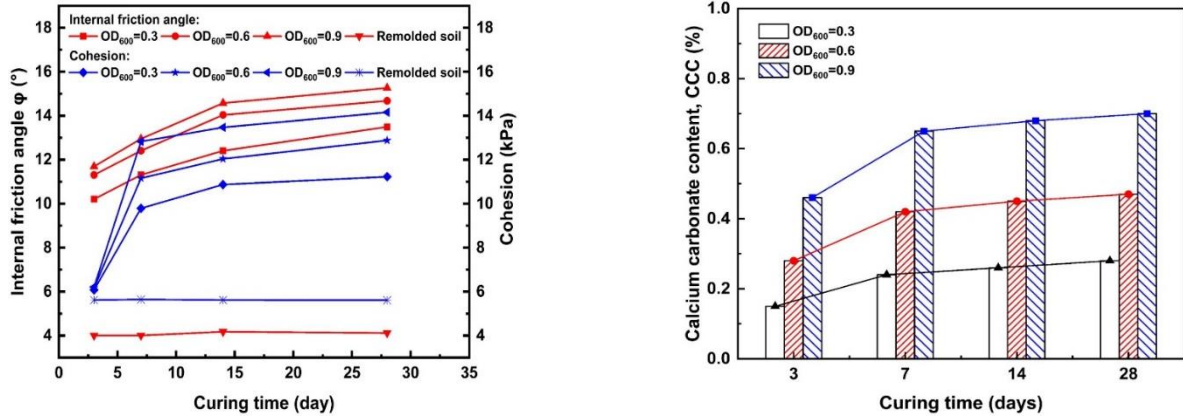
 Fig. 4 Variations of the ϕ of MICP-S soft soil

 (c) $OD_{600}=0.9$

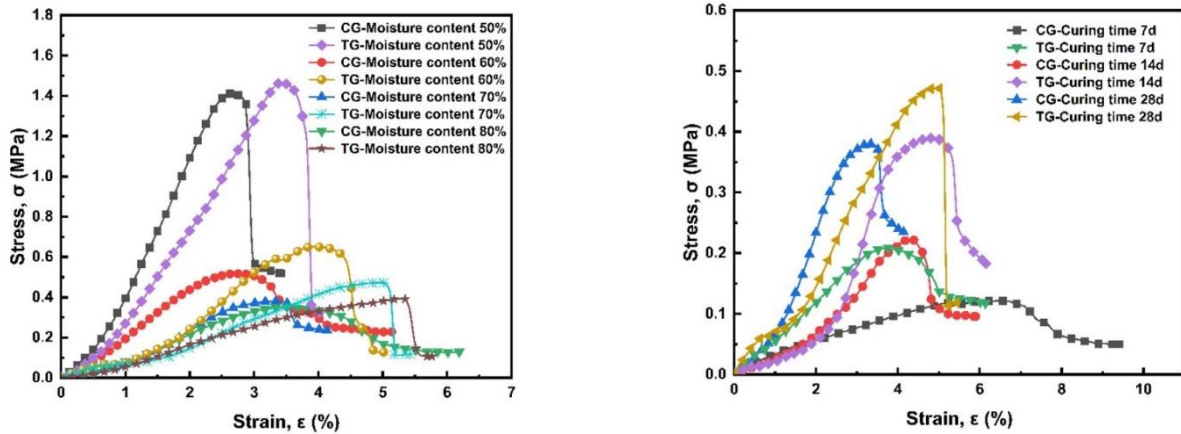
 Fig. 5 Variations of c of MICP-S soft soil

The variation of c and ϕ with respect to curing time and the calcium carbonate content versus curing time were presented in Fig. 6. The c values of bio-cemented soil samples increase with increasing curing time. In contrast, the c values of the remolded soil sample remain constant at about 5.6 kPa (Fig. 6(a)). Additionally, the curve reveals that the c values sharply increase with increasing curing

time, especially from 3 days to 7 days, with increment rates of 58.67%, 79.71% and 106.60%, respectively. When curing time varies from 7 days to 28 days, it shows a slow increase in c , indicating that the effect of curing time gradually weakens. As for the internal friction angle, the ϕ values of bio-cemented soft soil are about 2.4 times, 2.83 times, and 3.06 times, respectively, for $OD_{600}=0.3$, 0.6 and



(a) Variations of c and ϕ (b) Variation of calcium carbonate content
 Fig. 6 Variation of mechanical parameters and calcium carbonate with the increase in curing time



(a) Comparison between OPC soil (CG) and C-MICP-treated soft soil (TG) at curing time of 28 day (b) Comparison between ordinary cement-soil (CG) and C-MICP-treated soft soil (TG) at moisture content of 70%

Fig. 7 Stress-strain curves of C-MICP treated soft soil

0.9 compared with those of remolded soil samples at 3 days (Fig. 6(a)). As shown in Fig. 6(b), the maximum value of CCC was only approximately 0.72% when $OD_{600}=0.9$ at 28 days, indicating that MICP was limited in soft soil. Besides, it was found that the increment in CCC at a given OD_{600} gradually declined with increase of curing time, especially, the when the curing time varied from 14 to 28 days, the CCC almost no longer increased. However, it also could be observed that the increment in CCC rapidly increased in 7 days implying that the MICP process only played a role in the early stage of curing.

