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Mechanical Properties and Constitutive Model of Expansive Soil Improved by EICP

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Abstract

In order to study the improvement effect and mechanical properties of expansive soil under different EICP treatment rounds, a consolidated drained triaxial test with EICP treatment times and confining pressure as variables was carried out.The stress-strain curve, Mohr-Coulomb strength envelope, shear strength index c and Φ were calculated and plotted according to the experimental data. Finally, the Duncan-Chang model was used to explore the influence and relationship of EICP treatment times on the parameters of the constitutive model.The results show that : (1) Under the same confining pressure, the peak deviatoric stress of the expansive soil improved by EIPC increases and increases with the increase of the number of treatment rounds. (2) Compared with the unmodified expansive soil, the shear strength indexes c and Φ of the expansive soil after EICP treatment are improved, and also increase with the increase of the number of treatment rounds. (3) When the number of treatment rounds increases to 7 times, the improvement effect is significantly weakened, indicating that there is an optimal number of treatment rounds when EICP improves expansive soil. (4) The triaxial test data were analyzed by the Duncan-Chang constitutive model. It can be obtained that the number of EICP treatment rounds h has an effect on the parameters of the Duncan-Chang model : as the number of treatment rounds increases, the parameters a and b gradually decrease ; the initial tangent modulus Ei increases gradually ; the parameters K and n increase gradually. (5) Through data fitting, the number of EICP treatment h was connected with the Duncan- Chang model parameters K, n, c, Φ, and brought into the Duncan-Chang tangent modulus formula, and the modified tangent modulus equation of expansive soil under EICP treatment was obtained.

Keywords

EICP; Improvement of Expansive Soil; Mechanical Properties; Ducan-Chang Model.

1. Introduction

Expansive soil is a special kind of clay soil. Because it contains more clay minerals such as montmorillonite and illite, it has the characteristics of water swelling, water loss shrinkage and bearing capacity attenuation. In practical engineering, there are great security risks. Therefore, it is particularly important to study the reinforcement method and mechanism of expansive soil. Traditional soil reinforcement techniques such as compaction, dynamic compaction, reinforcement, replacement, compaction, chemical grouting and other methods have been widely used, but these methods are usually expensive, consume more energy, produce greenhouse effect and harmful gases, destroy the environment and threaten human health and life.

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Induced Calcite Precipitation (ICP), as an emerging environmental-friendly soil improvement technology, has received extensive attention in the field of geotechnical engineering. This technology is mainly divided into two types : Microbially Induced Calcite Precipitation (MICP) [1] and Enzyme Induced Carbonate Precipitation (EICP) [2]. Both methods promote the formation of calcium carbonate, and cement the soil particles with unstable properties or poor mechanical properties into a whole, thereby significantly improving their mechanical properties. Compared with MICP technology, EICP technology does not have biosafety risks and does not need to consider whether it is aerobic. For the scope of soil reinforcement, EICP is also more extensive : Since the volume of urease itself is much smaller than that of urease bacteria, EICP is suitable for soil treatment with smaller particle sizes. It can be seen that EICP technology has better feasibility for the reinforcement of expansive soil.

In the past few years, scholars have carried out multi-faceted explorations on the improvement of soil by EICP technology. In terms of the activity of EICP solution, Wu Linyu [3] conducted a comprehensive study of EICP technology, and obtained the optimum temperature and pH value for maintaining high activity of soybean urease and the optimum cementing solution concentration, pH and temperature for the yield of calcium carbonate. In terms of the process optimization of EICP technology for soil reinforcement, Cui Mingjuan [4] et al.proposed an efficient EICP method using a single-phase injection of low-pH solution strategy, which was improved by Li et al. [5] et al. A new EICP technology of unidirectional low-pH negative pressure grouting was introduced to improve sandy clay purple soil. The test showed that the unconfined compressive strength of sandy clay soil improved by EICP was significantly improved. Wu et al. [6] combined EICP technology with xanthan gum to improve the wind erosion resistance of fine sand. After multiple spraying treatments, the mass loss rate of sand was significantly reduced and the erosion resistance was significantly enhanced. At the same time, EICP technology to improve soil has also been applied to practical engineering. Dong Jin [7] applied EICP technology to the field of ancient building restoration to solve the defects of low initial strength, slow curing speed and poor weather resistance of traditional triad soil. These research results and theories also provide some theoretical support for the follow-up study of EICP improved soil.

