Micromechanical study of soil conditioning on Sandy Stratum for an EPB Shield

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Abstract. In the construction technology of an earth pressure balance (EPB) shield, soil conditioning is an important technology. It is possible to condition the properties of excavation soil and improve the excavation efficiency by injecting suitable conditioners. Soil conditioning is more important in cohesionless stratum because the flow plasticity of this stratum is typically poor. The soil is conditioned by the interaction between the soil particles and the soil conditioners, the internal principles of which need to be investigated by microscopic tests. Based on the CT test, the changes in porosity after soil conditioning were analyzed, and it was revealed that soil conditioners can make pores form separate structures. Based on the SEM test, the mechanism for the reduction in porosity of the soil was obtained: the flakes formed by the conditioners replaced the original pores.

1. Introduction
Following the invention of shield method, the technology of earth pressure balance (EPB) shield is successfully applied to underground construction in cities. Furthermore, it is widely used in various strata due to its excellent applicability, and it corresponds to the most commonly used mechanized tunneling technology in the world. Soil conditioning technology is an important technical means to improve the adaptability of shield construction, which can improve construction efficiency[1].

The earth pressure balance shield ensures the stability of the excavation face pressure by using a screw conveyor to adjust the amount of unearthed soil[2], and the soil conditioners typically correspond to bentonite, polymer, water, and other conditioners. They can be injected to the excavation face, chamber, and screw conveyor for soil conditioning. Its technical purpose is mainly as follows:

-By conditioning the excavated soil into a moderately homogeneous soil material, it increases the muck transportability in the screw conveyor, and thereby increases the stability of the excavation face during construction[3].

-Reducing the permeability of muck (especially in sand, silt, pebble, and other high permeability formations) to reduce the seepage effect of groundwater in soil.

-Reducing the friction between the soil particles[4], reducing the friction angle in soil particles by injecting the conditioned material, and reducing the torque of the cutter and screw conveyor[5].

Soil conditioning tests are used to test and exam changes in the properties and parameters of sludges after the addition of conditioners, and usually include slump tests, permeability tests, adhesion tests, etc[6].

The principle of soil conditioning is the physical and chemical reaction between the conditioned material and the soil. At present, researchers use microscopic experiments to study[7].
The main objective of the study is to investigate the intrinsic reasons for the changes in porosity and properties of the soil after conditioning. The study of the microscopic mechanism of soil conditioning can provide a theoretical basis for the suitability of the conditioners to the soil, which is important for improving the soil properties and reducing the soil permeability.

2. Research preparation

2.1. Soil parameters

The soil used for the study was from the Harbin Metro Line 2 project in China, a typical sandy stratum. The gradation curve of the soil is shown in Fig.1. Based on the analysis result of the gradation curve, the average particle size of soil is 0.564mm. Additionally, the curvature coefficient $C_c$ of the soil sample is 0.708, and the uniformity coefficient $C_u$ is 4.585, the soil gradation is poor. The soil permeability coefficient is $1.28 \times 10^{-2}$cm/s, which is a highly permeable material.

![Fig.1 Grain size distribution for the tested sands](image)

2.2. Soil conditioning

The main soil conditioning materials commonly used in shield construction are interface active materials, mineral materials and polymers, of which foam, bentonite and carboxymethyl cellulose can be used as representatives. Depending on the type of soil, better results can be obtained by means of compound improvement of different materials, which needs to be studied by laboratory tests.

Based on available research, in sandy stratum, the important goal of soil conditioning involves optimizing the behavior (flow plasticity) and reducing the permeability especially in the high water pressure strata.

Suitable soil conditioners' parameters were obtained through experimental studies, which are given in Table.1. The test results show that the slump of the conditioned soils increased by 400%, and the permeability coefficient decreased by 100 times.

| Soil Conditioners | Mass Concentration/Specific Gravity | Injecting Ratio (Volume Fraction) |
|-------------------|------------------------------------|----------------------------------|
| Bentonite slurry  | $\gamma = 1.2$ (specific gravity)  | 3%                               |
| CMC solution      | $C = 0.4\%$ (mass concentration)  | 8%                               |
| Foam solution     | $C_F = 7\%$ (mass concentration)  | 15%                              |

What changes occur when the conditioned material is mixed with the soil, which results in a dramatic change in soil properties, is something that needs to be investigated in microscopic experiments. Therefore, CT tests and electron microscopic scanning tests were used to study the soil before and after the conditioning.
3. Microscopic experimental studies

3.1. CT test

A high-resolution X-ray 3D microscope was used to scan and image the soils samples to obtain the true 3D structure. The scanned image of the soil was binarised and thresholded according to the difference in grey level of the different components in the image, and the soil specimen was thresholded along the vertical direction (Z-axis) layer by layer, as shown in Fig.2.

