Experimental on electro-osmotic consolidation of bentonite reinforced by nano-Fe$_3$O$_4$

Gang Li$^{1*}$, Rui Zhang$^{1}$, Jia Liu$^{2}$, Huanhuan Li$^{1}$ and Rui Liu$^{1}$

$^{1}$Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an, Shaanxi 710123, China

$^{2}$School of Geological Engineering and Geomatics, Chang’an University, Xi’an, Shaanxi 710054, China

*Corresponding author's e-mail: T_bag945@126.com

Abstract: In order to study the effect of nano-Fe$_3$O$_4$ on the electro-osmotic consolidation of bentonite, four groups of electro-osmotic consolidation tests (T1, T2, T3 and T4) of bentonite with different content of nano-Fe$_3$O$_4$ (0‰, 1‰, 2‰ and 3‰) were carried out with self-design electro-osmotic test device, and the change laws of current, potential, drainage, water content, pH value and shear strength during the test were analyzed. The results showed that the current and effective potential decreased with the increasing of time. After 48 hours, the current of T1-T4 decreased by 99.48%, 97.60%, 96.81% and 95.77%, respectively. The effective potential of T2 decreased the slowest, and the potential loss was significantly lower than the other groups. During the test, the drainage rate increased with the increasing of time. T2 has the largest drainage volume and the fastest drainage rate, and its water content is the lowest. The pH value increased with the increasing of the distance from the anode, while the shear strength decreased with the increasing of the distance from the anode. The results showed that nano-Fe$_3$O$_4$ could significantly increased the consolidation and drainage effect of bentonite.

1. Introduction
Soft clay is widely distributed in the coastal areas of China, which has the characteristics of high water content, large void ratio, high compressibility, low shear strength, low permeability. The commonly foundation treatment methods such as dynamic compaction, vacuum preloading, surcharge preloading, precipitation preloading usually cannot meet the needs of engineering construction. The electro-osmotic consolidation method is to insert electrodes in the foundation and apply direct current electric field, which causes the cation in the soil to move to the cathode and the anion to the anode. When the ion moves in the direction, it drags the surrounding water molecules to move together, thus forming the directional seepage flow from the anode to the cathode. Electro-osmotic consolidation method is a treatment method with good application prospect at present. It can not only improve the bearing capacity of the foundation in a short time and efficiently, but also cannot produce the phenomenon of foundation instability. Therefore, the treatment effect for soft clay foundation is significant[1-2].

In recent years, nano materials are widely used in civil engineering because of their unique mechanism and performance. Gallagher et al.[3] used nano materials to treat sandy cohesive soil, and its performance has been improved by 40% under the combined action of artificial vibration. Whittle et al.[4] pointed out that nanostructures in soil can improve the liquid and plastic limit. Kadivar et al.[5]
found that the specific surface area of nano materials is larger and the interaction between ions is more obvious. The gravity effect can be ignored, instead of the electric field force. And the nano pores and nanostructures in the soil deliberately greatly improve the water content, and nano materials also show some advantages in conducting electricity. Lu et al.[6], Nugent et al.[7] and Sato et al.[8] use SiO\(_2\) to synthesize nano fluid to apply in polymer electrolyte system. Compared with single lithium polymer electrolyte system, the conductivity increases by at least one order of magnitude, and the application of nano SiO\(_2\) material in soft soil electro-osmotic drainage will have a certain promotion. Ozkan et al.[9] found that nano materials injected into the soil can improve the drainage rate and shear strength of the soil. Paczkowska[10] found that adding polymethylmethacrylate to the soft clay with high expansibility for electro-osmotic reinforcement test can make the electro-osmotic drainage of soil faster and more uniform.

The results show that the electro-osmotic method has a significant effect on the consolidation of soft soil, and nano materials have a certain role in promoting the electro-osmotic consolidation. However, currently there are few researches on the electro-osmotic consolidation of bentonite. In this paper, the electro-osmotic consolidation model test is carried out for bentonite, and the influence of nano-Fe\(_3\)O\(_4\) on the current, potential, displacement, water content, pH value and shear strength of the bentonite was analyzed by adding nano-Fe\(_3\)O\(_4\). The research results have significance guiding for engineering practice.