The shear strength of expansive soil plays an important role in practical engineering design, and the expansion and contraction characteristics are one of the important reasons for the strength attenuation of expansive soil itself. According to Cao Guanghui 's research, [8] EICP can inhibit its expansion and contraction characteristics to a certain extent, thereby improving the shear strength of soil. In this paper, the stress-strain curve and shear strength index of EICP are measured by consolidated drained triaxial shear test with different number of reinforcement rounds as variables. The purpose of this paper is to explore the change rule of stress-strain of expansive soil under different treatment rounds and confining pressure and the influence of EICP treatment rounds on the shear strength index and establish the relationship. Finally, the experimental data are brought into the Duncan-Chang model to explore the influence of the number of EICP treatment rounds and confining pressure on the model parameters and establish a correlation.

2. EICP Solution and Sample Preparation

2.1 Preparation of Urease Solution

According to the previous research results of the research group [9], it was determined that the urease used in the experiment was extracted by soybean. The specific operation is as follows : Put the soybean in the drying oven and bake at 45 ± 5 °C for 6h ; crushing the soybean and then through the 0.25 mm sieve ; the sieved soybean powder was mixed with water in a beaker according to the ratio (10 %) and initially stirred with a stirring rod. After the initial stirring, the stirrer was placed at the bottom of the beaker and stirred again in the mixer for 20 min. After standing for 1h, the solution was placed in a centrifuge barrel for 25 min. Finally, the excess bean dregs were filtered out with filter

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paper, and the supernatant was urease solution, as shown in Fig. 1. The prepared urease solution should be stored in a refrigerator at 4 °C to ensure its activity.

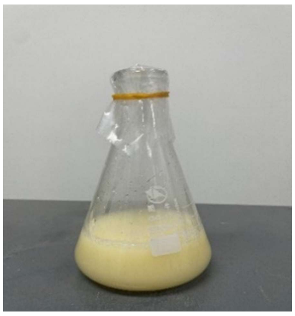

Fig. 1 Urease solution

2.2 Preparation of Cementation Liquid

The cementing solution is composed of anhydrous calcium chloride and urea. The ratio of the two is 1 : 1 and the molar concentration is 1mol. Anhydrous calcium chloride and urea were mixed with water according to the ratio and molar concentration, and the obtained solution was the cementing solution, as shown in Figs.2 and 3.

Fig. 2 Anhydrous calcium chloride and urea

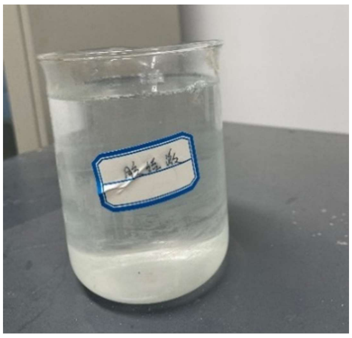

Fig. 3 Cementing solution

2.3 Sample Preparation and Maintenance

The expansive soil used in the test is taken from Guangxi, and the whole is grayish brown. The retrieved soil samples were loaded into a tray and baked in an oven for 24 hours, and then the dried soil was crushed and passed through a 2mm sieve to remove large particles of impurities.

The EICP reinforcement method in the test is mixing method. The required water consumption is calculated according to Formula 1, and the mass of soil required for a single sample is calculated according to Formula 2.

$$m_{\omega} = m_s \times \omega_0 \tag{1}$$

Where m_{ω} is the required water ; m_s is the dry soil quality ; ω_0 is the best moisture content.

$$m_c = \rho_0 \times V \times (1 + \omega_0) \times D_g \tag{2}$$

where m_c is the mass required for a single sample ; ρ_0 is the natural density of soil samples ; V is the specific volume ; ω_0 is the best moisture content ; D_g is the degree of compaction of the sample.