3.2 Mechanical behaviour of C-MICP-treated soft soil

3.2.1 Stress-strain behaviour

All stress-strain curves exhibit strain-softening behaviour. The stress-strain curves in Fig. 7 can be divided into four sections: the first stage: initial compaction; the second stage: elastic deformation; the third stage: plastic strengthening; and the fourth stage of post-peak failure. It is clear that the stress-strain curves of both the OPC soil (i.e., control group, CG) and C-MICP-treated soft soil (i.e., test group, TG) show that the slope of the curves and the peak

strength gradually decrease with the increase in moisture content; however, the strain corresponding to the peak strength gradually increases, as shown in Fig. 7. The stress of MICP-treated soft soil in the test group decreased rapidly after failure, and strain softening is more noticeable than in the control group, which indicates that MICP had a more significant influence on the brittleness of cement-soil than cement-granite residual soil (Li *et al.* 2020, Li *et al.* 2022). Additionally, the effect of curing time on the strength of OPC soil was shown in Fig. 8(b), which is consistent with granite residual soil treated by bio-cementitious mortars (Li *et al.* 2022). Moreover, the failure patterns of all specimens were shear failure and tensile failure (Fig. 8). It should be noted that the tensile failure in Fig. 8(a. II) and (b. V) was caused by stress concentration due to the shear failure. As for the tensile failure in Fig. 8(b. IV), it was due to the damage of the weak structural plane in the specimens.

3.2.2 Strength characteristics of C-MICP-treated soft soil

Figs. 9 (a)-9(c) presents the evolution of the UCS of all soil samples treated by C-MICP method. Results reveal that values of UCS decrease with the increase of moisture