2. Materials and methods

2.1. Test material
The bentonite produced by Sichuan Renshou Xingda Industry and Trade Co., Ltd, China with the chemical formula of Na\(_x\)(H\(_2\)O)\(_y\)(Al\(_x\)M\(_{0.83}\)Si\(_4\)O\(_{10}\)(OH))\(_2\). The bentonite has large water absorption and expansion times, high ion exchange capacity, good dispersion in water medium, high plasticity and strong cohesiveness. Table 1 list the basic physical parameters of bentonite. Nano-Fe\(_3\)O\(_4\) was purchased by Hubei Institute of material protection, China. The nano-Fe\(_3\)O\(_4\) has the advantages of small particle size, easy dispersion, high specific gravity, unique magnetic stability and small biological toxicity.

| w/d% | d/μm | w/p% | w/l% |
|------|------|------|------|
| 1.22 | 49   | 32.1 | 53.7 |

2.2. Test equipment
The test was carried out using a self-designed electro-osmotic model box (as shown in Figure 1(a)). The model box is made of 5 mm thick plexiglass with the size of 270 mm×120 mm×120 mm. There are two 30 mm compartments on both sides of the model box, and there are 5 mm diameter drainage holes in the middle of the compartment bottom. The model box can hold 190 mm×120 mm×100 mm soil samples. Iron electrode (as shown in Figure. 1(b)) is selected as the electrode. The electrode size is 120 mm×100 mm×2 mm, and there are 4 mm diameter drain holes distributed on the electrode. Table 2 listed the main test equipment during the test.
2.3. Test scheme

In order to explore the influence of different dosage (1‰, 2‰ and 3‰) of nano-Fe₃O₄ on electro-osmotic, the electro-osmotic promotion effect of nano-Fe₃O₄ is analyzed by measuring the change of current, electric potential, drainage, water content, pH value and shear strength after being electrified for 48 h at 24 V. Table 3 listed the test scheme of electro-osmotic consolidation. During the test, the current and displacement were measured every 1 h, the effective potential was measured every 12 h. After the test, the shear strength and water content of the bentonite were measured according to the distribution of the measuring points. Meanwhile, the dried soil sample is crushed and sieved, mixed according to the ratio of 1:5 of soil and distilled water, put the prepared solution into the centrifuge, and take the supernatant for pH measurement after centrifugation.

| Test number | t/h | U₀/V | w₀/% | Content/% |
|-------------|-----|------|------|-----------|
| T1          | 48  | 24   | 78.5 | 0         |
| T2          | 48  | 24   | 78.5 | 1         |
| T3          | 48  | 24   | 78.5 | 2         |
| T4          | 48  | 24   | 78.5 | 3         |

3. Results and discussion

3.1. Analysis of the effect of nano-Fe₃O₄ on current and potential
Figure 2 shows the curve of current and potential versus time under T1～T4 tests. It can be seen that the current decreases gradually with the increasing of time. When electrified for one hour, the current decrease rate slowed down after adding nano-Fe₃O₄; after electrified for 48 hours, the current of T1 decreased by 99.48%, T2 by 97.6%, T3 by 96.81%, and T4 by 95.77%. It can be concluded that the test current of the four groups decreased more, the current was smaller, the drainage rate was slower, T1 decreased the most, T4 decreased the least. Figure 2(b) shows the curves of effective potential with time under T1～T4 test. It can be seen that the effective potential decreased with time. The main reason is that the change of soil drainage volume leads to the decrease of water content, the increase of resistance and the decrease of effective potential. After 12 hours, the effective potential of each group began to slow down. After 48 hours, the effective potential of T2 decreased the slowest, and the potential loss in the bentonite was lower than the other three groups.