The main steps of EICP to improve soil samples are as follows : take out the soil mass of the sample calculated according to Formula 2, and calculate the water requirement of the soil mass according to Formula 1. The required water consumption was replaced with urease solution and cementing solution in a ratio of 1 : 1, and sprayed into the soil sample with a sprayer, slowly sprayed on one side and fully mixed on the other side. After mixing evenly, put it into a constant temperature box at 30 °C for 12 h to fully react. Before the next round of mixing, the soil sample needs to be put into the drying oven for 12 hours to dissipate its moisture. Finally, the repeated mixing is carried out until the number of experimental design mixing is reached. After the last mixing, the soil sample should be put into the moisturizing cylinder to ensure that the soil sample can achieve the best moisture content (21.4 %).

3. Consolidated Drained Triaxial Test

3.1 Experimental Design

The purpose of this study is to investigate the effect of EICP treatment rounds on the mechanical properties of expansive soil, especially the stress-strain relationship and shear strength index. In order to ensure the validity and reliability of the experimental results, all tests were carried out under the optimum moisture content conditions. A series of different EICP treatment rounds were set in the experiment (in this paper, the number of EICP treatment rounds is defined as the letter h) and different confining pressures were set to systematically evaluate the reinforcement effect and law of expansive soil under different confining pressures. This experiment is a consolidated drained triaxial test with a shear rate of 0.08 mm / min. The specific test scheme is shown in Table 1.

Table 1. Triaxial test scheme

Experimental group	Number of processing rounds	Confining pressure /kPa
1	0	50,100,200,300
2	3	
3	5	
4	7	

3.2 Procedure of Test

During the test, according to the standard of ' Geotechnical Test Method : GB / T 50123-2019 ', the compaction degree of the sample was controlled to be 95 %, and the layered compaction method was used to divide it into 5 layers. The amount of each layer of soil sample needs to be consistent, and each layer of soil sample needs to be scraped. The prepared soil samples were vacuumized in a vacuum saturated barrel for 2 hours and then put into distilled water for 12 hours of water absorption saturation. Finally, the vacuum saturated samples were tested on the machine. The triaxial apparatus selected in this paper is the TKA-TTS automatic stress path triaxial apparatus produced by Nanjing Taikeao Company.

4. Experiment Results and Analyses

4.1 The Effect of EICP Treatment Rounds on the Stress-strain Curve

From Fig. 4, it can be seen that there is no obvious peak value of the deviatoric stress in the test group under all working conditions, and the increase rate of the deviatoric stress increases first and then gradually stabilizes. The peak deviatoric stress of the expansive soil improved by EICP is higher than that of the unmodified expansive soil. At the same time, it can also be found that under the same confining pressure, with the increase of the number of EICP treatment rounds, the peak deviatoric stress of the soil under shear failure is also gradually increasing. Taking the confining pressure of 300kPa as an example : from plain soil to EICP treatment for 7 times, the peak deviatoric stress is 348kPa, 368kPa, 383kPa and 386kPa respectively. This shows that the strength of expansive soil after EICP treatment has been improved, and with the increase of the number of treatment rounds, the