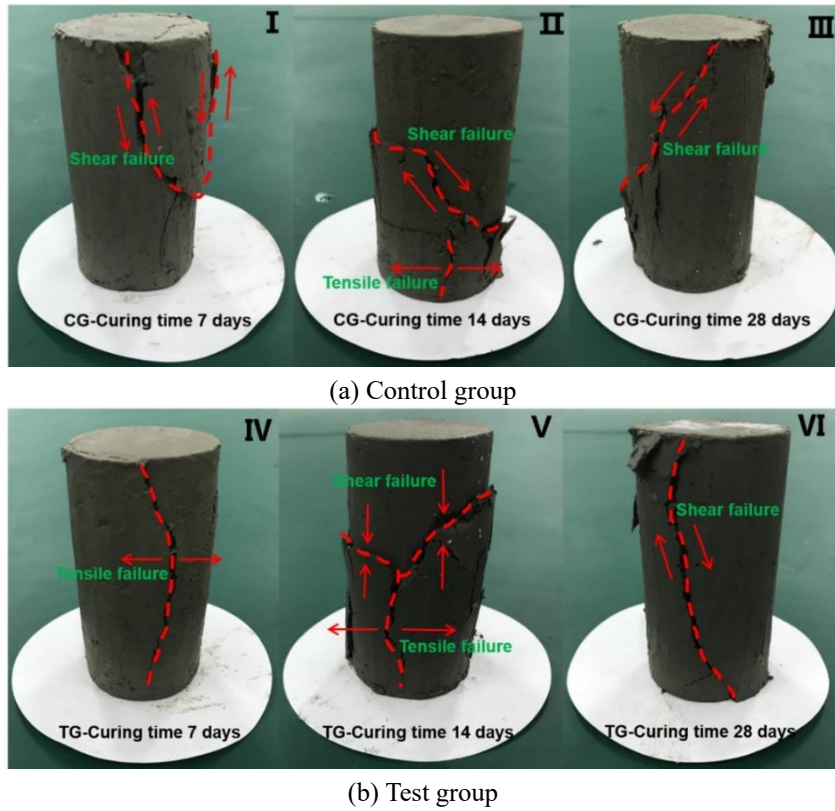


Fig. 8 The failure model after the UCS test

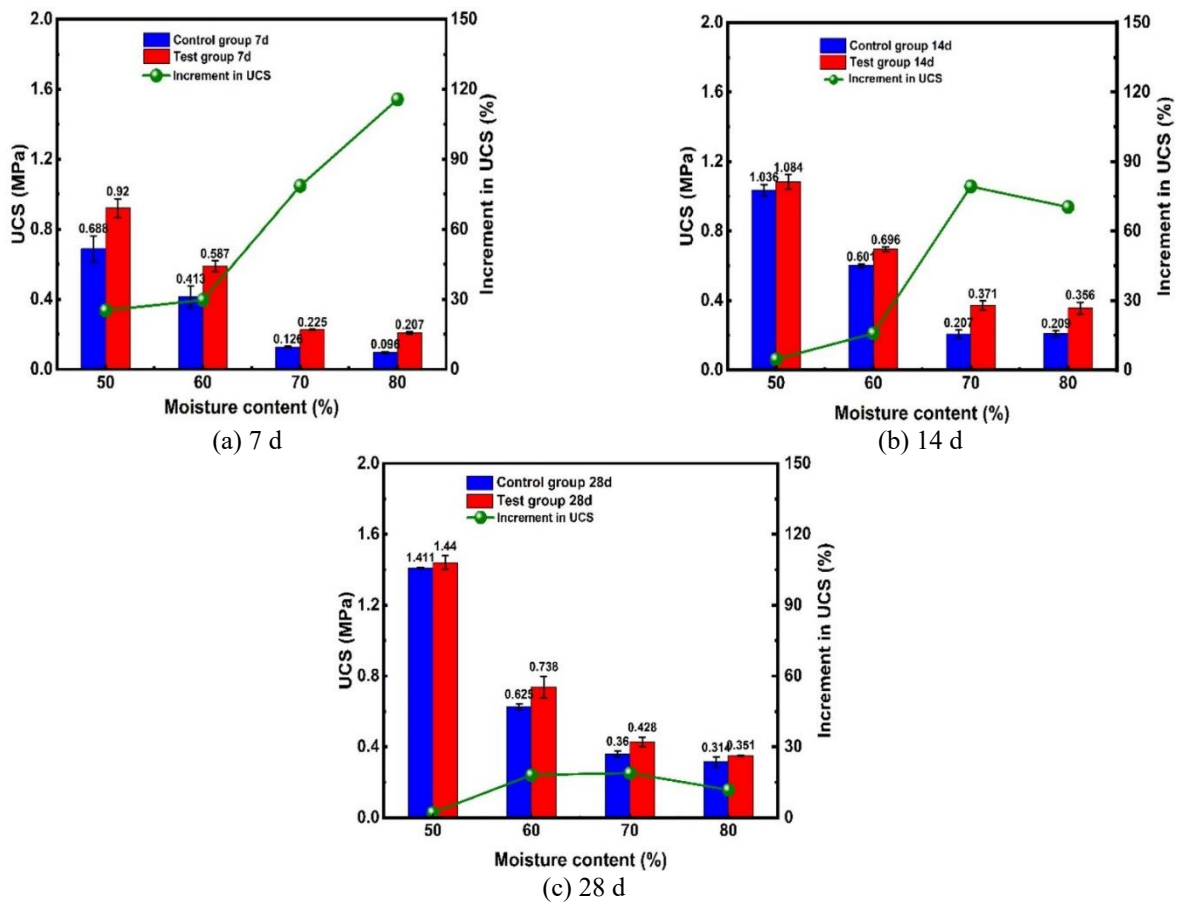


Fig. 9 Comparison of average UCS in different curing time

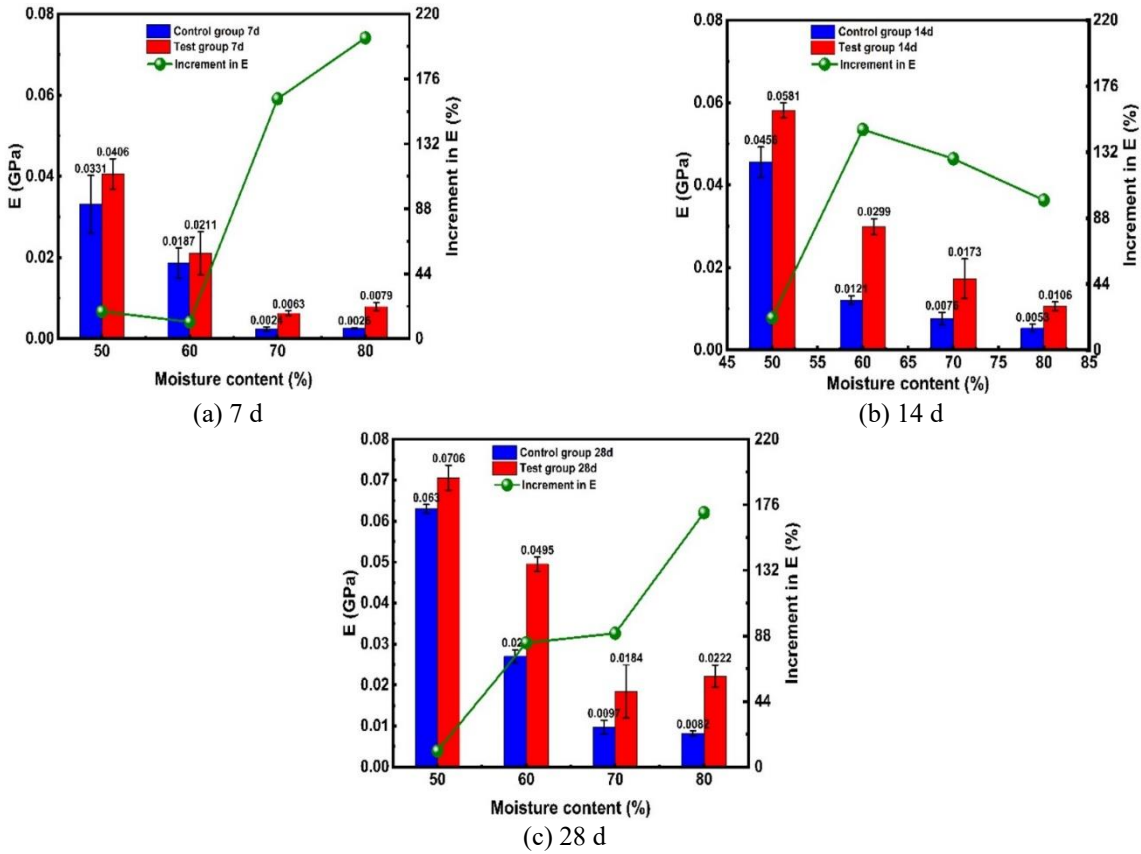


Fig. 10 Comparison of average elastic modulus in different curing time

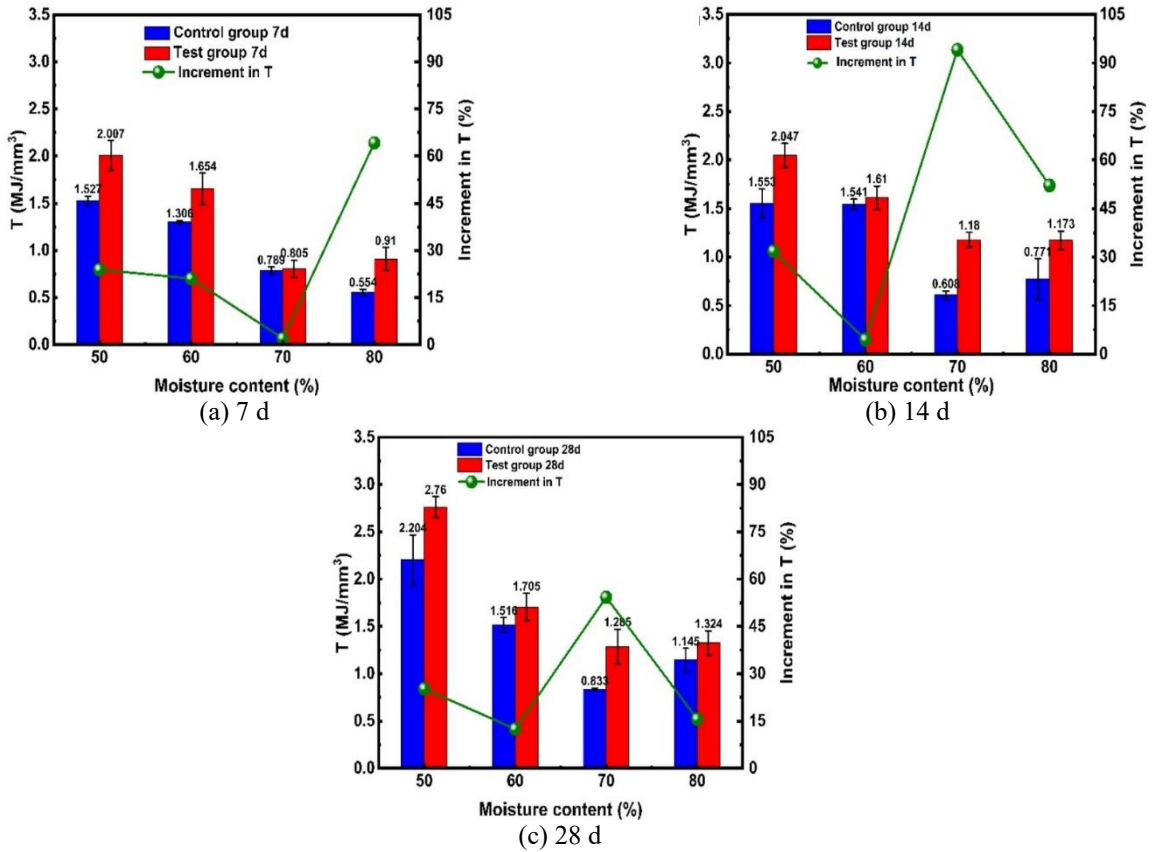


Fig. 11 Comparison of average toughness in different curing time

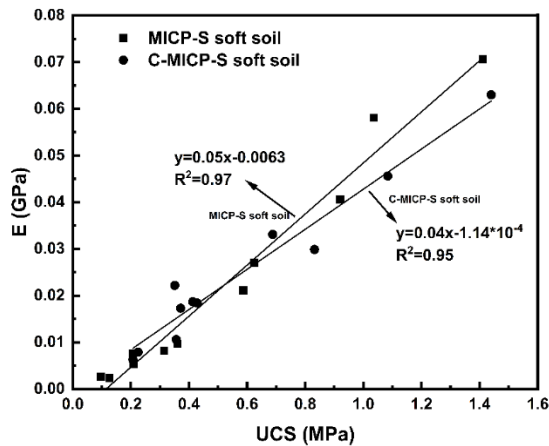


Fig. 12 Relationship between the elastic modulus and UCS

content, whereas they increase with the increase of curing time. The values of UCS of the test group are larger than those of the control group when the moisture content increased. Furthermore, the improvement in UCS is 64.3% and 115.63% when moisture content is 70% and 80%, respectively, compared to that of remolded soft soil at 7 days. It can be also seen that the larger improvement values in UCS were obtained when the moisture content is 70% and 80%. A similar trend could be observed in the variation of elastic modulus (Fig. 10(a)-10(c)) and toughness (Fig. 11(a)-11(c)). Overall, the effect of C-MICP-treated on the UCS, elastic modulus, and toughness is remarkable when the moisture content is higher than 70% and the curing time is longer than 7 days.