![Fig.2 Schematic diagram of soil sample segmentation along the Z axis](image)

3.1.1. Single layer porosity

After the soil conditioning, the porosity will change due to the aggregation of CMC and the filling effect of bentonite. The quantitative statistical calculation of the porosity values for the single-layer slice images of the soil specimens in the XY direction after the threshold segmentation is carried out, and the single layer porosity is calculated as follows.

\[ n_i = \frac{A_{pi}}{A_i} \]  

(1)

Where \( n_i \) is the porosity of layer \( i \), \( A_{pi} \) is the pore area of layer \( i \), and \( A_i \) is the total area of layer \( i \).

According to the results of the single-layer porosity calculation of the unconditioned soil according to Eq.1, the porosity along the Z-axis direction is relatively uniform with small fluctuations, mainly concentrated around 25%, and its maximum single-layer porosity is 29.76% and the minimum single-layer porosity is 23.69%. The variation curve of single-layer porosity distribution is shown in Fig.3, and the single-layer pore distribution of the unconditioned soil is shown in Fig.4, where the blue part is the pores of the unconditioned soil specimen.
The conditioned soil porosity decreases significantly, and the single layer porosity along the Z-axis direction fluctuates significantly, the minimum single layer porosity is 0.01% and the maximum single layer porosity is 3.90%, the change curve of the single layer porosity distribution of the conditioned soil is shown in Fig.5, the single layer porosity distribution of the conditioned soil is shown in Fig.6, where the blue part is the pores of the conditioned soil specimen.
3.1.2. Overall porosity
The overall porosity for a soil specimen is calculated as follows:

\[
p_i = \frac{\sum_{i=1}^{L} A_{pi}}{\sum_{i=1}^{L} A_i}
\]

Where \( L \) is the total number of layers scanned.

According to the calculation result of Eq.2, the overall porosity of the unconditioned soil specimen is 25.67\%. The original 3D image of the specimen and the 3D image of the pore distribution after threshold segmentation are shown in Fig.7. From the pore distribution 3D image, it can be seen that the pores of the soil specimen have been linked into several different pore channels, and the groundwater under pressure accelerates the flow in the channels formed by the pores, destroying the existing structure of the soil and leading to rapid seepage in the unconditioned soil.

According to the calculation result of Eq.2, the overall porosity of the conditioned soil specimen is 1.84\%. The original 3D image of the specimen and the 3D image of the pore distribution after threshold segmentation are shown in Fig.8. According to the three-dimensional image of the pore distribution of the conditioned soil after threshold partitioning, it can be seen that the pores of the conditioned soil show a discrete distribution pattern. Although there are some pores with larger pore sizes, each pore basically exists independently of each other and does not form a channel, which greatly slows down the flow rate.
of groundwater between the soil bodies, blocks the connection pathway between the groundwater flow in the soil bodies and reduces the permeability of the soil bodies.

![Original 3D image of conditioned soil](image1) ![3D distribution of conditioned soil pores](image2)

**Fig.8 Overall reconstructed image of the conditioned soil**

The CT test results reveal the mechanism of soil permeability reduction. The pores of the soil are linked into several different channels and the groundwater flows faster in the channels formed by the pores under pressure, destroying the existing structure of the soil and leading to rapid seepage. The filling effect of the soil conditioners reduces the porosity of the soil and makes the soil pores into separate structures, blocking the channels of groundwater flow between the soil and reducing the permeability of the soil.

### 3.2 Electron microscope scanning test

The soil particles were further magnified for electron microscopic scanning, as shown in Fig.9, the unconditioned soil scan image on the left and the conditioned soil scan image on the right. At the magnification of 5000 times, it can be observed that pores of approximately 1μm in size are present in large quantities in the unconditioned soil, while distinct flakes and flattened materials appear in the conditioned soil replacing the pore portion of the unconditioned soil and forming an obvious stacked aggregation structure with a single flake of approximately 2μm in width.

![unconditioned soil](image3) ![conditioned soil](image4)

**Fig.9 Soil scanning results at 5000 times magnification**

### 4. Conclusion

Based on the tests and results presented above, the conclusions are obtained as below:

1. It is shown that single layer porosity reduced from 29.76% to 0.01% and overall porosity reduced from 25.67% to 1.84% by soil conditioning.
(2) It is shown that the soil conditioners reduce the porosity of the soil and make the soil pores into separate structures, blocking the channels of groundwater flow between the soil and reducing the permeability of the soil.

(3) It is shown that the soil conditioners form flakes and flattened material, replacing the pore portion of the unconditioned soil and forming an obvious stacked aggregation structure.

The results reveal the microscopic effects of the conditioners on the soil. The bonding, separating and replacement effects of the conditioners effectively improve the soil properties, reduce the porosity of the soil, block the connecting channels of the soil pores and reduce the permeability of the soil, which is important for EPB shield projects in high porosity and high permeability strata (like sandy stratum).

The chemical reactions between various conditioners and the soil also affect the results of soil conditioning, which can be a further study.

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