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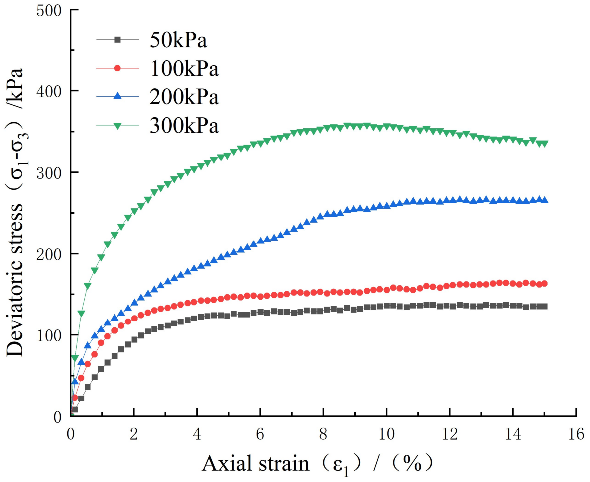
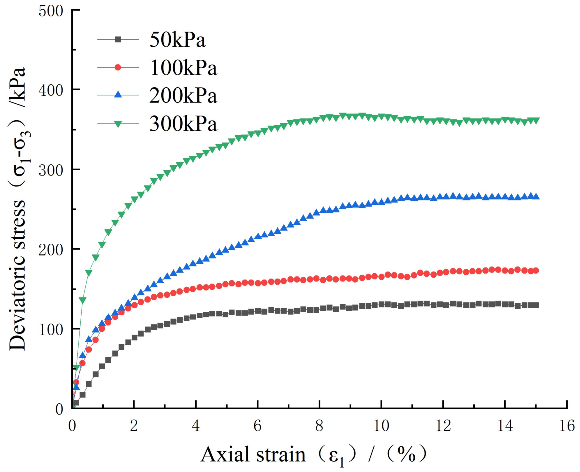
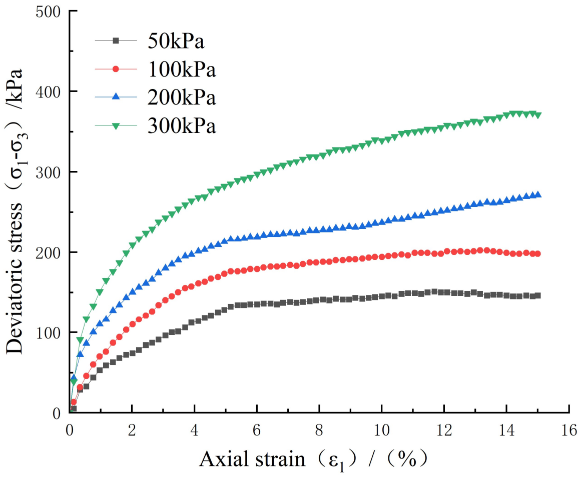
strength increases. However, when EICP was treated for 7 times, the increase of peak deviatoric stress was reduced, and the value was only increased by 3kpa. This shows that there is an optimal value for the number of EICP processing times.



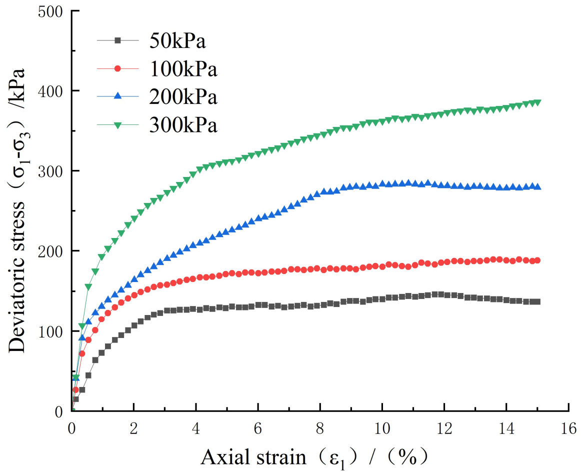
(a) Plain soil



(b) EICP treatment 3 times



(c) EICP treatment 5 times



(d) EICP treatment 7 times

Fig. 4 Relationship between deviatoric stress and axial strain of expansive soil improved by EICP

4.2 The Effect of EICP Treatment Rounds on Strength Index and its Relationship

According to the triaxial test data of plain soil and different EICP treatment rounds, the variation of cohesion c and internal friction angle φ can be obtained by calculating and drawing the Mohr stress circle and strength envelope of the results. Cohesion c and internal friction angle φ are one of the important indexes to evaluate the shear strength of soil. As shown in Table 2 : With the increase of the number of treatment rounds, the cohesion c increased from 29.85 kPa to 34.84 kPa. The internal friction angle φ also increased from 16.31 ° of the plain soil to the final 18.96 °. The test results show that under the same confining pressure, the maximum principal stress of expansive soil treated by EICP is higher than that of unimproved expansive soil. At the same time, with the increase of the number of EICP treatment rounds, the shear strength indexes c and φ of expansive soil are gradually increasing, and the increase of shear strength indexes c and φ becomes smaller when the number of EICP treatment reaches 7 times. The results of this study corroborate the conclusions in summary 4.1.