3.3 Relationship between UCS and elastic modulus

The strength could be predicted by elastic modulus measured through nondestructive examination, which ensures that the mechanical parameters could be obtained without destroying the specimen. The relationship between strength and elastic modulus were studied in rock deformation prediction (Wang and Aladejare 2016) and concrete cracks limited in early stage (Shen et al. 2016). The elastic modulus of each group of C-MICP-treated soft soil tests is fitted with the corresponding UCS, shown in Fig. 12. The elastic modulus of C-MICP-treated soft soil increases linearly with the increase of UCS, and the correlation between them is consistent with that of the control group. According to the relationship between elastic modulus and UCS, obtaining either of the two parameters is convenient.

3.4 Microstructure analysis

The SEM analysis was conducted with the soft soil treated using MICP or C-MICP and the images are compared in Fig. 13. For the untreated soft soil samples (Fig. 13(a)), it can be seen that the soil particles are mainly irregular flaky aggregates and spongy structures, with loose connections among the particles and numerous pores. Fig. 13(b) indicates that soil units appear as debris and particle aggregates, with indistinctive directional arrangement

characteristics; furthermore, minerals are in edge-to-edge or edge-to-surface contact. For the treatment using MICP, calcium carbonate crystals can be observed on the surface of soil (Fig. 13(c)), and these crystals are irregular schistose (Fig. 13(d)). Moreover, from the images of C-MICP-treated soft soil (Figs. 13(e)-13(f)), a bulk formation of ettringite crystals was observed on the surface of soft soil particles. The ettringite appears as a needle-like and/or cluster-like polymer, the volume of which expands during its formation process resulting in filling the pores of the soft soil. The ettringite was considered one of the main sources of strength of C-MICP-treated soft soil in the early stage (Bian et al. 2021, Zeng et al. 2021).

4. Discussion

It has been widely accepted that the bacteria act as the nuclear site for calcium carbonate precipitation (Rajasekar et al. 2017, Wang et al. 2017, Lee and Park 2018, Yao et al. 2021, Yue et al. 2021, Jiang et al. 2022). In this study, Figs. 13(c) and 13(d) show that calcium carbonate crystals deposited on the bacterial cell wall resulting from the chemical reaction listed in Eqs. (3) and (4). Meanwhile, it can be seen that the size of calcium carbonate crystals is smaller than that of bacterial cells, which also form a rod-like aggregate. Hence, the calcium carbonate precipitated in soft soil is mainly used to fill pores rather than bonding soil particles. Consequently, the MICP method has a weak solidification effect in soft soil reinforcement compared with the studies about bio-cemented sand (Montoya and DeJong 2015, Cui et al. 2021a, Cui et al. 2021b, Wang et al. 2021, Xiao et al. 2021, Ma et al. 2022).

It is obvious that the c and ϕ were improved by introducing the MICP method to soft soil (Fig. 6(a)). On the one hand, the c and ϕ significantly increased in 3 to 7 days and fractionally increased in 7 to 28 days. On the other hand, the c and ϕ increased with the increase of OD_{600} . This phenomenon indicated that the bacterial concentration had more significant effect on the c and ϕ of MICP-treated soft soil compared to curing time. The change trends were in line with the results of CCC in Fig. 6(b). The effect of OD_{600} on the CCC is straightforward: higher bacteria concentration could catalyze more urea to CO_3^{2-} and NH_4^+ , leading to production of more CaCO_3 (Eqs. (1)-(4)) at given curing time. However, the impact of curing time on the CCC in MICP-treated soft soil has been unexplored in current studies (Li 2015, Cheng and Shahin 2015, Islam et al. 2020, Arpajirakul et al. 2021). In this work, the hypothesis was that the MICP process mainly took effect in first 7 days, as indicated by the significant augment in CCC during this initial period.

According to the aforementioned results, the mechanical properties of C-MICP-treated soft soil were improved. It was clear that the increment in UCS increased within 14 days, whereas they decreased at 28 days, which indicated that the MICP process mainly played a role in the early stage, but after 14 days, this process weakened. The reasons are similar to the hypothesis about the MICP-treated soft soil. However, there is a difference between the MICP-