3.2. Analysis of the influence of nano-Fe₃O₄ on the drainage and water content

Figure 3 showed the curve of drainage versus time during electro-osmotic consolidation test. In the whole process of electro-osmotic, the drainage rate shows a good linear relationship. The drainage curve of T1 and T3 has little difference, and the drainage rate is larger within 0～15 h, and increases slowly after 15 h. When reached 19 h, the displacement of T2 and T4 was almost the same and significantly larger than that of T1 and T3. During the period of 19 h to 48 h, T2 drainage increased continuously. At the end of test, T1-T4 drainage was 292.5 ml, 404 ml, 311 ml and 391 ml, respectively. The initial water content of the sample is 78.50%. At 48 h, the total water content of the four groups is 20.70%, 28.59%, 22.01%, 27.76%, respectively. The drainage of T2, T3 and T4 is 38.12%, 6.32% and 33.68% higher than that of T1, respectively. Therefore, T2 has the largest drainage volume and faster drainage rate. In order to better compare the change of water content under different content of nano-Fe₃O₄, the average values of water content at the same position of four groups of test
distance from anode are calculated respectively, and the results are shown in Figure 3(b). It can be seen that the water content of T2 with 1%\textsubscript{w} nano-Fe\textsubscript{3}O\textsubscript{4} is significantly lower than that of other groups, and the consolidation effect is better.

3.3. Analysis of the influence of nano-Fe\textsubscript{3}O\textsubscript{4} on pH value

![Figure 4. Distribution curves of pH value after electro-osmotic consolidation test](image)

Figure 4 showed the pH versus the distance from anode after electro-osmotic test. It can be seen that the pH value increased with the increasing distance from the anode. The process of electro-osmotic is actually the process of the cation dragging the polar water molecules in the double electric layer and pore water. The more the cations, the greater the drainage rate of electro-osmotic. After adding nano-Fe\textsubscript{3}O\textsubscript{4} material at 24 V voltage, with the progress of electro-osmotic test, H\textsuperscript{+} is continuously generated on the anode surface, OH\textsuperscript{-} is continuously generated on the cathode surface, and the migration of hydrogen ion and hydrogen oxide ion will change the pH value near the anode, so the pH value near the cathode is lower, and the pH value near the cathode is higher. The drainage volume of T2 is the largest, and the pH value at the cathode is the largest, indicating the degree of consolidation is more intense and the effect of electro-osmotic is stronger, which leads to better consolidation effect.

3.4. Analysis of the influence of nano-Fe\textsubscript{3}O\textsubscript{4} on shear strength

![Figure 5. Distribution curves of shear strength after electro-osmotic consolidation test](image)
The purpose of drainage and consolidation under the action of electro-osmotic is to improve the shear strength of bentonite. Figure 5 showed the curves of shear strength versus the distance from anode. It can be seen that the increase of shear strength of soil after electro-osmotic is positively related to the decrease of water content. With the decrease of water content and the closer to the anode, the shear strength of bentonite increases gradually. The shear strength of bentonite measured before electro-osmotic is less than 0.2 kPa, while the minimum shear strength of four groups of test after electro-osmotic is 0.5 kPa, which shows that electro-osmotic method have obvious effect on the strengthening effect of bentonite foundation. Among the test results of T4 with 3% nano-Fe₃O₄, the strength was the highest which reached 30.5 kPa.

4. Conclusions
(1) The current and effective potential decreased gradually with the increasing of time. When it reached 1 hour, the current decrease rate slowed down after adding nano-Fe₃O₄. After 48 hours, the current of T1-T4 decreased by 99.48%, 97.6%, 96.81% and 95.77%, respectively. The effective potential of T2 decreased the slowest, and the potential loss was significantly lower than the other groups.

(2) During the test, the drainage rate increased with the increasing of time. At the end of the test, the total drainage of T1-T4 were 292.5 ml, 404 ml, 311 ml and 391 ml, respectively. T2 has the largest drainage volume and the fastest drainage rate. Meanwhile, the water content of T2 is obviously lower than other groups, and the consolidation effect is the best.

(3) The pH value increased with the increasing of the distance from the anode. The T2 drainage volume was the largest, and the pH value at the cathode was the largest, indicating that the T2 had a better consolidation effect.

(4) The shear strength of the soil decreased with the increasing of the distance from the anode. The shear strength at the anode is the largest, and the shear strength at the cathode is the smallest. The shear strength of T4 is the highest.

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