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Table 2. Shear strength index of specimens

EICP processing times h	c/kPa	φ/°
0	29.85	16.31
3	30.16	18.12
5	34.82	18.61
7	34.84	18.96

Further, according to the data in Table 2, the relationship between the number of treatments h and the shear strength indexes c and φ can be drawn as follows :

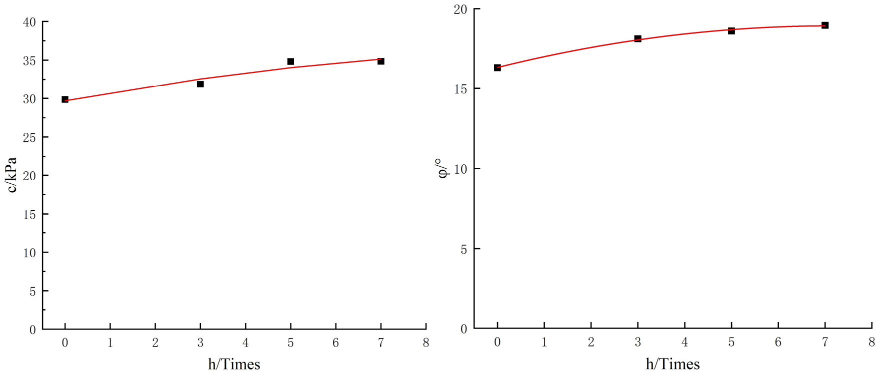

Fig. 5 Process the fitting curve of the number of rounds and the parameters c and φ.

According to the relationship curve in Fig.5 and the nonlinear curve fitting by origin, the relationship between the number of treatment rounds h and the shear strength indexes c and φ can be established and expressed by the function equation :

$$c(h) = -0.043h^2 + 1.076h + 29.694 \tag{3}$$

$$\varphi(h) = -0.0507h^2 + 0.727h + 16.326 \tag{4}$$

5. Constitutive Model of Expansive Soil Improved by EICP

In 1963, Kondner [10] proposed a stress-strain relationship curve that can fit the general triaxial test results based on a large number of triaxial test data. Based on this relationship curve, an incremental elastic model was proposed. The expression of the hyperbola is,

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_a}{a+b\varepsilon_a} \tag{5}$$

In the formula, σ_1 is axial pressure, σ_3 is confining pressure, *a* and *b* are test constants, and ε_a is axial strain. For the traditional triaxial test, there is $\varepsilon_a = \varepsilon_1$, so the formula (5.) can be written as follows :

$$\frac{\varepsilon_1}{\sigma_1-\sigma_3} = a + b\varepsilon_1 \tag{6}$$

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At the same time, the confining pressure σ_3 is constant in the traditional triaxial test process, and satisfies $d\sigma_2 = d\sigma_3$. Therefore, according to the elastic theory, the tangent modulus can be obtained.

$$E_t = \frac{d(\sigma_1-\sigma_3)}{d\varepsilon_1} = \frac{a}{(a+b\varepsilon_1)^2} \tag{7}$$

In Eq. (7), when $\varepsilon_1 = 0$, the initial tangent modulus $E_t = E_i$, so the initial deformation modulus E_i can be written as.

$$\mathrm{E_i} = \mathrm{E_t}|_{\varepsilon_1=0} = \left.\frac{\mathrm{a}}{(\mathrm{a}+\mathrm{b}\varepsilon_1)^2}\right|_{\varepsilon_1=0} = \frac{1}{\mathrm{a}} \tag{8}$$

When $\varepsilon_1 \to \infty$, the limit deviatoric stress can be written as.

$$(\sigma_1-\sigma_3)_{\mathrm{ult}} = \lim_{\varepsilon_1\to\infty}(\sigma_1-\sigma_3) = \lim_{\varepsilon_1\to\infty}\frac{\varepsilon_1}{a+b\varepsilon_1} = \frac{1}{b} \tag{9}$$

In the hyperbolic relationship, the peak value of the curve is usually defined as $(\sigma_1-\sigma_3)_f$. Then the damage ratio can be expressed as.

$$R_f = \frac{(\sigma_1-\sigma_3)_f}{(\sigma_1-\sigma_3)_{\mathrm{ult}}} \tag{10}$$

The tangent modulus expression can be obtained by taking the formula (8) ~ (10) into the formula (7).

$$E_t = \left[1 - R_f\frac{\sigma_1-\sigma_3}{(\sigma_1-\sigma_3)_f}\right]^2 \tag{11}$$

It can be obtained by Mohr-Coulomb strength criterion,

$$(\sigma_1-\sigma_3)_f = \frac{2c\cos\varphi + 2\sigma_3\sin\varphi}{1-\sin\varphi} \tag{12}$$

Combined with the triaxial test data and the fitting analysis of the Duncan-Chang model, the influence of the number of EICP treatment rounds h on the model parameters E_i, $(\sigma_1-\sigma_3)_{\mathrm{ult}}$, K and n can be obtained. At the same time, the relationship between the number of EICP treatment rounds h and the relevant parameters of the model can be established, which provides a theoretical basis for the application of EICP to improve expansive soil in engineering practice.