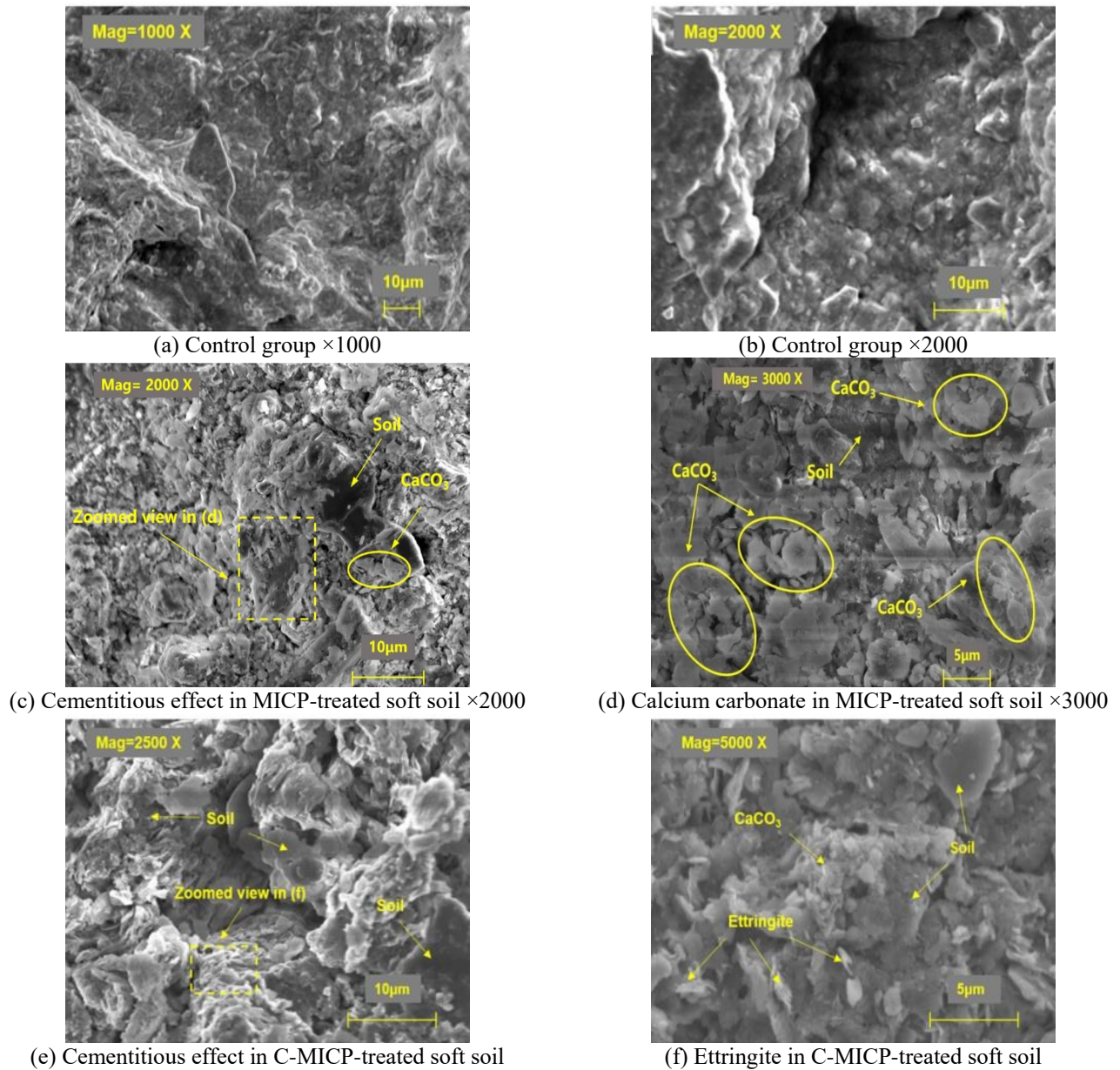


Fig. 13 SEM images of MICP and C-MICP treated soft soil samples

treated soft soil and C-MICP-treated soft soil that the hydration of cement would last throughout curing time. Furthermore, the contribution to the increment in UCS in the later period was greater for C-MICP-treated soil than for MICP. Additionally, ettringite is one of the products of cement hydration reaction, whose volume of ettringite expands by absorbing the amount of water during its formation process leading to denser soil structure. Ettringite is a source of strength of C-MICP-treated soft soil in the early stage in addition to the filling effect of calcium carbonate (Ahmed 2015, Zeng *et al.* 2021).

It can also be observed that the mechanical strength of bio-cemented soft soil is lower despite the findings of this study and other researches (Islam *et al.* 2020, Xiao *et al.* 2020, Arpajirakul *et al.* 2021). Indeed, the increment in UCS was improved in this work, indicating that MICP has the positive effect on improving the strength of soft soil

(Fig. 14). It is important to note that both Arpajirakul *et al.* (2021) and Islam *et al.* (2020) utilized grouting method to reinforce cohesive soil, leading to larger experimental results compared to the other two groups. Furthermore, the incorporation of additives such as bamboo fibers and scallop shell powder (Chen 2021, Gowthaman *et al.* 2021) results in a notable increase in the absolute strength of clay soil, while still maintaining a substantial increment in UCS (Fig. 15). This is particularly evident in the study of C-MICP-treated soft soil, suggesting that the MICP method could be successfully applied in cement-soil scenarios. The use of bio-cementitious mortars demonstrates a significant potential to enhance the mechanical strength of soft soil.