5.1 The Effect of the Number of EICP Treatment Rounds on the Initial Modulus Ei (*h*) and the Ultimate Deviatoric Stress (σ1-σ3) ult (*h*)

According to the formula (8) and formula (9), the initial deformation modulus E_i and the ultimate deviatoric stress $(\sigma_1-\sigma_3)$ ult are determined by the test constants a and b, and a and b can be obtained by drawing the $\varepsilon_1 / (\sigma_1-\sigma_3) \sim \varepsilon_1$ relationship curve and linear fitting, where a is the intercept of the straight line and b is the slope of the straight line. The details are shown in Fig. 6 and Table 3.

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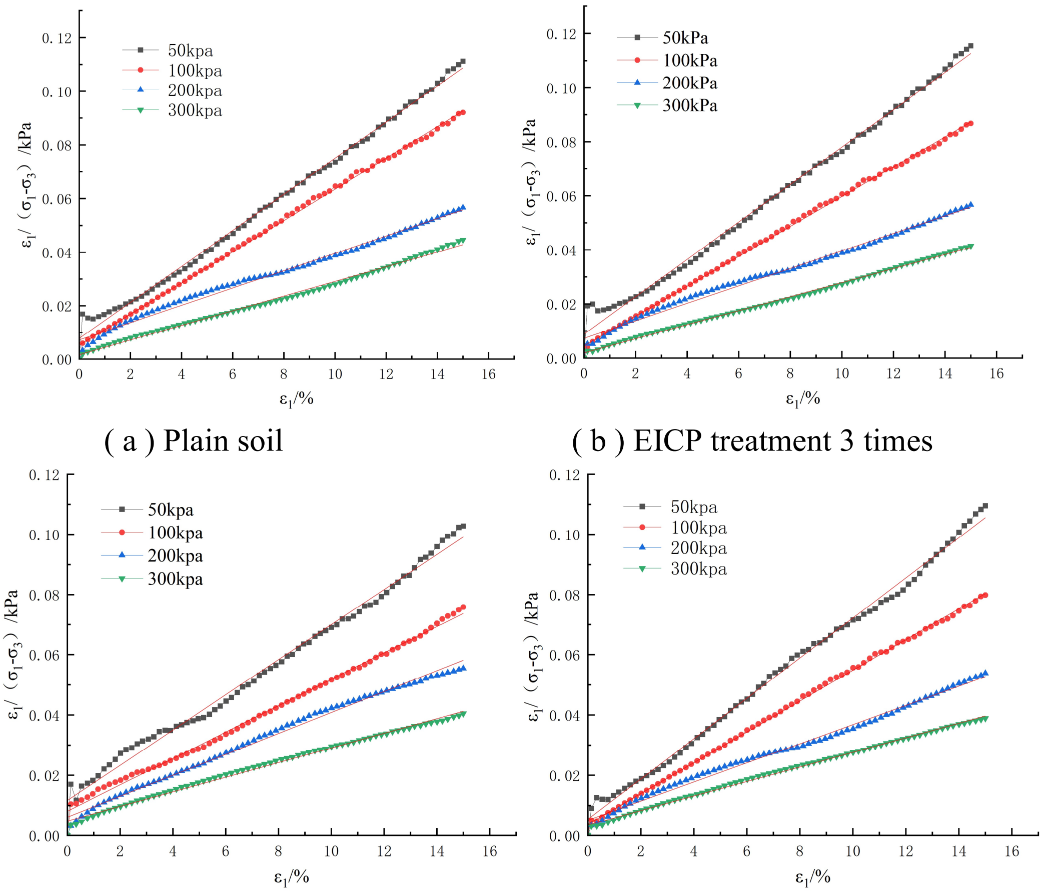

(a) Plain soil (b) EICP treatment 3 times

(c) EICP treatment 5 times (d) EICP treatment 7 times

Fig. 6 $\varepsilon_1 / (\sigma_1-\sigma_3) \sim \varepsilon_1$ curve of the sample

Table 3. Fitting results of test constants, initial modulus and ultimate deviatoric stress of specimens

Treatment times	Confining pressure(kPa)	a	b	E_i ($\times10^3$kPa)	$(\sigma_1-\sigma_3)_{ult}$(kPa)	R_f
0	50kpa	0.00715	0.00773	139.86014	129.36	0.98171
	100kpa	0.00452	0.00583	221.238938	171.52	0.95612
	200kpa	0.00446	0.00324	224.215247	308.64	0.86184
	300kpa	0.00146	0.00275	684.931507	363.63	0.9845
3	50kpa	0.0071	0.00692	140.84507	144.50	0.91344
	100kpa	0.00386	0.00552	259.067358	181.15	0.96048
	200kpa	0.00356	0.00323	280.898876	309.59	0.85918
	300kpa	0.00118	0.0026	847.457627	384.61	0.9568
5	50kpa	0.00598	0.00667	167.22408	149.92	0.94047
	100kpa	0.00338	0.0051	295.857988	196.07	0.9792
	200kpa	0.00246	0.00317	406.504065	315.45	0.85907
	300kpa	0.00113	0.00241	884.955752	414.93	0.89893
7	50kpa	0.00374	0.00583	267.379679	171.52	0.85118
	100kpa	0.0024	0.00437	416.666667	228.83	0.82593
	200kpa	0.00203	0.00246	492.610837	406.50	0.74784
	300kpa	0.00074	0.00212	1351.35135	471.69	0.8162

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It can be seen from Table 3 that the parameters a, b, initial tangent modulus E_i and ultimate deviatoric stress (σ_1-σ_3) $_{ult}$ are affected under the same number of treatment rounds : with the increase of confining pressure, the parameters a and b show a downward trend, while the initial deformation modulus and ultimate deviatoric stress show an upward trend. Similarly, under the same confining pressure, the parameters are also affected by the number of treatment rounds h : with the increase of the number of treatment rounds, the parameters a and b show a downward trend, while the initial deformation modulus and ultimate deviatoric stress show an upward trend. However, R_f has no special rule in the table.

5.2 The Effect of EICP Treatment Rounds h on the Parameters K (*h*) and n (*h*) and Their Relationship

Combined with the initial deformation modulus in Table 3, the model parameters K and n can be further solved. The parameters K and n are test constants, which can represent a certain relationship between the initial deformation modulus and the confining pressure. It is determined by the linear relationship between lg (E_i / P_a) and lg (σ_3 / P_a). The intercept of the line is K, the slope is n, and P_a is atmospheric pressure, usually 101.3 kPa. In model theory, the formula is expressed as.

$$E_i = K\text{pa}\left(\frac{\sigma_3}{P_a}\right)^n \tag{13}$$

According to Equation (13), the data in Table 3 are integrated and calculated and linearly fitted. The results are shown in Fig. 7 and Table 4.

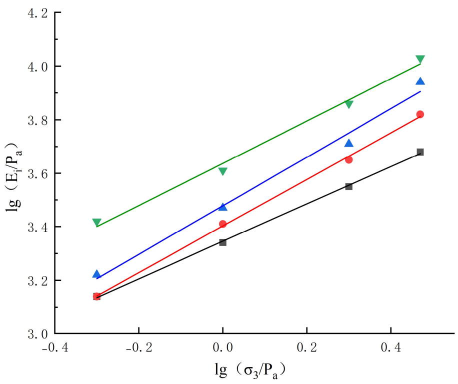

Fig. 7 Relationship curve between initial tangent modulus and confining pressure

Table 4. Values of parameter *K* and parameter *n*

Treatment times *h*	$K/\times10^2$	*n*
0	33.85	0.6991
3	34.03	0.8709
5	34.78	0.9079
7	36.37	0.9297

It can be seen from Table 4 that with the increase of the number of treatment rounds, the parameters K and n are on the rise. The results further demonstrate that the increase of the number of treatments can effectively enhance the improvement effect of EICP reinforced expansive soil.