Lastly, it could be observed from Figs. 14 and 15 that the change trends of UCS differed from those of corresponding increment in UCS, particularly noticeable in Figs. 14(c) and 15(c). The objective of the study depicted in Fig. 14(c) was to

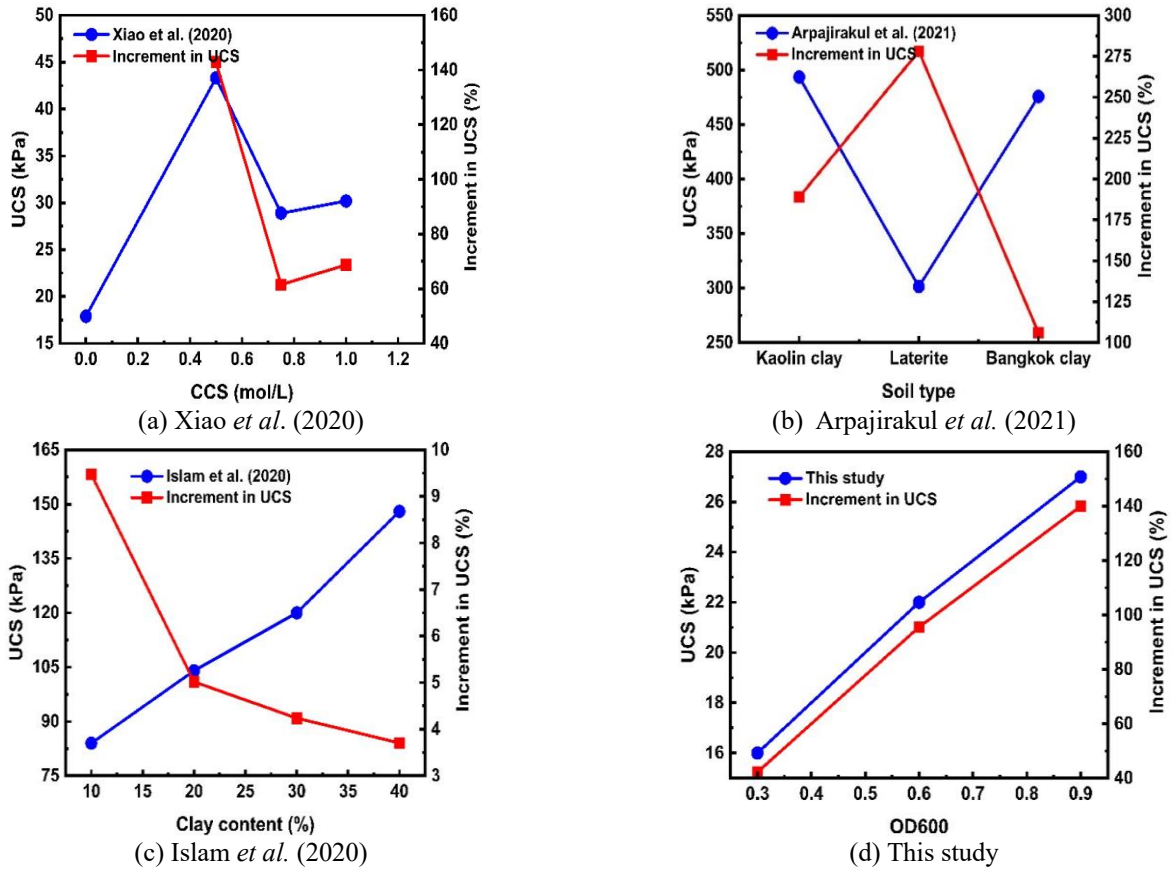


Fig. 14 Variations of the bio-cemented soft soil strength in this study and other literature