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Further, in order to establish the relationship between the number of EICP treatment rounds h and the Duncan-Chang model parameters K and n, the scatter plot of the number of treatments h and the model parameters K and n can be drawn according to Table 4, and the nonlinear curve fitting is performed by origin software. Under the premise that the fitting accuracy is not less than 98 %, the function expression of the number of treatments h and the model parameters K and n can be obtained as follows :

$$K(h) = 0.0663h2 - 0.1392h + 31.8762 \tag{14}$$

$$n(h) = -0.002h2 + 0.02362h + 0.4883 \tag{15}$$

According to Duncan-Chang theory, the tangent deformation modulus formula can be obtained by bringing the formulas (12) and (13) into the formula (11) :

$$E_t = KP_a\left(\frac{\sigma_3}{P_a}\right)^n\left[1-\frac{R_f(\sigma_1-\sigma_3)}{2ccos\varphi+2\sigma_3\,sin\,\varphi}\right]^2 \tag{16}$$

In summary, the above formula (3), (4), (14), (15) into the formula (16) can be obtained to deal with the number of rounds of tangent deformation modulus equation is :

$$E_t = K(h)\times P_a\left(\frac{\sigma_3}{P_a}\right)^{n(h)}\left[1-\frac{R_f(\sigma_1-\sigma_3)}{2c(h)cos\varphi(h)+2\sigma_3\,sin\,\varphi(h)}\right]^2 \tag{17}$$

5.3 Model Verification

By re-introducing the model parameters a and b into the Duncan-Chang hyperbolic formula, the fitting stress-strain curve can be obtained. By comparing the fitting curve with the measured curve, it can be concluded that the applicability of this experiment to Duncan-Chang model is good. Taking the test group treated with EICP for 5 times and 50 kPa as an example, as shown in Fig.8, it can be seen that the Duncan-Chang model parameters a and b obtained from the test are suitable for EICP to improve expansive soil.

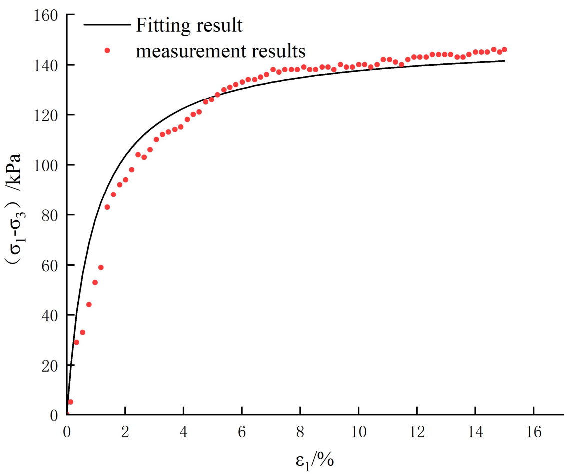

Fig. 8 Comparison of stress-strain curves of improved expansive soil

6. Conclusion

(1) Under the same confining pressure, the peak deviatoric stress of expansive soil improved by EICP method under shear failure is improved, and with the increase of treatment times, the peak

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deviatoric stress is also gradually increased. This shows that EICP technology has a certain effect on improving the mechanical properties of expansive soil. And there is a nonlinear relationship between the improvement effect and the number of treatments.

(2) According to the data of triaxial test, the Mohr stress circle and strength envelope are calculated and drawn. Compared with the unmodified expansive soil, the shear strength indexes c and φ of the expansive soil treated by EICP were improved, and increased with the increase of the number of treatment rounds.

(3) By comparing and analyzing the triaxial test data, it can be obtained that when the number of EICP treatments reaches 7 times, the improvement effect is attenuated. Comparing the two test groups of EICP treatment 5 times and EICP treatment 7 times, it was found that the peak deviator stress increased by only 3kpa. The shear strength index c of the same two adjacent experimental groups increased by only 0.02kpa. It shows that there is an optimal number of processing rounds.

(4) The Duncan-Chang model is used to analyze the experimental data. The influence of the number of EICP treatment rounds on the model parameters a, b and the initial tangent modulus E_i is obtained. Under the same confining pressure, with the increase of EICP treatment times, the parameters a and b are gradually decreasing, while the initial tangent modulus E_i is gradually increasing. At the same time, the model parameters K and n also increased with the increase of EICP treatment times.

(5) Through data fitting, the number of EICP treatment h is related to the Duncan-Chang model parameters K, n, c, φ, and brought into the Duncan-Chang tangent modulus formula, and the modified tangent modulus equation of expansive soil under EICP treatment is obtained.

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