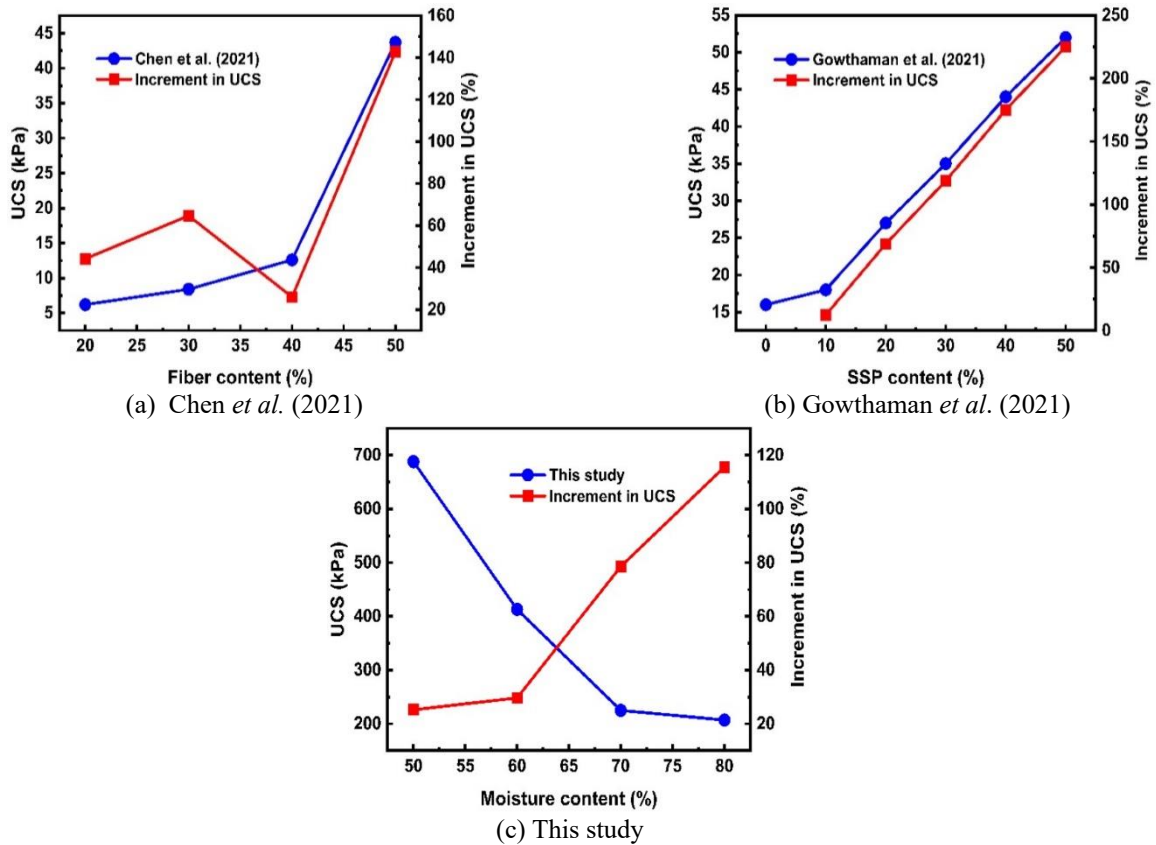


Fig. 15 Variations of the bio-cemented soft soil combined with additives in this study and other researches

investigate the effect of clay content (i.e., medium to fine sand) on the UCS of MICP-treated soil. In this work, the indigenous bacteria were used, and the authors highlighted that the soil with higher clay content had more bacterial population, leading to a more effective MICP process, and consequently, an increase in UCS. However, a higher clay content could result in rapid clogging of the soil, thereby weakening the reinforcement of soil and causing a decline of increment in UCS. Regarding the study presented in Fig. 15, the UCS was found to be sensitive to the initial moisture content of soft soil causing a decrease in UCS of C-MICP-treated soil with the increase of moisture content.

However, with the same cement mixing ratio and biomass in all C-MICP-treated soil specimens, the increment in UCS increased with the increase in moisture content, the reason of which might be that the higher moisture content can dilute the pH of cement-soil (as shown in Table 3), thereby reducing the impact of pH on bacterial activity. Consequently, the increment in UCS of C-MICP-treated soft soil with higher moisture content surpassed those of specimens with lower moisture content, but the specific impact mechanism has yet been unclear, necessitating further research for elucidation.

5. Conclusions

This study aimed to investigate the effect of OD_{600} , concentration of cementation solution and curing time on the mechanical properties of MICP-treated, as well as the effect of moisture content and curing time of C-MICP-treated soft soil. The optimal values of OD_{600} and CCS for MICP-treated soft soil were determined through the triaxial compression test. Additionally, the stress-strain curves of soil samples were obtained by an unconfined compressive strength test, from which the unconfined compressive strength, elastic modulus, and toughness were calculated. Based on the analysis and discussion in this study, the following conclusions can be drawn:

MICP process can effectively improve the strength of soft soil. The variation of internal friction angle and cohesion has the same pattern which exhibits increase with the increase of OD_{600} whereas it increases first and then decreases with the increase of cementation solution. The curing time positively affects the mechanical properties, with the most substantial increment in UCS occurring within the initial 14 days.

Utilizing bio-cementitious mortars at different moisture contents (50%, 60%, 70%, 80%), resulted in significant improvements in UCS, elastic modulus, and toughness compared to ordinary cement-soil. Maximum increment in UCS reached 115.63%, 203.8%, and 94.07%, respectively.

Elastic modulus (E) for C-MICP-treated soft soil correlated with unconfined compressive strength (q_u), consistent with the studies involving ordinary cement-soil without MICP. In this work, a first-order relationship between E and q_u can be expressed as $E=0.04 q_u$. The SEM analysis revealed the precipitation of calcium carbonate crystals on the surface of MICP-treated soft soil. The presence of ettringite and calcium carbonate, filling the

pores of C-MICP-treated soft soil, contributes to the enhanced strength of the soft soil.

Acknowledgments

The authors gratefully acknowledge the financial support of National Natural Science Foundation of China (Grant nos. 41972276, 52108307, 52378392), "Foal Eagle Program" Youth Top-notch Talent Project of Fujian Province (Grant no. 00387088), Natural Science Foundation of Fujian Province (Grant no. 2020J06013), and Qishan Scholar Project of Fuzhou University (Grant no. XRC-22015, GXRC21047).

Data Availability Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Consent to Participate We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

Consent for Publication We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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